Spring 2010

Strategic process integration of energy and environmental systems in wastewater treatment plants

Bharath Kumar Gangichetty

Recommended Citation

Gangichetty, Bharath Kumar, "Strategic process integration of energy and environmental systems in wastewater treatment plants" (2010). *Masters Theses*. 4985.
https://scholarsmine.mst.edu/masters_theses/4985

STRATEGIC PROCESS INTEGRATION OF ENERGY AND ENVIRONMENTAL SYSTEMS IN WASTEWATER TREATMENT PLANTS

by

BHARATH GANGICHETTY

A THESIS

Presented to the faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In partial fulfillment of the requirements for the degree

MASTER OF SCIENCE IN ENGINEERING MANAGEMENT

2010

Approved by

Suzanna Long, Advisor
Abhijit Gosavi
Elizabeth Cudney

ABSTRACT

Green environmental practices are increasingly important in combating serious global energy and environmental issues. Most wastewater treatment facilities were built when energy costs were not a concern; however, an increasing demand for energy, changing climatic conditions, and constrained energy supplies have resulted in the need to apply more energy-conscious choices in the maintenance or upgrade of existing wastewater treatment facilities. A detailed analysis of the majority of water and wastewater treatment services shows that most facilities operate far below the efficiency levels needed for effective energy use. Failure to comply with regulated environmental standards is also a problem. Although standards exist for both energy and environmental management systems, no integrated process has been developed to address the concerns of communities wishing to lessen their environmental impact while also reducing energy utilization rates. The current research has developed an integrated model that combines both energy and environmental management systems models. It offers a holistic view of both approaches, maps linkages, and suggests an integrated process design capable of meeting high-performing energy management and environmental standards.

The model presented here has been validated by a case study on the Rolla Southeast Wastewater Treatment Plant. Data on plant performance was collected, studied, and analyzed and the results provide the basis for suggestions to improve operational techniques. The significant factors contributing to both energy and environmental systems are identified and balanced with considerations of cost.

ACKNOWLEDGEMENTS

Many individuals at Missouri University of Science and Technology have inspired me and moulded my graduate career. I wish to express my deepest gratitude to my advisor, Dr. Suzanna Long, for providing me an opportunity to pursue a master's degree and for stimulating my interest in research. Her suggestions, guidance, personal attention, and flexibility have provided important motivation for this research.

I would also like to thank my committee members, Dr. Abhijit Gosavi and Dr. Elizabeth Cudney, for their time and effort in reviewing my progress and helping in my research. I owe additional thanks to Dr. Long, the Energy Research Development Center at Missouri S&T, and the Department of Engineering Management for supporting me financially with a fellowship. I am also very grateful to the many professors and staff who have added great value to my work through their courses, suggestions, and experience.

I wish to thank Angela Hedgecock of Siemens Building technologies, Inc., and Kerry Herndon and Ruben McCullers of the U.S. Environmental Protection Agency for their initial guidance to my research.

And for their continual support, I would like to thank the members of my research group: Kiran Rangarajan, Susmitha Akula, Sandhya Gopalakrishnan, Norbert Ziemer, Tyler Lipscomb and Issam Algraiw.

I would like to express my gratitude to my parents, Jyothi and Muralidhar Gangichetty, my brother Chaitanya, my sisters Sireesha and Ramya, and my friends who have been very supportive throughout my studies with their love and encouragement.

TABLE OF CONTENTS

Page

SECTION

LIST OF ILLUSTRATIONS

LIST OF TABLES

Table Page

NOMENCLATURE

Symbol	Description
Y	Dependent Variable
X	Independent Variable
n	Number of independent variables
α	Regression Coefficient
β	Regression Coefficient
ε	Error
$\sum$	Summation

1. INTRODUCTION

Green environmental practices are increasingly important in combating serious global energy and environmental issues. Most wastewater treatment facilities were built when energy costs were not a concern; however, increasing energy demand, changing climatic conditions, and limited energy supplies have resulted in the need to apply more energy-conscious choices in the maintenance or upgrade of existing wastewater treatment facilities. Wastewater treatment systems have significant economic, social, and environmental effects on a community's resources. The major expense of any wastewater treatment facility is electricity. Pumping and aeration alone account for about 75% of a facility's total energy budget [1].

