EVALUATION OF RECLAIMED WATER FOR COOLING IN COAL-FIRED POWER PLANTS OF NORTH CAROLINA

By

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Abstract

Cooling systems for thermoelectric power generation are responsible for 39% of the freshwater withdrawal in the US. As the demand for electricity increases, finding alternative water source is crucial. Studies have shown that reclaimed water can be used in certain applications, including makeup water in power plant cooling systems. Concerns about reclaimed water for cooling purpose include potential environmental health impacts during the cooling process, and reclaimed water availability for the cooling systems. This study reviewed the federal and NC state regulations governing the use of reclaimed water for cooling purposes, and the toxicological and epidemiological studies on potential human health impacts of hazards emitted from the cooling systems. In addition, a scenario analysis was conducted to assess reclaimed water availability for coal-fired power plants in NC regarding water transportation costs. The result showed that using a spatial-economic optimization model considering pipeline construction conditions and the potential of pipeline merging can effectively minimize the pipeline construction cost and obtain the least-cost pipeline network infrastructure. The unit transport cost analysis for each power plant also provided the power plant companies the practical information they need for evaluating the feasibility of reclaimed water application for each power plant. Considering the potential issues from water quality and availability, establishing stable supply-demand relationships between reclaimed water source and power plants can be beneficial for both water quality control and makeup water security for power plants.

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1 Introduction

Coal with its relatively low cost and abundance has been utilized to generate half of the electricity consumed in the US. A number of studies have focused on the pollutants released to the environment during coal burning process. Coal-burning results in significant emissions of greenhouse gas, airborne particles, sulfur and nitrogen oxides, and heavy metals into the atmosphere [1]. Therefore, the operation of coal-fired power stations has caused human health and environmental impacts. Both federal and state authorities have established clear regulations and guidelines for the burning operations with respect to potential environmental impacts. In addition to the pollution during combustion, a rising issue of coal-fired power generation is that the use of steam turbines requires significant amounts of water for cooling of the exiting steam. Cooling in electric power facilities is responsible for 39% of freshwater withdrawn in the US [2]. As the demand of electricity resulting from rapid economic development increases, alternative sources of cooling water are needed. This study aims at conducting a comprehensive analysis to evaluate the feasibility of using impaired water for cooling in coal-fired power plants in North Carolina. To evaluate the feasibility of water reuse in North Carolina, potential health risk from use of reclaimed water as well as the spatial availability and transportation of reclaimed water to the power plants is analyzed.

1.1 Cooling system for thermoelectric power plants

Cooling procedures are critical for electricity generation efficiency. In thermoelectric power plants, process water is heated to produce steam that then drives the turbine and generates electricity. The steam is then exhausted from the turbine, cooled and condensed for reuse. The condensing process requires additional water to serve as coolant. Two major types of water-based cooling systems are currently used. These are the once-through and the closed-cycle systems. The former withdraws large volumes of cooling water from adjacent water body. This water is then pumped through the condenser and returned to the water body. The operation of water intake system and the heated water discharge have been shown to cause significant impacts on the natural habitats in the adjacent water bodies. It follows that new construction of the once-through cooling systems are being challenged.

Due to the constraints of constructing once-through cooling systems, closed-cycled cooling systems are increasingly used in newly-built power plants. The closed-cycled cooling system recycles warm water to cooling tower and exposes it to ambient air for cooling through evaporation, which is enhanced by the material used in cooling tower and the natural draft to increase the contact between water and air. Closed-cycled systems may also utilize cooling pond with similar mechanism with cooling tower except that cooling ponds rely on natural heat transfer from water to air. The volume of water withdrawn for closed-cycled cooling system is smaller than once-through system since water will be circulating for reuse, but consumption of cooling waters occurs through blowdown and evaporation. Water withdrawal volume required for cooling in thermoelectric power plants varies depending on the fuel type and cooling systems.

The increase of electricity demand has further burdened limited local water resources in some regions of the US. Figure 1 shows the county-level Thermoelectric Cooling Constraints Index considering local water supply sustainability and the growth of electricity generation in 2025 [3]. Cooling water constraints occur in a nation-wide scale, especially in pacific coast states. This phenomenon indicates that alternative cooling water sources to sustain freshwater consumption is inevitable in the future.

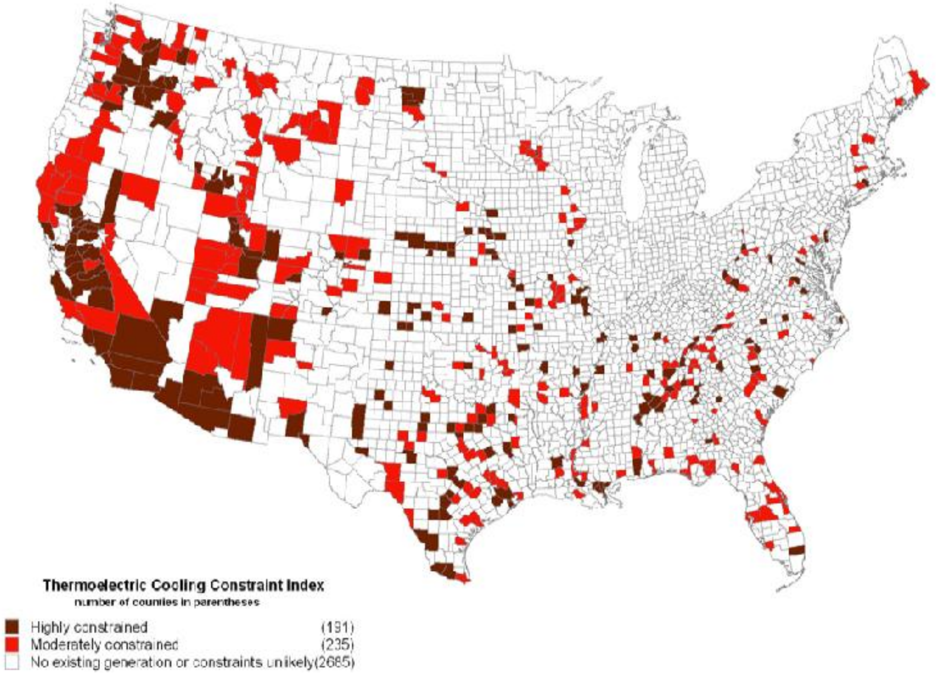

Figure 1: County-wide Thermoelectric Cooling Constraint Index for 2025 of the US [3].

1.2 Publicly Owned Treatment Works (POTWs) and reclaimed water reuse regulation

Three potential alternative sources of cooling water have been proposed including: treated wastewater, treated mine drainage, and ash transport water from coal-fired power plants [4]. Among the alternatives, secondary treated waste water from POTWs is the most common and widespread recycled water source in the US. Owned by local governments, POTWs receive domestic sewage and some non-domestic wastewater from residential, commercial, and industrial facilities for pre-treatment processes before waters are transported to treatment plants. In the US, an estimated 21,594 POTWs are currently providing wastewater collection, treatment, and disposal service to 226.4 million people [5]. The general wastewater treatment process is illustrated in Figure 2.

The level of required treatment depends on how reclaimed water is to be used. The treatment process can be divided into primary, secondary, and tertiary (advanced) treatments [6]. Before entering the sewer system, wastewater is strained to remove the large items by bar screens to prevent their flowing into and damaging the clarifier. After the preliminary treatment, wastewater undergoes primary treatment, which further removes suspended solids by sedimentation creating a generally homogeneous liquid for subsequent biological processes. Secondary treatment uses activated sludge in an aeration environment to remove up to 90% suspended organic matters as well as heavy metals and other impurities attached to the suspended solids. The clarified liquid then continues on to disinfection mainly through chlorination. After removing the disinfectant, the water is then clean enough for discharge to the environment and for some reuse processes. Tertiary treatment usually proceeds under the requirement for specific reuse purposes. The advanced treatment can be accomplished by a variety of methods including coagulation sedimentation, filtration, reverse osmosis, and nutrient removal by secondary biological processes.

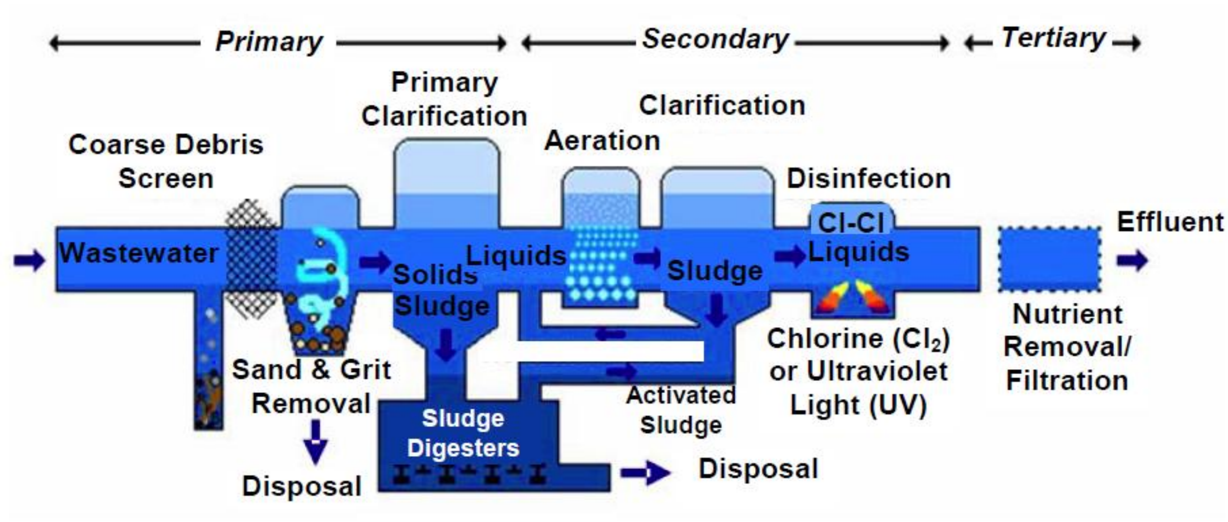

Figure 2: Conventional wastewater treatment process [7]

1.3 Local availability of reclaimed water for power plant cooling needs

Local availability of reclaimed water for power plants is critical when considering feasibility of water reuse for cooling. Several spatial studies have been conducted to investigate amount of reclaimed water supply in the vicinity of power plants. This is needed to analyze the potential of replacement of fresh cooling water by local reclaimed water sources. An internet-based geospatial information system (GIS) catalog for non-traditional water source for coal fired power plant cooling purpose has been developed to provide the overview of reclaimed water availability in the US and information for reclaimed water suppliers [8]. Alternative water source within 15 miles of a given location can be identified with information on water supply volume, quality and distance to provide power plant operators the basis for evaluating feasibility of using reclaimed water for cooling needs.