Water and wastewater facilities are among the largest and most energy-intensive systems owned and operated by local governments; they account for approximately 30% to 50% of municipal energy use. The water and wastewater sector accounts for nearly 3% of U.S. electricity consumption, which is estimated to be 75 billion kWh, and the cost of pumping, treating, delivering, collecting, and cleaning water is estimated to be about $4 billion. These electricity requirements are estimated to increase by 20% during the next 15 years, primarily due to the expansion of treatment capacity to serve a growing population. If these facilities reduce their energy usage by 10%, they could save approximately $400 million and 5 billion kWh annually.

Energy represents the largest controllable cost of water and wastewater treatment. By controlling this consumption we can reduce the operating costs, increase efficiency, reduce pollution, and provide a cleaner environment and limit green house gases (GHG) and other air pollutants. In addition, more and better-trained employees using more advanced equipment could lead to improved effluent and surface water quality and more compliant facilities [2], [3]. Further energy use directly affects the amount of GHG emissions, and indirectly affects the biological oxygen demand (BOD) and chemical oxygen demand (COD), and pollutions levels. Hence, these energy issues invite the need for an immediate action plan to control the various factors of energy use and environment that affect the system.

A detailed analysis of the majority of water and wastewater treatment services in the United States shows that most facilities operate far below the efficiency levels needed for effective energy use [3]. Failure to comply with environmental standards is also a problem. Aging equipment drives up maintenance costs and energy consumption to unacceptable levels. Effective energy management plans can reduce future energy use. Environmental protection is equally important and plays a major role in reducing the pollution levels. Wastewater treatment plants (WWTPs) should be designed not only to clean wastewater, but also to supply nutrients. These plants should be better integrated with municipal ecosystems and function as a component of local water and nutrient cycles so that natural systems may also play a role in the treatment of wastewater.

ISO 14001 is the standard set for environmental management systems to ensure an appropriate response to environmental issues and provide guidelines for various elements and applications of environmental management systems. Although standards exist for both energy and environmental management systems, no integrated process has been developed to address the concerns of communities wishing to lessen their environmental impact while also reducing energy consumption.

This research seeks to integrate energy and environmental management systems. It studied the feasibility of such systems and analyzed the various factors that significantly affect energy and environmental systems. The project developed the process flow models of energy and environmental management systems that are the basis for an integrated model that combining both. It then identified the factors that significantly affect energy use and the environment and applied linear programming techniques to obtain an optimal solution that balances all. To validate the integrated model, the Rolla Southeast WWTP facility was used for a case study. Data on the plant’s performance was collected and analyzed. The significant factors affecting energy use were identified, and the integrated model was then applied.

2. LITERATURE REVIEW

Many proposed wastewater management techniques have focused on utility management, energy efficiency, and sustainability issues. Effective utility management is a combined effort to ensure product quality, customer satisfaction, optimal operation, functional viability, infrastructure stability, operational resiliency, community sustainability, and water resource adequacy [4]. Successful utility management demands strategic planning, measurement, implementation, and continuous improvement of techniques.

2.1. GOALS OF THE SYSTEM

Table 2.1 provides a comparative summary of energy and environmental management systems. Energy management systems are directed mainly toward minimizing energy consumption. Any process that consumes energy is carefully analyzed, and a suitable methodology is applied to optimize the facility. Environmental systems focus mainly on protecting the environment, reducing pollution levels, and decreasing the effects of chemical reactions. All plants should be built according to ISO 14001, which is the standard set for environmental management systems (ISO, 1996). Few WWTPs, municipalities, and utilities, however, follow these standards. Government agencies are taking steps to create awareness of the standard and make it mandatory for all WWTPs. For example, the sustainability assessment model (SAM) was developed to assess water main replacement options [6]. This model has been beneficial in reducing environmental impact. The technique exemplifies the various alternatives available to measure the sustainability of a water supply facility. It can also measure the sustainability of WWTPs. As estimated by the Alliance to Save Energy, U.S. municipal water and wastewater systems consume nearly 75 billion kWh every year, generating an electricity bill for approximately $3.6 billion. Wastewater treatment facilities account for 40% of the total energy consumed [1].