University of Pittsburgh conducted the nation-wide study on the supply-demand analysis of regional and local reclaimed water from POTW as cooling water for power plants using GIS [4]. The total volume of reclaimed water from POTW within 10 and 25 miles radius from power plants were inventoried to determine whether water supply is sufficient to meet the cooling needs. The results show that the reclaimed water supply from POTW within 25 mile radius from proposed power plants can fulfill the cooling water demand in 9 out of 11 North American Electric Reliability Corporation (NERC) regions, including Region SERC where North Carolina is located. The nation-wide study provides an overview of the regional proximity of POTWs to power plants and the number of POTWs needed to fulfill the cooling water demand for any proposed power plants.

1.4 Pipeline deployment for reclaimed water transport

The transport of reclaimed water from POTWs to power plants requires pipeline connection. Pipeline construction and route for deployment are greatly influenced by the geographic elevation and land use patterns. To further identify POTW sites with most potential for certain power plants and to minimize pipeline construction cost, the cost surface representing relative cost of constructing a pipeline through various types of terrain must be determined. Both geographic features and land cover data should be considered in the POTW selection process. A cost surface for the transportation of carbon dioxide from source to sink developed at Massachusetts Institute of Technology (MIT) for carbon dioxide capture and storage (CCS) deployment can be utilized [9]. The cost surface quantified the difficulties of pipeline construction based on those surfaces with higher cost such as the crossing of waterways, highways, railroads, and slopes, as well as the environmental impacts for sensitive areas including national parks, state parks, wetlands, and populated areas. Choosing the water sources for the power plants considering the transportation difficulties provide more feasible assessment for future practice.

1.5 Health concerns about reclaimed water for cooling

According to "Guidelines for Water Reuse" [10] released by US Environmental Protection Agency (USEPA), secondary treatment is the minimum standard for municipal waste water in POTW, and the quality of treated water effluent is also regulated including pH values, and the concentration of BOD_5, TSS, and fecal coliform. 40CFR423 also limits the concentrations of free chlorine, Chromium, and Zinc in discharge. However, some additional concerns are still needed for regulating contaminants in cooling tower using reclaimed water. For example, both organic matter and nutrients in the reclaimed water provide the growth environment for microorganisms. Thus, free chlorine has been utilized as a biocide in waste water treatment with the minimal concentration of 1 mg/L. However, high concentration of chlorine will produce trihalomethanes and other byproducts which are considered carcinogenic or mutagenic [11].

Another significant hazard identified from the cooling tower is Legionella, a pathogenic bacterium and the cause of Legionnaires' disease (LD). Legionella can be transmitted from cooling towers to the susceptible receptors through aerosols. LD has been definitively linked by retrospective epidemiological studies with exposure to contaminated water in cooling towers [12, 13]. Improper maintenance of cooling towers can result in outbreak of Legionella due to temperature conditions around cooling towers creating a favored environment for bacterial growth. California state government regulates the emission of Legionella through requiring the addition of chlorine or other biocides during the treatment, yet neither federal nor North Carolina governments include this requirement.

The exposure routes for hazards in reclaimed water include water- and airborne routes. Waterborne routes include the blowdown water from the cooling tower, waste streams from treatment processes associated with the cooling circuit, and sludge generated from cooling system maintenance. Airborne routes include evaporation during the cooling process and drift exhausted with air into atmosphere from the cooling towers. Among these routes, drift contains highly concentrated metals, nutrients, and microorganisms and can pose health risks for workers and residents in the vicinity areas; thus, the airborne exposure route is considered as the most important for hazards associated with cooling towers [14].

1.6 Aim and scale of study

My study aims at providing a comprehensive evaluation for the application of reclaimed water from POTW for cooling in coal-fired power plants in NC. I shall confine my scale of analysis to NC to provide analysis under the same state regulation and limitation. Potential hazard, Legionella, is assessed regarding their health risks to examine current water quality regulations. Reclaimed water availability for individual power plants with the optimal pipeline transportation network is also included using a spatial-economic optimization model. This analysis results in both reclaimed water quality and availability for the reuse application and provides an analytical basis for future strategic planning and decision making.

2 Methodology of the study

The flowchart of the analysis procedure is shown in Figure 3.

The federal and NC state regulations and guidelines including wastewater standards, reclaimed water treatment standards, and the regulations on cooling tower water discharge and air emission on reclaimed water reuse for power plant cooling were first reviewed. The epidemiological and risk assessment studies on the potential human health risks from reclaimed water applied to power plant cooling systems were also reviewed. These focused on the potential hazards from drift released to the atmosphere during cooling processes. Further reviews on toxicological and epidemiological studies, guidelines, and management standards for Legionella were also conducted.

In addition to water and risk assessment, water availability analysis in NC was also conducted. The inventories of POTWs and coal fired power plants were developed considering their geospatial information availability and state regulation. The volume of water supply was derived from the database, and the water demands from power plants were estimated according to annual electricity generation. Both POTWs and power plants in NC were transferred to digital spatial data. A scenario study was then conducted to assess water availability considering water transportation costs and properties in NC. Water availability regarding the least linear distance from POTWs, the least distance from POTWs considering pipeline construction conditions, and the cost minimization considering both the construction conditions and the potential of pipeline merging are assessed as three scenarios. A unit transport cost analysis for each power plant was also conducted to evaluate the feasibility of reclaimed water for cooling in each power plant. The suggestion for the reuse of reclaimed water for power plant cooling was based on the risk assessment reviews and the cost analysis of water pipeline network.

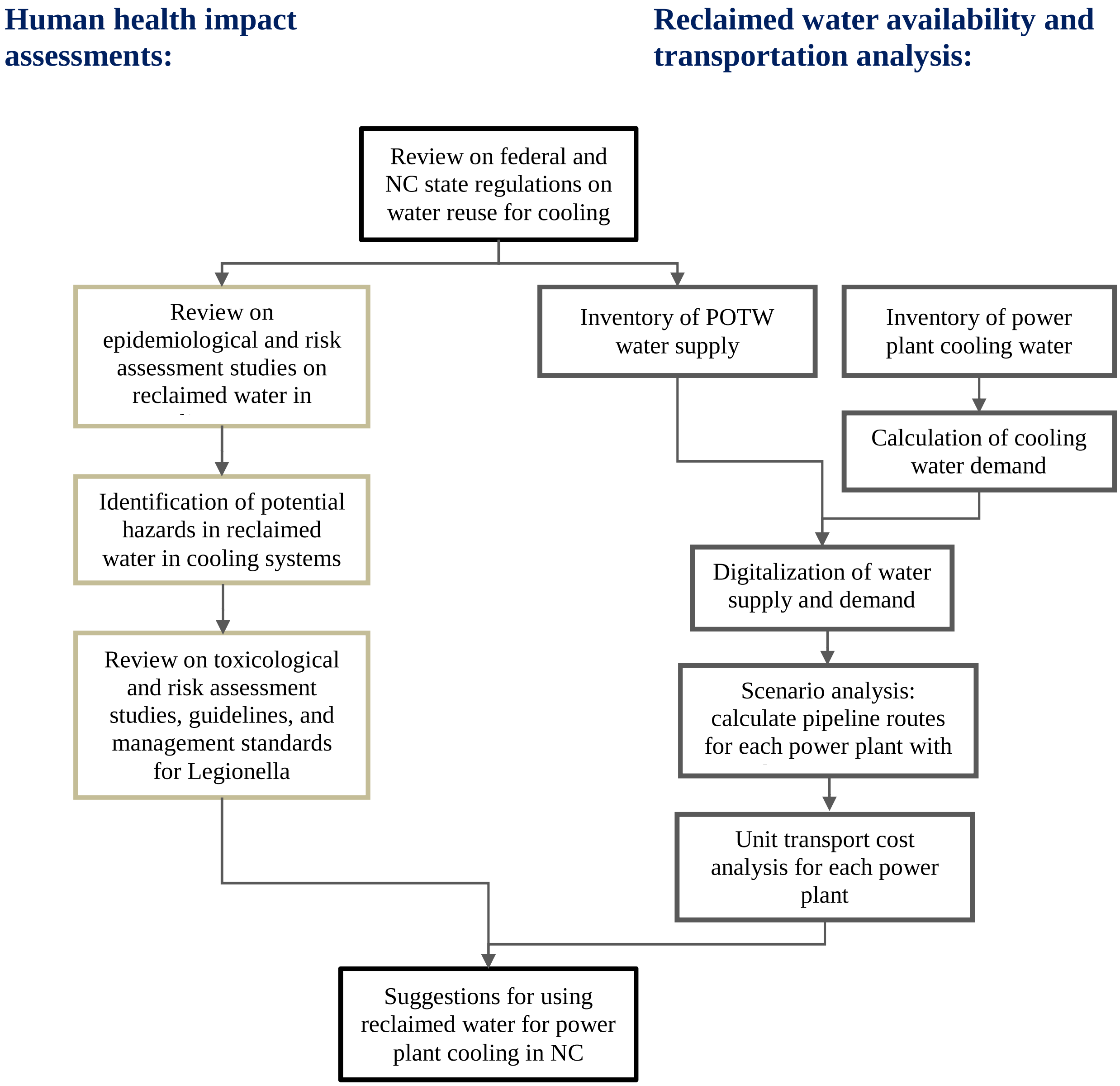

Figure 3: Methodology flowchart of the study.

The human health impact assessment as well as the reclaimed water availability and transportation analysis led to the suggestions for using reclaimed water for power plant cooling in NC

3 Regulations and risk assessments of reclaimed water for cooling

The process of wastewater reuse, as cooling water, contains three main steps. Municipal and industrial wastewater is first transported to vicinity POTWs for treatment and become reclaimed water. The reclaimed water is then transported to the site of power plants through water pipelines, and reclaimed water is then imported into cooling tower as makeup water. Wastewater typically contains a range of hazards including heavy metals, pathogens, and organic matters that are proven to be harmful to human health and ecological environment. Therefore, intense regulations regarding treatment operations and discharge of POTWs have been established by both federal and state governments. In contrast, the requirements and regulations for the following reuse process for reclaimed water from POTWs have not yet been specified. The related regulations and guidelines of reclaimed water reuse for cooling were reviewed in this chapter.

In addition to current regulations, increasing studies are conducted to identify the potential risks for reclaimed water reuse for cooling. Although no current study has conducted a complete environmental risk assessment specifically for the reuse, a number of potential hazardous materials in the reclaimed water and their potential exposure routes to human have been discussed. In this chapter, the studies related to the risks from the reuse processes were reviewed, and potential approaches for future studies were also reviewed and discussed.

3.1 Federal and state regulations of reclaimed water for power plant cooling

Federal and North Carolina state regulations for the reclaimed water reuse process are summarized in Table 1. According to the hierarchy of American legal system, state regulations will only be equal to or stricter than federal regulations for the states to comply. If the states do not have specific regulations, federal regulations or guidelines are applied. For the reclaimed water reuse related regulations, North Carolina has specific regulations on the reclaimed water quality requirements and on the cooling tower discharge, which are considered in the following feasibility analysis for North Carolina.

Table 1: Summary of federal and NC regulations and guidelines on reclaimed water reuse.

	Federal	North Carolina
Wastewater treatment	**Clean Water Act** • Prohibited Discharge Standards (40 CFR 403.5) • Categorical Pretreatment Standards (CWA S307) • Local Limits (40 CFR 403.8(f)(4), 40 CFR 403.5(c))	N/A
Reclaimed water reuse	**Guideline for Water Reuse** • >secondary treatment • <30 mg/L of BOD and TSS • <200 fecal coliform/100 ml • >1 mg/L residual chlorine • pH 6-9	**15A NCAC 02T.0906** • >tertiary treatment • <10 mg/L (monthly) and 15 mg/L (daily) of BOD • <5 mg/L (monthly) and 10 mg/L (daily) of TSS • <4 mg/L (monthly) and 6 mg/L (daily) of NH$_3$ • <14/100 mL (monthly) and 25/100 mL (daily) of fecal coliform • >10 NTU Turbidity **15A NCAC 02T.0910** • notification, education, records
cooling tower discharge	**CWA** • NPDES permit **40CFR423** • pH 6-9 • <0.2 mg/L (monthly) and 0.5 mg/L (daily) Chlorine • <0.2 mg/L Chromium • <1.0 mg/L Zinc	**15A NCAC 02B.0208** **15A NCAC 02B.0211** **Thermal (Temperature) Variances to North Carolina Water Quality Standards** • water quality standard for temperature for specific water bodies
air emission	**NAAQS** • PM$_{10}$: 150 ug/m^3 (24 hrs) • PM$_{2.5}$: 15 ug/m^3 (annual) • 35 ug/m^3 (24 hrs)	N/A

3.1.1 Regulations for wastewater treatment and POTW operation

From Table 1 above, POTW operations are regulated by the Federal Clean Water Act (CWA). CWA is the statutory authority for both the National Pollutant Discharge Elimination System (NPDES) Permit Program and the National Pretreatment Program. A POTW is identified as a point source that discharges pollutants to surface waters and thereby requires a NPDES permit for the treatment operations. Section 307(b) regulates industrial facilities and requires that pre-treatments be conducted before discharging wastewater to ensure the effectiveness of treatment for POTWs. In addition, the National Pretreatment Program regulates the source of wastewater that flows to POTWs with discharge standards and pretreatment standards for particular industrial categories.

The National Pretreatment Program applies three types of discharge standards:

- **Prohibited Discharge Standard**: the standard applied to all Industrial Users (IUs) forbids the discharge of specified pollutants, including pollutants that will affect or damage the function of POTW or cause health and safety problems to a POTW. The standard, however, does not set up specific pollutant limitations, so the additional regulations, such as Categorical Pretreatment Standard and Local Limit, are needed.
- **Categorical Pretreatment Standard:** the standard is applied to Significant Industrial Users (SIUs) defined by 40 CFR 403.3(v). EPA developed general pretreatment standards for many industrial categories.
- **Local Limit:** EPA gives POTWs the authority to develop their own local limits for their potential waste water source in order to achieve the effluent limitations as specified in its National Pollutant Discharge Elimination System (NPDES) permit.

3.1.2 Regulations for reclaimed water reuse

Federal regulation

Although the limitations for POTW water effluent quality are clearly identified in CWA, the reuse of reclaimed water as power plant cooling water has not been specifically regulated. In 2004 Federal EPA published "Guidelines for Water Reuse" [10], which includes the types of water reuse, treatment suggestions, related technical issues, and a number of water reuse examples for different purposes. The federal guidelines for using reclaimed water for cooling are listed below [14].

- The minimum treatment requirements include secondary treatment, disinfection, and possible chemical coagulation and filtration. Additional treatment may be performed by the user to prevent scaling, corrosion, biological growth, fouling, and foaming.
- The reclaimed water should contain <30 mg/L of biochemical oxygen demand (BOD) and total suspended solids (TSS), <200 fecal coliform/100 milliliters (ml), a minimum of 1 mg/L residual chlorine, and a pH range of 6.0–9.0.
- Windblown spray should not reach areas accessible to workers or the public. This requirement can be met by providing a setback distance of 90 meters. The setback may be reduced or eliminated if a high level of disinfection is provided.

NC regulation

In general, North Carolina has developed stricter regulations regarding reclaimed water reuse and discharge from industrial cooling systems. Specific information regarding the North Carolina Administrative Code (NCAC) for Reclaimed Water Utilization was reviewed in National Energy Technology Laboratory report [4]. Tertiary treatment is required for reclaimed water to be reused for cooling. The limitations for BOD, TSS and fecal coliform are also stricter than the federal standard. In addition, the concentration of NH_3 and the turbidity of water are also regulated. Other requirements for reclaimed water reuse in NC includes the notifications to public and employees of the reuse about the non-potable properties of reclaimed water, the appropriate education to reclaimed water users and approval from the reclaimed water generator, the records of reclaimed water distribution, and the inspection and review of the pathways for water transportation.

3.1.3 Regulations for cooling tower discharge

Federal regulation

The application of federal regulations also does not have specific regulations on the discharge of reclaimed water from cooling tower [15]. In CWA, cooling tower is regulated as a point source discharge of pollutants to surface water bodies, requiring an authorized NPDES permit. Specific Clean Water Act regulations in the Code of Federal Regulations (40CFR423) set up the standards for steam electric power plant discharges, including the limitations for pH values, free chlorine, total chromium and zinc for once-through cooling water and cooling tower blowdown water.

NC regulation

NCAC develops thermal discharge water requirements to protect the destination water bodies [16]. The rule limits thermal discharges to 2.8 degrees C above the natural temperature of the destination water bodies. The permit is required for exceptions to the limits. In North Carolina, 8 coal-fired power plants hold the permits by demonstrating that the less stringent thermal limitations will not affect aquatic systems in a site-specific manner.

3.1.4 Regulations for cooling tower air emission

In addition to blowdown water, air emission through evaporation and aerosol drift during cooling process is addressed in the Guideline for Water Reuse [10]. This suggests that when reclaimed water is used in industrial cooling, windblown spray should not reach areas accessible to workers or the public, since the drift usually contains highly concentrated contaminants including metals, chlorine metabolites, nutrients, and microorganisms. Most of the power plants have also installed drift eliminators to reduce the amount of drift released into the environment. Although no federal regulations specifically limit the air emission from cooling towers using reclaimed water, Clean Air Act (CAA) regulates cooling tower as potential point emission source, which is required to comply with National Ambient Air Quality Standards (NAAQS).

3.2 Risk assessment of applying reclaimed water to power plant cooling system

The human health risk assessment of reclaimed water reuse has focused more on irrigation. This is mainly due to the multiple exposure routes of environmental toxicants through irrigation, including crop contamination, inhalation and dermal contact by the farmers and workers. As more reclaimed water is applied to industrial cooling, potential environmental impacts from water reuse as cooling water have led to increased concern [4]. The potential hazards in cooling water, exposure routes of contaminants from cooling towers to the environment, and the toxicity of contaminants to human will be reviewed in this chapter.

3.2.1 Potential hazards in reclaimed water

Hazards in reclaimed water largely depend on the source and composition of the wastewater. The contaminants from POTWs that are of the most concern include: pathogens, trace organics, heavy metals, endocrine disrupting chemicals, pharmaceutically-active compounds, and nutrients. In addition, the byproducts of chlorine, the common disinfectant used in wastewater treatment, are also found both in the effluent and the emitted drift from cooling towers [17]. Emission of particulates from air drift is also of major concern in cooling towers due to salt deposition and concentration during the cooling process. Although federal regulations and guidelines have set up standards and limitations for most hazardous materials, the limitations to some pathogens are still not well-defined in North Carolina state regulation. The most concerned pathogen that has been detected in both the drift and blowdown water from cooling towers is Legionella that causes LD. Also, the additional disinfection treatment required for reclaimed water in the cooling towers may also cause excessive concentrations of hazardous chlorine byproducts with their subsequent release to the environment. Among all potential hazards, Legionella is the most prevalent contaminant currently associated with cooling towers, especially when reclaimed water is reused as the alternative cooling water source [1, 4, 13].