A study conducted by the United States Environmental Protection Agency (EPA) in 2008 revealed the facts shown in Table 2.2 about water and wastewater treatment facilities in the United States.

Table 2.1. Goals of energy and environmental management systems [5]

Goals of Energy Management System	**Goals of Environmental Management System**
Optimize energy efficiency	Reduce pollution levels
Minimize energy waste	Decrease chemical effects on filtered water
Increase energy efficiency	Follow ISO 14001 standards
Measure energy consumption accurately and apply methodologies appropriate to facility conditions	Measure performance data accurately

Table 2.2. Publicly owned treatment works in United States [1]

Total number of POTWs	**16,600 (approximately)**
% of US population served by POTWs	75%
Small-capacity POTWs (<1Million Gallons per Day MGD)	82%
Contribution of small POTWs for the whole treatment	8%
Large-capacity POTWs (>1 MGD)	18%

Commonly used energy management techniques and strategies include variable frequency drives (VFDs), high efficiency pumps and motors, dissolved oxygen controls, supervisory control and data acquisition (SCADA) systems, fine bubble aeration, efficient sludge handling, mixing of aerobic digesters, and ultraviolet disinfection lamps and controls that are more effective than mechanical and chemical filtration and consume less energy than fine bubble aeration and staging of treatment capacity. Despite the potential of these energy management techniques, few WWTPs have adopted them. Many states have implemented projects to address issues of energy and improve the energy efficiency of WWTPs. These projects include the Enhanced Commercial Industrial Performance Program, the Anaerobic Digester Gas-to-Electricity Program, the Flex Tech Program, and the Research, Development and Demonstration Program, among others. The United States has a major share of the world's WWTPs accounting for nearly 39% of world's total [7]. Public-private partnership options for WWTPs are being explored because these facilities demand significant investment and can quickly reduce energy consumption.

Increasing energy efficiency can immediately ease the effects of the energy crisis, whereas the development of renewable energy will have effects in the longer term. Nearly over 75% of electricity comes from traditional energy sources, and electricity is a major contributor to environmental pollution around the world. Therefore, it is of paramount importance to increase energy efficiency and thus reduce energy consumption and its negative impacts on the environment [8].

2.2. COMMON ENERGY CONSUMING PROCESSES IN WWTPs

The processes that use the most energy are aeration and pumping. Aeration is a process in which dissolved oxygen is introduced into the wastewater to support aerobic oxidation and also to remove nitrogen. Often, mechanical aeration is used to promote the bacterial process of waste oxidation. Pumping is used to circulate the water and solids through the sequence of treatment processes. Other wastewater treatment processes that consume significant energy are mechanical mixing, chemical dosing, media and membrane filtration, dissolved air flotation, sludge handling and disposal, and digester heating. The wastewater sector is attempting to include more and better energy intensive treatment processes over time. Such processes will allow them to meet stringent water quality standards. They will also involve additional steps to remove remaining contaminants and thus permit the reuse of wastewater. Although such processes will extend the water supply, they will also increase energy use [1].