3.2.1.1 Legionella - Environmental source

Legionella is commonly found in natural aquatic environment such as rivers and ponds. Widely spreading via aerosols and capable of surviving extreme environmental conditions, Legionella is also found to contaminate a wide range of human water facilities. Cooling tower provides one of Legionella’s favorite environments for growth. The following conditions are particularly important:

1. The warm water environment between 68 and 113 degrees F (the optimal reproduction temperature for Legionella is 95 degrees F)
2. Sediment and food sources supporting the growth of Legionella and the microbiota that supply essential nutrients for Legionella

3. Certain amoebae and other protozoa that provide the habitats for the environmental survival and reproduction of Legionella

Other potential sources of contaminated water include large air conditioning systems, whirlpools and spas, fountains, ice machines, vegetable misters, shower heads, and even potable water system [18]. The wide spread of Legionella in the urban water systems would increase the risk of potential outbreak of LD and thus raise the public health concern.

3.2.1.2 Legionella - Pathogenesis and epidemiology

Legionella is a pathogenic Gram negative bacterium including L. pneumophila that is the major species to cause LD. Legionella typically proliferates intracellularly in protozoa within biofilms. The growth within protozoa enhances the capability of Legionella to survive under less favorable conditions and also protects Legionella from disinfection treatment. Legionella is transmitted via aerosols. Person-to-person transmission does not occur in the existing outbreaks [19].

LD was first recognized as a distinct pneumonia during the outbreak of pneumonia in Philadelphia in 1976 [20]. 182 cases with 29 deaths were reported, including the members of the Pennsylvania State American Legion who attended the annual convention in the summer of 1976, visitors, and residents. Legionella were isolated from lungs of patients and identified as the etiologic agent of Legionnaires' diseases. The potable water system in a hotel where the Legion members stayed was identified as the source of Legionella, which was spread through aerosols to patients in town.

A number of epidemiological studies have also found that the Legionella-contaminated cooling tower systems in urban areas, including hospital and air conditioner cooling towers, were linked to the regional outbreak of LD. In 1994, a community outbreak of LD with 29 cases was reported in Delaware [21]. The case-control study found that for those people who lived, worked, or visited within 4 miles of the hospital, the odds ratio for the disease increased when the distance from the hospital decreased and when the time spent near the hospital increased. The dose of exposure was quantified by "Aerosol Exposure Unit" (AEU). The water samples taken from the main cooling tower were found to contain identical subtypes of Legionella species with water samples from the homes of 2 patients. The results suggested that contaminated aerosols from the hospital cooling tower were responsible for the outbreak.

An outbreak in Pas-de-Calais, France in 2004 demonstrated that the contaminated aerosols emitted from an industrial cooling tower can undergo transport over a long distance [22]. The case-control study confirmed 86 cases as having LD. The living locations of these cases were compared with the concentration contours of aerosols from the plant simulated by the air dispersion model. The consistency between estimated concentrations of the presumably contaminated aerosols and the commune-attack rate suggested that the cooling tower in the petrochemical plant was the source of Legionella. The results showed that the Legionella-contaminated aerosols spread at least 6 kilometers from the petrochemical plant and, after spread, remained pathogenic.

3.2.1.3 Legionella - Detection and disinfection

Due to the symbiosis of Legionella with protozoa within biofilms, detection and disinfection of the pathogen become more difficult. The standard method for detection is to cultivate samples in selective media. The pretreatment of inhibitors for other bacteria in the sample is usually needed to enrich Legionella species [18]. In addition to cultivation, other techniques have been developed to detect Legionella in various environments, including direct fluorescent antibody techniques for natural aquatic environment and the gas chromatographic-mass spectrometric method for detecting unique fatty acids of the L. pneumophila lipopolysaccharides in biofilms in potable water with complex microbial communities [18]. Polymerase chain reaction methods have also been developed and used as a detection kit for initial analysis of water [23].

The association with biofilms also makes Legionella more resistant to conventional chlorination. Legionella are able to survive in low levels of chlorine for relatively long periods of time [24]. Legionella have been detected in all phases of the sewage treatment processes, and the population number of Legionella failed to decline during treatment processes [25]. Another study detected Legionella in reclaimed water after tertiary treatment and in the aerosols obtained above a secondary sewage treatment basin [26]. Legionella in reclaimed water was also found to reestablish in the reservoir and during the distribution after treatment due to the loss of residual disinfectant and high assimilable organic carbon (AOC) [27]. These findings suggest that additional and continuous chlorination may be required to inhibit the growth of Legionella during reuse process, although additional chlorine treatment may raise the issue of emissions of hazardous chlorine byproducts.

3.2.2 Exposure routes to workers and general populations

Human exposure routes to Legionella have been documented in various epidemiological and experimental studies. Legionella is found to directly transmit from environment to humans. Little evidence showed that Legionella can transmit in a human-to-human manner [18]. In most epidemiologic cases, Legionella transmitted through contaminated airborne aerosols from types of aerosol generators [28] and was subsequently inhaled by humans. Other less common exposure routes includes ingestion of contaminated potable water, immersion in raw water, inhalation of contaminated water/oil mixtures, and excavation in dusts or soil [19].

Legionella enters human respiratory systems and reaches the lower respiratory tract of humans to begin the pathological process of infection [29, 30]. Legionella can also be deposited in the upper airways and then aspirated to deeper portion of the lung to trigger serious pneumonia [31].

The symbiotic characteristic of Legionella with microorganisms further enhances its prevalence and resistance to disinfection. Legionella-filled vesicles are formed and expelled by the microorganisms in cooling towers after biocide treatment. Such vesicles enable transmission of Legionella and protect Legionella from dessication during the transmission, thereby maintaining the infectious dose of Legionella when reaching the respiratory systems of vulnerable receptors [32].

3.2.3 Risk factors and management

The low attack rates of Legionella in the U.S. represent the resistance of general populations to the infection [19]. However, several risk factors have also been identified to increase the incidence of LD. Patients living in the hospital requiring intubation, ventilation assistance, and respiratory therapy have increased risks to cause LD [33]. Also, patients with diseases such as chronic obstructive pulmonary disease, diabetes, head or neck cancer, or end-stage renal disease also have a significant increased risk of LD [34, 35].

Due to the widespread prevalence of Legionella in cooling towers, workers at industrial plants or power plants have become susceptible population for the exposure to Legionella. To control and assess the potential Legionnaires' disease at worksites, Occupational Safety & Health

Administration (OSHA) at United States Department of Labor has designed an eTool [36] to provide information on disease recognition, potential disease source identification, investigation procedure, and the response and control strategies once an outbreak occurs. Given the fact that Legionella is widely found in cooling towers and the inhalation and aspiration of contaminated aerosols or water are major exposure routes to Legionella, adequate risk management at the worksites can be effective to prevent the outbreak of LD.

4 Water availability and transportation analysis

With the construction of new power plants, the most urgent concern with the wet cooling system has been water availability. Competition from municipal and agricultural water demand has decreased the amount of freshwater and causes the alternative water source more important for industrial use. To evaluate reclaimed water availability for each power plant, the distance from POTWs to the power plant was used as the single most important criterion in the previous national study [4]. POTWs with lowest linear distance to the power plant were considered the most cost-effective reclaimed water source [4]. However, when considering the difficulties and cost of pipeline construction, geographic properties and land use pattern become important. The shortest linear distance does not necessarily represent the most cost-effective choice of water source. In addition, the potential for use of pipeline networks rather than individual pipelines potentially increases water transportation efficiency and should also be taken into account to minimize pipeline transportation costs [37].

To solve this problem, I employed the concept of a spatial and economic optimization model modified from OptimaCCS, a CO_2 pipeline transportation network model established by Nicholas Institute for Environmental Policy Solutions [37]. OptimaCCS, a spatial economic optimization model, can help minimize costs by simultaneously considering costs of CCS pipeline construction and injection [37]. The algorithm of OptimaCCS first identifies every single pipeline segment through a spatial permutation process and obtains the cost for each segment spatial optimized using ArcGIS by considering the cost surface which reflects the multiple factors listed in Table 4. Each CO_2 source can be a potential hub in which small pipelines can merge to become a trunk pipeline [37]. In my study, each POTW was also considered as a hub that connects other POTWs to a downstream POTW or to the destination power plant. In addition, the pipe size for each pipeline segment was obtained from the model. Factors affecting pipeline transportation were considered in the model using both geospatial analysis and mathematical modeling to optimize pipeline routes for reclaimed water supply for each power plant. I also conducted scenario study to compare the difference of pipeline routing when considering different pipeline transportation factors.

4.1 Factors affecting water transportation efficiency

Two factors affecting water transportation efficiency include pipeline construction conditions and the potential of cost-effective pipeline network design. As shown in Table 2, the concept of cost surface in ArcGIS was applied to assess the spatial obstacles in the area of pipeline construction. For the cost-effective network design, pipeline merging and route permutation were conducted using The General Algebraic Modeling System (GAMS) [38]. The concepts of the two factors are described in the following sections. The spatial and economic optimization model integrates ArcGIS and GAMS to design optimal pipeline transportation network for each power plant.

Table 2: Factors considered in reclaimed water pipeline transportation design.

Factors	**Methods**	**Programs**
Pipeline construction conditions	Cost surface	ArcGIS: Spatial analysis
Cost-effective network design	• Pipeline merging • Route permutation	GAMS: Mathematical programming and optimization

4.1.1 Cost surface of pipeline transportation

A cost surface reflects the spatial obstacles for constructing pipelines in the area. The cost surface used in this study is a raster layer of North Carolina derived from the cost surface used for MIT CO_2 transportation cost model [9] with a cell size of 1 km^2. This cost surface is also incorporated in OptimaCCS model [37]. The cell values are multipliers of an assumed baseline pipeline cost. This baseline pipeline cost (cost multiplier of 1) is for a pipeline that traverses a flat surface (without any obstacles) and includes the fixed cost of material, labor, and miscellaneous costs. The multiplier adjusts cost by factoring in the contribution of land slope, protected areas, and crossings of three line-type obstacles (waterways, railroads, and highways) [9]. Once all of the multiplier variables are assigned for each cell, they are added to the base value to give each cell its final cost surface multiplier value. The weight factors for the different construction conditions are shown in Table 3.

Table 3: Obstacles encountered during pipeline construction and the relative cost factors [9].

Construction Condition	**Cost Factor**
Base Case	1
Slope[1]	
10-20%	0.1
20-30%	0.4
>30%	0.8
Protected Area	
Populated Place	15
Wetland	15
National Park	30
State Park	15
Crossing	
Wateway Crossing	10
Railroad Crossing	3
Highway Crossing	3

To identify those POTWs needed for power plants with the water transportation cost and the routes from each POTW to the next POTW or to the power plant, the CostDistance function in ArcGIS was used [39]. The CostDistance function is designed to identify the accumulating cost from a beginning point to an end point on the cost surface, and also provides a way to trace back the back link grid between two points. The CostPath function uses the intermediate output from CostDistance to come up with the optimized route (represented as a vector) between two points. The combination of these two functions enables the routing modeling of the least-cost path between two points. Each of the above is described in detail in ArcGIS Desktop Help 9.3 Document [40].

For instance, there are two points (P1 and P2) on a uniform cost surface with each pixel having a level difficulty multiplier of 1 (baseline), such as a desert. Since it is a uniform cost surface, the least-cost path between P1 and P2 will be a straight line path with cost distance of 5 units (Figure 4A). Another instance is that the two points are located on a mixed cost surface area (Figure 4B). This surface area contains some pixels with a pipeline development multiplier of 2 (e.g urban areas), which means that those areas are twice as expensive as the baseline development cost. Using the least-cost path function to move from P1 to P2 results in a pipeline route that avoids high-cost development areas. A normalized distance is used to reflect the weighted distance related to building a pipeline over varying terrain. For example, if it is twice as difficult to build a pipeline over a 1 km stretch of terrain, the cost distance for that 1 km distance is 2. In the above example, a straight line route results in a cost distance of 9 units (purple arrows), while the spatially-optimized, least-cost path has the cost distance of 6.8 units (red arrows) (Figure 4B). This demonstrates that the CostDistance and CostPath functions in ArcGIS are capable of identifying the least-cost path between two points [39].

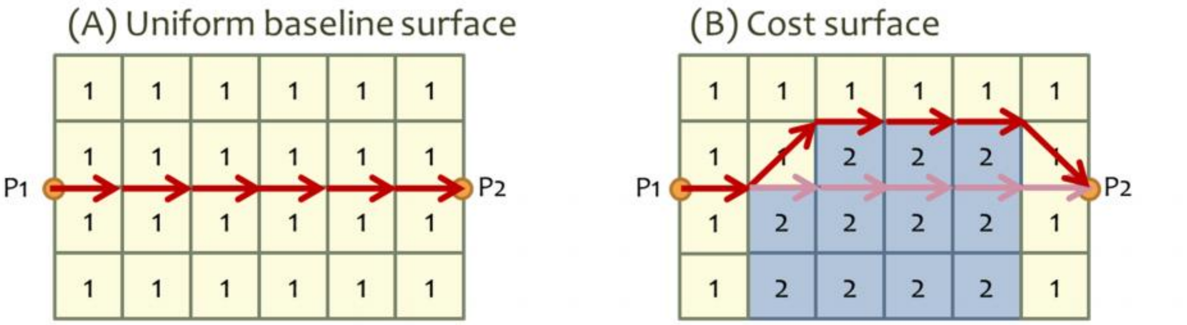

Figure 4: Least-cost pipeline routing on (A) baseline surface and (B) cost surface.

4.1.2 Pipeline merging and spatial permutation

Rather than individual small pipelines, merged pipelines with larger pipe size are more cost-efficient in terms of unit cost for transporting reclaimed water. This concept can be derived from pipeline engineering principle of CO_2 transportation that is characterized by the decreasing of average cost of transporting a unit ton of CO_2 per unit distances as the pipe diameter increases [41]. The same concept can also be applied in the water transportation study. Figure 5 shows the relationship between the unit cost of water transportation and the pipeline size. The data of water flow rate and pipeline unit cost for different sizes of pipelines are obtained from the engineering data of stainless steel Schedule 40 pipe (flow to size) [42], and the unit cost of steel pipes are estimated from the cost for CO_2 steel pipelines in OptimaCCS proportional to the thicknesses of the pipes (size to cost) [43]. The cost of pumping device for the pipelines is ignored in this study. According to Figure 3, the average cost-per-ton per km of water decreases at a decreasing rate as the pipeline diameter increases. This means that there is an incentive to aggregate water flow from multiple sources into larger diameter pipelines to reduce costs.

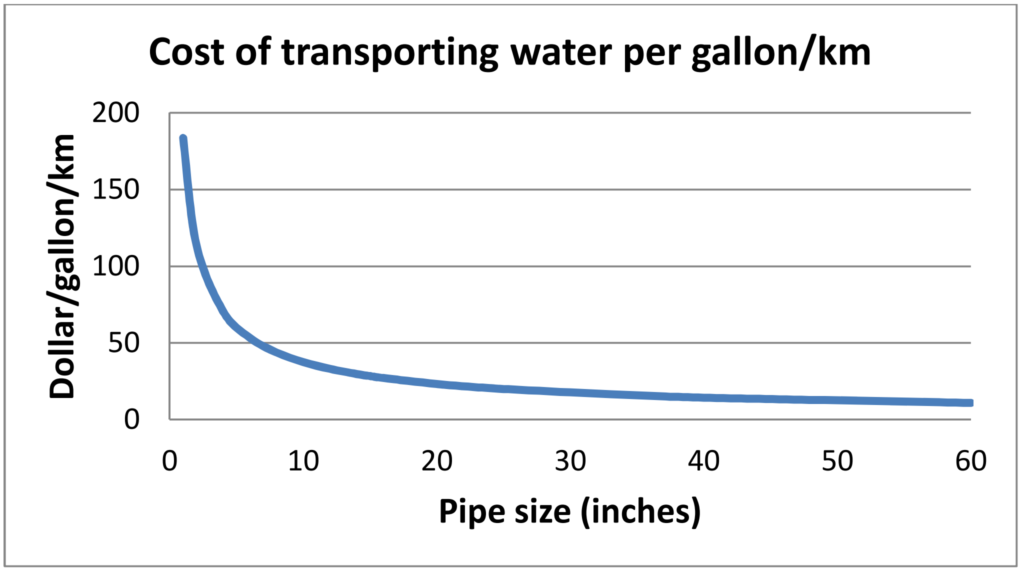

Figure 5: Pipe diameter vs. average CO_2 transport cost.
The data is calculated based on “flow to size” [42] and “size to cost” [43] data for water pipelines.

Given that each pipeline segment between points can be the candidates of the pipeline network, the pipeline cost for each segment is required to identify optimal pipeline routes [37]. The concept of spatial permutation is used to obtain the cost distance for each segment. The permutation result is then input to the optimization model to identify the least cost combination of pipeline segments. For example, if a power plant requires the reclaimed water demand from both POTW1 and POTW2 for cooling, the spatial permutation and optimization outcome can be shown in Figure 6. The cost distances for the four segments among two POTWs and one plant demonstrate that if POTW1 and POTW2 connect to the plant individually, the cost distance for the two pipelines is 50 (30 from POTW1 to the plant and 20 from POTW2 to the plant). However, if the reclaimed water supplied from POTW1 is transported to POTW2, and then the joint water is transported to the plant, the cost distance will be 30 (10 from POTW1 to POTW2 and 20 from POTW2 to the plant). In addition, the joint water from POTW2 to the plant will use a larger pipeline with lower unit water transport cost, which means the pipeline cost can be further reduced. More detailed information can be found in the OptimaCCS study [37].

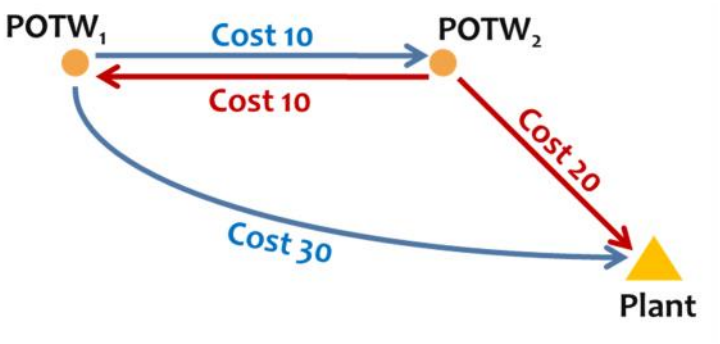

Figure 6: Spatial permutation for two POTWs and one power plant.

The number of possible pipeline segments can be counted by multiplying the number of beginning and ending points. Given n POTWs (circles in Figure 6) and s power plants (triangle in Figure 6), the number of pipeline segment beginning points is simply n. Pipeline segment ending points could be either another POTW with (n-1) possibilities or a power plant with s possibilities with total count of (n-1+s). Hence, the number of exhaustive spatial permutations which also reflects the number of pipeline segment candidates is the product of the number of beginning points multiplied by the number of ending points: n(n+s-1). In our example in figure 7 we have two POTWs and one power plant with a total number of pipeline segments 2(2-1+1) which is equal to 4. Exhaustive spatial permutation facilitates the cost minimization process by considering every possible pipeline convergence.