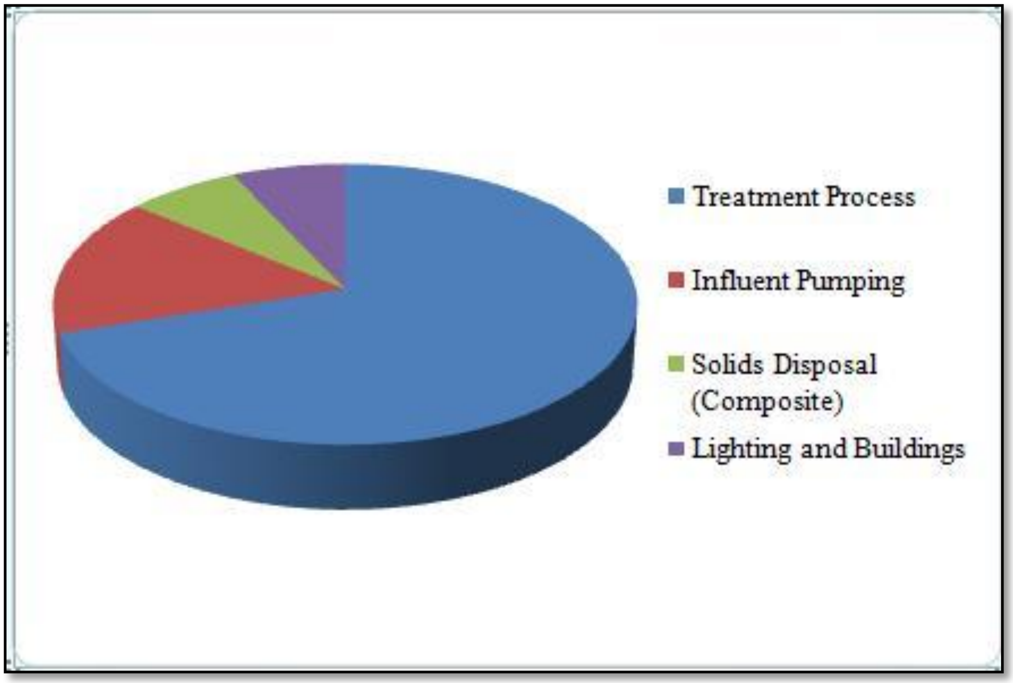

Figure 2.1. Common energy consuming processes in WWTP [1]

2.3. ENERGY EFFICIENCY TECHNOLOGIES USED IN WWTPs

A large variety of technologies and opportunities exist for increasing energy efficiency and reducing energy consumption in the wastewater management sector while maintaining the productivity levels. These technologies can be categorized based on their design, control, and efficiency among other factors. Improved equipment operates more efficiently than standard equipment, delivering the same service with less energy input, offering improved controls, and permitting use based on the demand to minimize losses.

Table 2.3 lists the most common energy efficiency technologies used in wastewater treatment facilities.

Table 2.3. Common energy efficiency technologies [1]

Energy Efficiency Technology/Strategy	**Description**	**Typical Payback (Years)**
High-Efficiency Motors	Motors with lower internal losses; used for pumps, blowers, mixers, etc.	Variable
Variable-Frequency Drives (VFDs)	Electronic controller that match motor speeds to the required load to avoid running at constant full power	½ to 5
High-Efficiency Pumps	Pumps with lower internal friction and head losses	variable
Variable Air Flow Rate Blowers	Efficiently match air supply to aeration requirements	<3
High-Efficiency Blowers	Air blowers with lower internal losses	variable
Dissolved-Oxygen Controls	Maintain the dissolved oxygen (DO) levels of the aeration tank(s) at a preset control point by varying the rate of air to the aeration system	2 to 3
SCADA System	Collects facility-wide data and allows control of equipment to more precisely meet required flows	variable
Fine-Bubble Aeration	Fine-pore diffusers generate smaller bubbles for aeration processes and improves oxygen transfer to wastewater	1 to 7
Staging of Treatment Capacity	Treatment systems designed and installed to operate efficiently at multiple stages (i.e., across a range of flow conditions)	<2
Excess Heat recovery from Wastewater	Excess heat from wastewater reused in low- temperature heating applications	<2
Efficient Mixing of Aerobic Digesters	Mechanical mixing used rather than aeration where possible; mechanical mixing uses less energy	1 to 3

Table 2.3. (Continued)

Efficient Sludge handling	Screw presses and gravity belt thickening use less energy for sludge dewatering and thickening	variable
Efficient Ultraviolet (UV) Disinfection Lamps & Controls	High-efficiency UV lamps convert more of the power they consume into useful light; controls turn down lights when not needed	variable

Table 2.4. Environmental effects in WWTPs and measures to control them [9]

Effect	**Measure**
Overflow or bypassing of wastewater	Install standby equipment at pumping stations; use dual power source supply system; implement proper maintenance program; enhance operational monitoring and emergency measures
Wastewater discharge to watercourses	Intercept discharges; impose stringent environmental management and pollution controls
Contamination of raw water source	Implement and enforce water and land protection zones
Water stress / insufficient water allocation	Study water yields; draft and conclude allocation contract
Damage to sewers or wastewater treatment plant from corrosive industrial discharges	Adequately pre-treat industrial wastewater; select appropriate construction materials; adequately control WWTP processes
Pollution of receiving water courses following upset of wastewater treatment process by industrial discharges	Adequately pre-treat industrial wastewater. Efficiently monitor and enforce standards
Pollution of receiving water courses caused by improper operation of WWTP	Control WWTP processes