4.1.3 Optimization model for pipeline transportation network

The optimization model employed in this study combines the capabilities of ArcGIS spatial optimization and mathematical programming based cost minimization. POTWs and power plants are first analyzed by ArcGIS to obtain the least cost distance value for each possible segment between points. The result of spatial permutation is then input to GAMS mathematical model along with the information of water supply volume from each POTW and water demand from the given power plants. The mathematical model is capable to identify the pipe size and cost required for each segment including all possible combinations of pipeline merging. The objective function of the mathematical model is to minimize the pipeline cost for each power plant while the sum of reclaimed water supply from selected POTWs meets the cooling water demand of the given power plant. The optimal pipeline network is then identified and input back to ArcGIS to visualize the routes. The structure of the optimization model is illustrated in Figure 7.

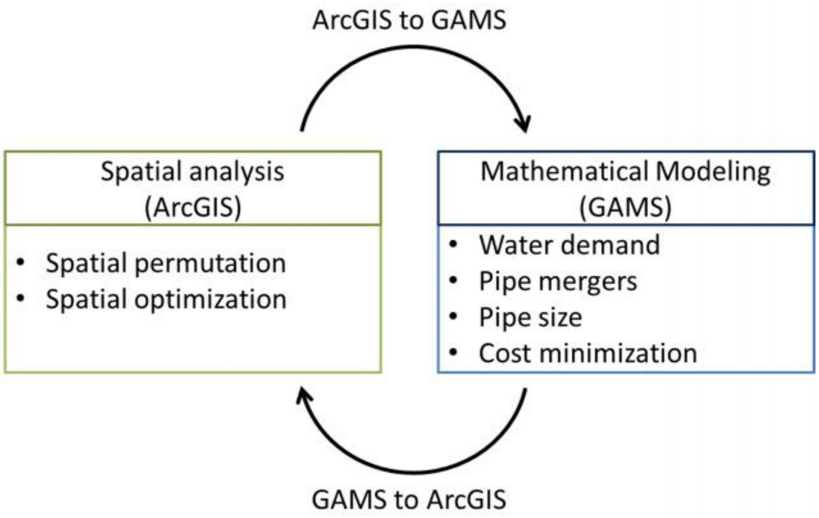

Figure 7: Optimization model consists of spatial analysis and mathematical modeling.

4.2 Assumption and Scenario analysis

This study focuses on existing coal-fired power plants given the trend of natural gas as the major fuel type for the future power plants. The type of cooling system for each power plant is assessed to estimate makeup water demand for each power plant. In addition to the base case with current status, this study also proposed a second case that all once-through cooling systems of existing coal fired power plants in NC are converted into re-circulating cooling towers. As mentioned above, once-through cooling tower requires larger water withdrawal with large amount of warm water discharge into water bodies, which usually damages the local aquatic habitats. The construction of once-through system is thus highly restricted by water intake regulation in CWA section 316(b) and the point source discharge standard in NDPES program.

To tackle the increasing water demand from thermoelectric generation sector, NETL [44] has developed 5 future cases to describe the water needs analysis, considering different addition and retirement rates for current cooling systems, as well as different levels of regulation. Case 5 is the conversion case describing the retrofit of once-through cooling systems to become re-circulating systems under regulatory and public pressures. In this study, both base case (the case continues current status) and the conversion case are assessed. I ignored the timeline for conversion, assuming that the all power plants in NC have already converted into re-circulating cooling system when starting using reclaimed water as makeup water. The two cases will be assessed at the reclaimed water inventory stage to see if the overall reclaimed water supply fulfills the makeup water demand from all existing coal-fired power plants in NC.

To understand how the geographical properties and the potential of pipeline merging affect the route design for pipelines, I conducted the pipeline transportation analysis with three scenarios described below and in Table 4.

- **Scenario 1:** Those POTWs that supply reclaimed water for each power plant were selected according to the least linear distance from the POTW to the plant. This scenario does not consider the difficulties of water pipeline construction.
- **Scenario 2:** The POTWs for each power plant were selected according to the least cost distance considering the MIT cost surface from the POTW to the plant. This scenario considers the pipeline construction conditions, so the selected POTWs have the lowest pipeline construction cost if we only consider individual pipelines between POTWs to the power plant.
- **Scenario 3:** The spatial-economic optimization model described above is used in this scenario. The scenario considers both the cost surface for pipeline construction conditions and the pipeline merging. These factors affecting pipeline transportation are quantified to estimate the optimal pipeline networks with minimal pipeline cost for each power plant.

Table 4: Factors considered in three scenarios.

Scenario	Minimal linear distance	Minimal cost distance	Pipeline merging	Minimal pipeline cost
1: Linear distance	√			
2: Cost distance		√		
3: Optimal network		√	√	√

4.3 Water consumer inventory - existing coal-fired power plants in NC

Data of coal fired power plants in NC were obtained from NETL Coal-Fired Power Plants database [45]. Those power plants with longitude/latitude, net annual electrical generation, and cooling system information in the database were included in the study. 14 power plants were finally selected. The information of 14 power plants was compiled from the database and listed in Table 5. Power plants with larger water demands are located at northen and western areas of NC (Figure 8). The largest three cooling water demands are from Roxboro, Marshall, and Belews Creek power plants.

Table 5: Existing coal-fired power plants in NC [45].

Plant Name	**Cooling Water Source**	**Current Primary Cooling System**	**Net Annual Electrical Generation (MW-h)**	**Water withdrawal – BAU (million gal/year)**	**Water withdrawal - conversion case (million gal/year)**
Asheville	Lake Julian	Recirculating	2,845	2,845	2,845
Cape Fear	Cape Fear River	Once through	2,251	93,809	2,251
Lee	H F Lee Lake	Recirculating	2,459	2,459	2,459
Roxboro	Lake Hyco	Recirculating	22,850	22,850	22,850
L V Sutton	Sutton Lake	Recirculating	3,703	3,703	3,703
W H Weatherspoon	Weatherspoon Lake	Recirculating	957	957	957
G G Allen	Lake Wylie	Once through	7,699	320,774	7,699
Buck	Yadkin River	Once through	1,976	82,351	1,976
Cliffside	Broad River	Once through	4,480	186,662	4,480
Dan River	Dan River	Once through	779	32,466	779
Marshall	Lake Norman	Once through	18,599	774,962	18,599
Riverbend	Catawba River	Once through	2,203	91,789	2,203
Mayo	Mayo Lake	Recirculating	5,945	5,945	5,945
Belews Creek	Belews Lake	Once through	18,416	767,321	18,416
Sum			79,302,597	2,388,894	95,163

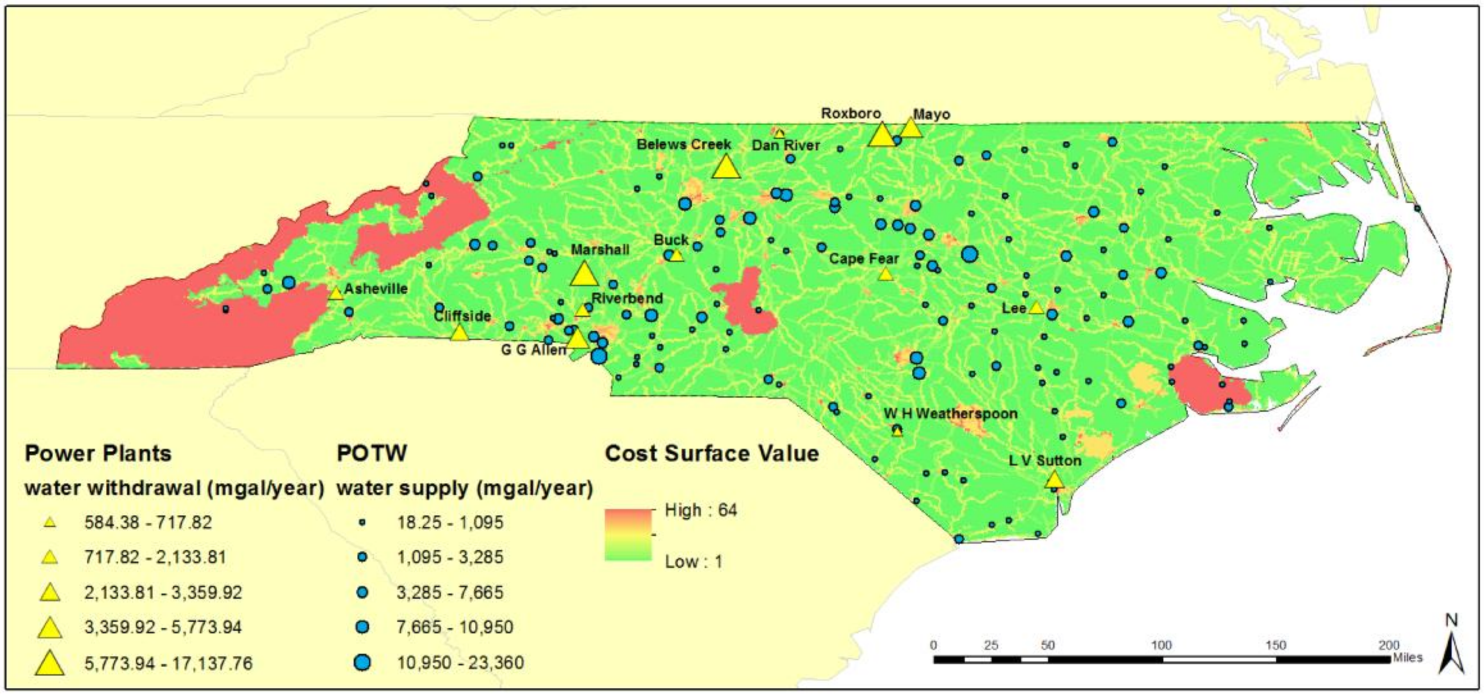

Figure 8: Power plants and POTWs distributions in NC.

Water withdrawal volumes and the locations of power plants were estimated and digitized based on NETL database [45]. Reclaimed water supply volume from POTWs and the locations were obtained from CWNS 2008 database [5]. The cost surface is derived from MIT CO_2 transportation cost model [9].

The cooling water demand for each power plant is estimated according to their annual generation, water to energy ratio, and capacity factor based on the following equation [4]:

$E = G * R$

Where

E = Estimated water demand, gal/year

G = Net annual electrical generation, MW*h

R = Water withdrawal factor, gal/MW*h

The net annual electrical generation was obtained from NETL database [45]. The water withdrawal factor was derived from the National Renewable Energy Laboratory (NREL) [46] estimating the average water withdrawal and consumption for different type of power plant cooling systems. The withdrawal factors for coal fired power plants are listed in Table 6. Two cases were considered for cooling water demand. The first case represents the current status of cooling systems for existing power plants, and the second case assumes that existing power plants using once-through cooling systems are all compelled to converse into wet recirculating systems. The volume of withdrawal water needed for each plant in both scenarios is listed in Table 5.

Table 6: Water withdrawal factors for electricity generating technologies (gal/MWh) [46].

Cooling type	Technology	Median	Min	Max	Number of studies
Recirculating	Generic	1,005	500	1,200	4
	Subcritical	531	463	678	7
	Supercritical	609	582	669	7
	IGCC	390	358	605	11
	Subcritical with CCS	1,277	1,224	1,329	2
	Supercritical with CCS	1,123	1,098	1,148	2
	IGCC with CCS	586	479	678	6
Once-through	Generic	36,350	20,000	50,000	4
	Subcritical	27,088	27,046	27,113	3
	Supercritical	22,590	22,551	22,611	3
Cooling pond	Generic	12,225	300	24,000	2
	Subcritical	17,914	17,859	17,927	3
	Supercritical	15,046	14,996	15,057	3

4.4 Water supplier inventory – POTWs in NC

The inventory of POTWs was developed to identify the locations and the volume of water supply of POTW available in NC. The data are derived from the Clean Water Needs Survey (CWNS) 2008 database [5]. 862 facilities were listed in NC database. The facilities were further screened according to the following criteria:

1. The facilities should reflect public owned treatment works
2. The facilities should include longitude/latitude information
3. The facilities should be within NC boundary

4. The minimum level of treatment should be tertiary treatment to comply with NC regulation 15A NCAC 02T.0906

After screening, 150 POTWs are identified as reclaimed water suppliers to power plants for cooling needs in NC. The sum of volume supplied is 330,989 million gallon per year. The 150 POTWs were imported into GIS with World Geodetic Survey 1984 (WGS 84) as the geographic coordinate system for further spatial analysis. The distribution of POTWs is shown in Figure 8.

Comparing with total water needed for NC coal fired power plants in Table 4, the total water supply from POTW in NC does not meet the needs for existing power plants with current cooling systems (2,388,894 million gallons per year), indicating that the large amount of water withdrawal required by once through cooling system exceeds the water reuse capacity in NC. On the other hand, in conversion case where all existing once-through cooling systems are assumed to be converted into recirculating systems in the future, the cooling water demand is 95,163 million gallon per year, which is 28% of total tertiary treated municipal water supplied in NC. Therefore, in the following analysis, the conversion case is used, assuming recirculating cooling systems are to be used in all power plants in the future in NC.

4.5 Reclaimed water transportation analysis

The POTWs for each power plant and the pipeline transportation routes were selected and delineated in 3 scenarios. The analysis for Roxboro power plant, the largest coal-fired power plant in NC, was demonstrated in Figure 9 as an example. As shown in Figure 9, the pipelines in scenario 1 and 2 appear to be complex and redundant. All pipelines from each POTW connect to Roxboro plant individually and pipelines share the same route where the cost surface is “flatter” when approaching the power plant. This indicates that merging those pipelines on the same route can substantially reduce the pipeline construction cost. It is also shown that POTW selection is different in scenario 1 and 2. In scenario 1, some selected POTWs (red dots) locate at the area with high cost meaning that the selection of POTWs in scenario 1 disregards the geographical properties and pipeline construction conditions, which is practically infeasible. In scenario 2, the selected POTWs are all locate at low cost areas, while overlapped pipelines are still not cost-efficient.

The optimization model is used for scenario 3 to further consider pipeline merging and cost minimization. The result shows that the amount of pipelines is largely reduced due to pipeline merging, and the selection of POTWs is also different from that in scenario 2. In scenario 3, a POTW at high cost area on west is selected, while two power plants at lower cost area on north are not selected. The reason is that the POTW on west supplies more reclaimed water than the two POTWs on north, so selecting one POTW instead of two is more cost-efficient. In addition, selecting POTW upstream is preferred because larger single pipeline is more cost-efficient than smaller pipeline branches. This example demonstrates that the optimization model estimate the least cost pipeline network in a comprehensive manner with multiple dimensions. The optimization assessment provides power plants substantial cost estimation for applying reclaimed water for their cooling systems.

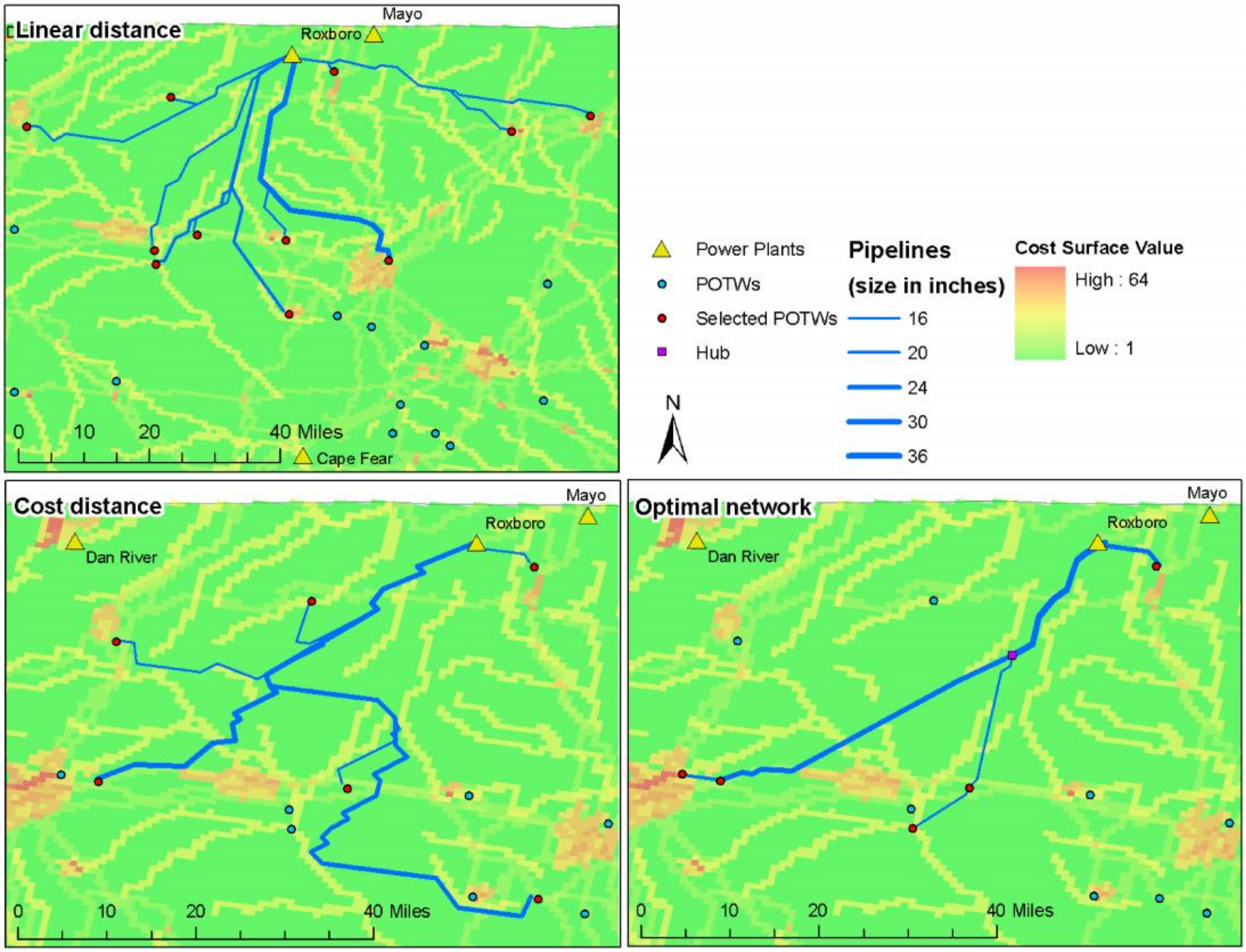

Figure 9: POTWs selected and the pipeline routes for Roxboro power plant under 3 scenarios. See above descriptions for the different criteria of selecting POTWs in three scenarios.

The sum costs and pipeline lengths for 14 power plants under 3 scenarios are compared in Figure 10. A significant decline of both cost and length from scenario 1 to 3 can be seen. The decline indicates that considering cost surface and pipeline merging are crucial in designing pipeline transportation infrastructure.