Table 2.4. (Continued)

Odor	Cover potential odor sources; transport sludge and other residues in covered containers
Safety risk from toxic gases	Install inspection and control equipment; space manholes appropriately; provide ventilation; monitor atmospheric conditions; adopt safe working systems and emergency measures
Noise generated by pumps and machinery	Select low-noise machines; locate high-noise equipment indoors; install noise enclosures or buffers
Pollution by sludge from water and wastewater treatment plants	Dispose of sludge at sanitary landfills if testing shows sludge to be unsuitable for beneficial reuse
Sludge or silt from wastewater pumping stations and wastewater collection systems	Clean up quickly; transport in covered containers
Pollution of raw water supply from upstream wastewater discharge from communities, industries, agriculture, and soil erosion runoff	Implement appropriate water and soil conservation and environmental management plan

3. WASTEWATER TREATMENT PROCESSES AND ENERGY EFFICIENCY OPPORTUNITIES

3.1. ENVIRONMENTAL MANAGEMENT SYSTEMS IN WWTPs

The EPA defines an environmental management system (EMS) as a set of management processes and procedures that allows a facility to analyze, control, and reduce the environmental impact of its activities, products, and services, and to operate with greater efficiency and control. An EMS is appropriate for all kinds of facilities of varying sizes in both the public and private sectors. [10]

WWTPs should follow the internationally recognized ISO standard 14001. It provides a systems approach; and it is one of a series of environmental standards developed by the International Organization for Standardization. ISO 14001 includes all the elements needed to develop an organization's EMS.

There are various methods to treat water, but the most common approach uses primary, secondary, and tertiary treatment stages. The primary treatment stage includes screening and clarification to remove solids from the influent water. The secondary stage involves aerobic, suspended-growth, activated sludge treatment to reduce organic pollutants, along with chlorine disinfection to remove pathogens. These steps are followed by pumping and sludge processing. The secondary treatment phase is the greatest energy consumer in the treatment plant, requiring about 30% to 60% of the total energy used. Many plants are shifting from traditional chlorine disinfection to more advanced UV disinfection to eliminate the risk of storage and handling of toxic chemicals. The UV method also eliminates the chemical effects of chlorine on discharged water. Although UV is more energy intensive, it adds no chemicals to the residue, an important consideration for wastewater reuse and sensitive aquatic environments.

Energy consumption can be reduced by the use of fine bubble diffusers, dissolved oxygen control of aeration, high frequency blowers, variable frequency drives on pumps and blowers, premium efficiency motors, and a reduction of the head against which pumps and blowers operate. However, none of these methods has been standardized for energy efficiency in all plants. There is great variability from plant to plant in terms of capacity, flow rates, environmental conditions, and concentration of contaminants, process types, discharge regulations, rainfall levels, and disinfection methods. These variations prevent development of a generalized energy and environmental management systems model.

3.2. PRIMARY TREATMENT

Primary treatment includes screening, grinding, and sedimentation or clarification to remove floating and settle-able solids from the influent water. When the raw wastewater enters the treatment plant, it is screened for large objects, then subjected to grinding, which reduces the size of the remaining solids. The water then flows to primary sedimentation tanks where the particles are allowed to settle. Particles with higher specific gravity settle at the bottom of the tank, and those with lower specific gravity float to the surface of the water. Generally, a well designed and well operated primary treatment removes 50% to 70% of the suspended solids and 25% to 40% of the BOD from the influent wastewater. Free oil, grease, and other floating materials are removed from the surface of the primary sedimentation tanks by skimmers. Chemical flocculants or polymers are frequently added to the primary sedimentation tanks to facilitate removal of solids. Solids removed during primary treatment are dewatered and disposed of as part of the sludge treatment.