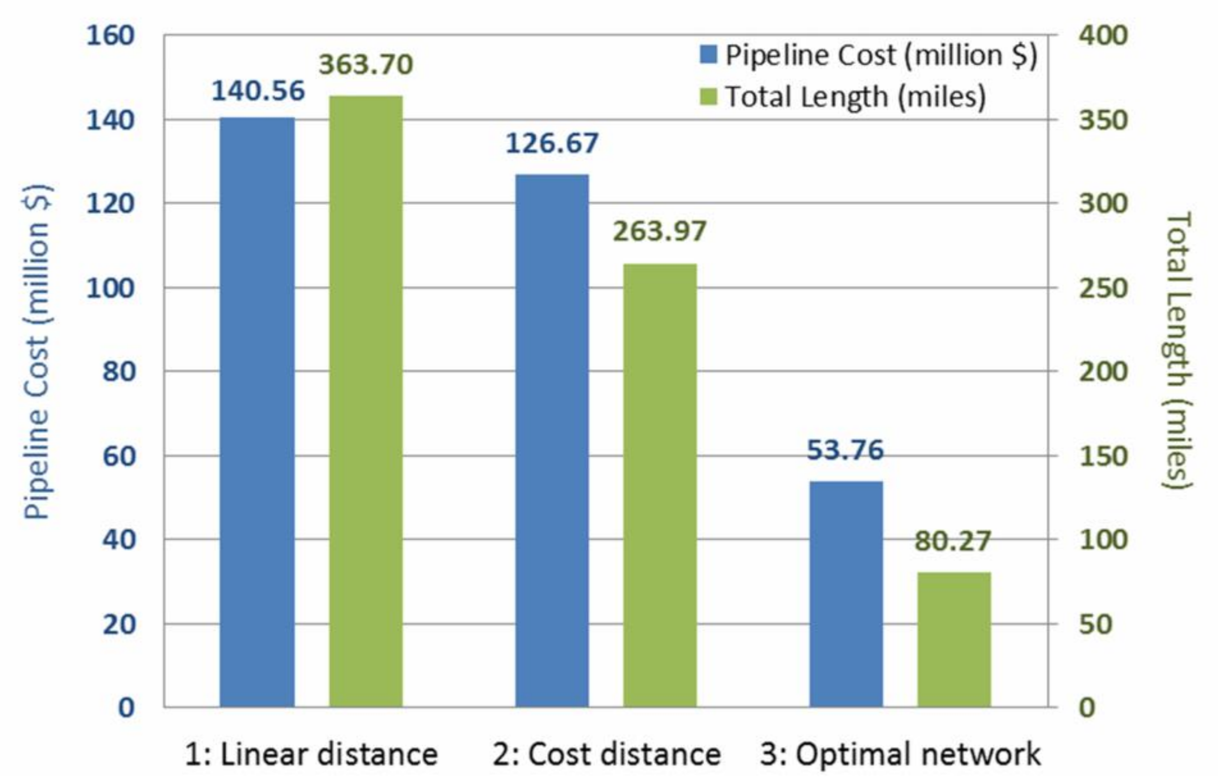

Figure 10: Pipeline construction costs and total lengths for Roxboro with three scenarios.

Figure 11 shows the unit transport cost ($/million gallon) for each power plant under scenario 3. In the view of a power plant company, the feasibility of using reclaimed water as the substitute of freshwater depends on the unit transport cost for the reclaimed water application. As shown in Figure 9, the unit costs vary among power plants ranging from $20 to $564 per million gallons. Among the 14 power plants, Dan River and L V Sutton power plants show the largest unit transport cost. This can be due to three reasons. First, the POTWs surrounding the two power plants supply smaller amount of reclaimed water, so more and longer pipelines are required for the two plants to reach out farther POTWs to fulfill their cooling water demands. Second, the two power plants are located at the regions with higher costs that the pipelines have to bypass some areas, resulting in higher transport costs. In addition, these two power plants require small amounts of cooling water, which means that the pipelines for these two plants are smaller and less cost-efficient. The difference of unit transport cost among the power plants shows the properties of power plants that are unfavorable for using reclaimed water as cooling water for power plants.

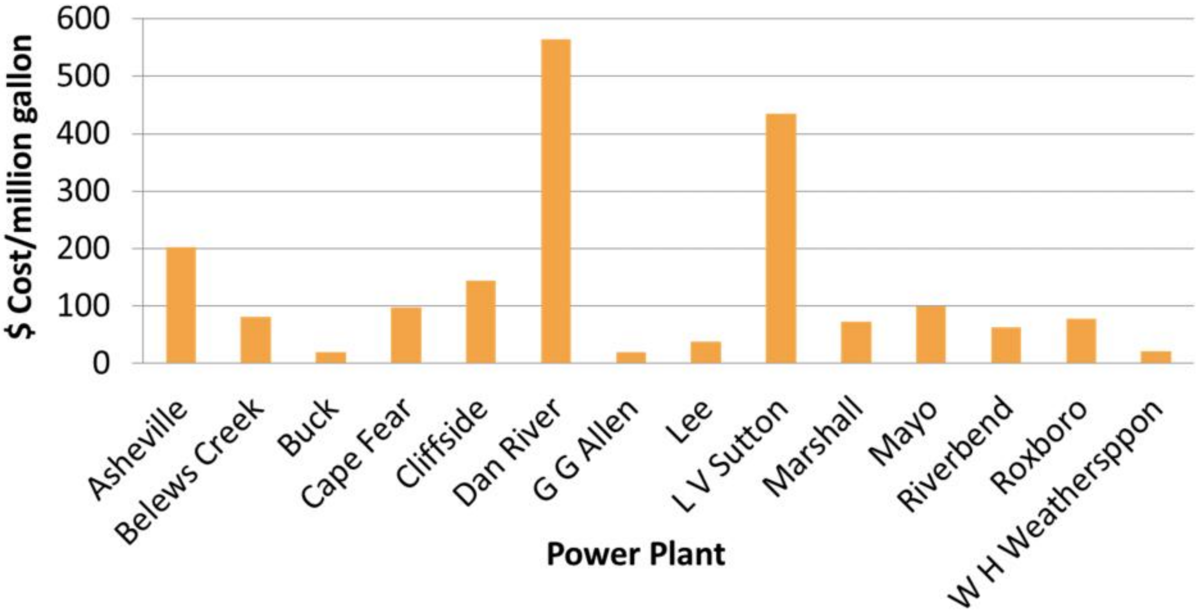

Figure 11: Unit transport cost for each power plant for scenario 3.
See descriptions above for the implications of unit transport cost for each power plant. See above explanation for the high transport cost for Dan River and L V Sutton power plants.

5 Conclusions and Recommendations

The use of reclaimed water for coal-fired power plant cooling was evaluated in this study. The federal and North Carolina state regulations and guidelines regarding the process of reuse were reviewed, as well as the studies on risk assessments related to potential hazards in the reclaimed water. L. pneumophilahas been shown as a potential pathogen to cause LD in both potable and reclaimed water. Cooling towers that generate aerosols are the main source for Legionella that can be exposed to humans through aerosols inhalation; and, Legionella can spread and remain pathogenic for a long distance from the source plant. Adequate risk management and monitoring of Legionella levels at worksites have been well established by OSHA in the US to can reduce potential risk of LD.

In addition to water quality assessment, reclaimed water availability is of more concern. It is crucial to consider water pipeline transportation feasibility when assessing water availability for cooling of power plants. Using the spatial-economic optimization model considering pipeline construction condition and pipeline merging potential, I was able to identify the optimal pipeline network infrastructure for reclaimed water transportation with minimal pipeline construction cost. The unit transport cost analysis for each power plant provides the necessary information to evaluate the feasibility of applying reclaimed water for cooling in each power plant.

If regulations from source wastewater treatment and reclaimed water reuse standard to cooling tower discharge and air emissions are followed, the water quality concern of reclaimed water reuse for cooling will be minimized. Given the variety of water quality from different wastewater sources, some potential problems may require further assessment and investigation to ensure the safety of specific reclaimed water for reuse. Conclusions of this master’s project are:

- Legionella infection is a health problem in reclaimed water systems globally. Although some states have established standards for Legionella monitoring and treatment in cooling towers, there is no specific regulation for detecting and monitoring Legionella in cooling towers using reclaimed water under both federal and NC state regulations. Although there is currently no Legionella outbreak reported in NC, periodical monitoring is recommended given the high capability of Legionella bacteria to transmit and cause diseases.

- Reclaimed water reuse in industrial cooling systems can lead to health effects through evaporation and drift emissions. In addition, concentrations of other pathogens and chlorine byproducts in air drifts from the cooling systems must be carefully monitored.

Reclaimed water availability and water transport cost for power plants are crucial for evaluating the feasibility of applying reclaimed water as makeup water for cooling towers. Several perspectives are worthy of consideration for future investigations and real-world practices.

- When assessing reclaimed water availability for power plants, the construction of transportation pipelines and the potential of pipeline merging should be considered to minimize the construction costs and design the optimal pipeline transportation network infrastructure.
- In North Carolina, tertiary treatment is required for reclaimed water reuse. While this is beneficial for controlling water quality and reducing potential health and environmental impacts from reuse, water availability will also decrease under the requirement and thus the cost of reuse will increase. A cost-benefit analysis can be used to evaluate the overall cost for tertiary treatment requirements and the costs of secondary treatment with specific additional treatment for specific reuse purposes. Further investigation should focus on prioritizing reclaimed water with higher quality for more vulnerable purposes.
- The establishment of reclaimed water pipeline networks for the power plants provides stable supply-demand relationships between POTWs and power plants. Because reclaimed water quality varies with wastewater sources, the stable reclaimed water supply provides consistent water quality for certain power plants and thus can be beneficial for water quality control and risk management in specific conditions.
- A large number of water transportation projects in the U.S. are currently using PVC pipes. PVC pipes have a number of useful properties including resistance to corrosion and chemicals, light weight, flexibility, and low price. However, the material is non-biodegradable and can pose adverse environmental impacts. The addition of phthalate also poses health problems to human throughout the life cycle of the pipes. Therefore, stainless steel pipes may be a better choice when deploying a large scale of pipeline network construction.

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