3.3. SECONDARY TREATMENT

A typical secondary treatment involves a biological process called aerobic, suspended- growth, activated sludge treatment. This process accounts for 30% to 60% of total plant energy consumption. Effluent from primary treatment is treated in large reactors or in basins within these reactors. An aerobic bacterial culture (the activated sludge) is maintained in suspension in the liquid contents. Colloidal or dissolved organic material is removed at this point. This secondary treatment is the main stage in the waste water treatment since it substantially reduces the BOD level of the wastewater is substantially reduced. Secondary treatment typically removes 70% to 85% of the BOD that enters with the primary effluent. The conditions for aeration are created by injecting dispersed air or oxygen by mechanical agitation. These processes allow the bacteria in the wastewater to metabolize the organic carbon and thus produce carbon dioxide, nitrogen compounds, and a biological sludge. Treated effluent from the aeration basins flows to secondary clarifier. A portion of the sludge from the clarifier is recycled to the aeration basins or reactors, and the rest is withdrawn or "wasted". The waste sludge is dewatered and disposed of by various methods. Finally, the effluent from the secondary treatment is disinfected and discharged. As mentioned above, secondary treatment is the most energy intensive process in wastewater treatment; however, most plants do not calculate energy consumption data in sufficient detail.

3.4. TERTIARY TREATMENT

Tertiary treatment is a more advanced wastewater treatment process. It has gained importance due to the increasing number of discharge regulations required by EPA and other environmental organizations and the need for removal of specific contaminants from the effluent that are not removed during the secondary process. Removal of nutrients (particularly nitrogen) prior to discharge requires additional treatment. Nutrients encourage algal growth in the receiving waters, and this growth reduces the dissolved oxygen, killing aquatic life and odor.

In addition to nutrient removal, tertiary treatment also removes suspended solids, reducing them to very low levels, this step is usually accomplished by filtration, refractory toxic organic compounds (using activated carbon), or dissolved inorganic solids (using ion exchange or membrane processing).

3.5. DISINFECTION

3.5.1. Chlorine: Clarified effluent from secondary treatment is usually subjected to chlorine disinfection, which adds chlorine to the discharged water. Chlorine gas is fed into the water to kill pathogenic bacteria and reduce odor. With proper care, chlorine can kill nearly 99% of harmful bacteria in the effluent. A few municipalities have shifted from chlorine to sodium hypochlorite disinfection to avoid the risks of storing and transporting of chlorine gas. Using chlorine or hypochlorite for disinfection, however, results in effluent water with chlorine levels that may be harmful to fish and aquatic life; therefore excessive chlorine must be removed from discharged water through a de-chlorination process that may increase energy consumption [11].

3.5.2. Ultraviolet Disinfection: Ultraviolet irradiation is becoming more common for disinfection due to its advantages over the traditional chlorine disinfection. It eliminates the risk and cost of storing and handling chlorine gas or other toxic chlorine-containing chemicals. In addition, it leaves no chemical residue in the effluent, which is important if the water is to be reused or discharged to a river.

An ultraviolet (UV) disinfection system transfers electromagnetic energy to an organism's genetic material and disables the reproducing capability of the cells. The effect of this UV disinfection depends on the length of exposure, the intensity of UV radiation and the characteristics of the wastewater [11].

3.5.3. Sludge Processing: Sludge processing is a complex process including several operations; sludge thickening, sludge stabilization by lime addition or digestion (either aerobic or anaerobic), sludge dewatering, and ultimately disposal by landfill, composting, land application, or incineration. In most plants, primary and secondary sludge are combined, thickened by sedimentation or flotation, stabilized, and dewatered using a belt filter press or centrifuge.

Thickening: Thickening reduces the volume of sludge prior to further treatment. Combined primary and secondary waste-activated sludge is typically less than 1% of total solids. Thickening can increase this proportion to 4% to 6%, and thus greatly reducing the volume of sludge that must be handled in subsequent processing.

Stabilization: Stabilization reduces pathogens and eliminates odor. Lime stabilization involves mixing the sludge with lime to achieve a ph level of 12 or higher. Aerobic stabilization is similar to activated sludge secondary treatment; it is carried out in open tanks with air introduced from the bottom of the tank. Aerobic digestion not only stabilizes the sludge, but also reduces the sludge volume as organic material is biodegraded. Digested sludge is decanted from the tank and dewatered.

Dewatering: Sludge dewatering is usually accomplished by either a belt filter press or a centrifuge. A belt filter press is a continuous-feed dewatering device that uses gravity drainage and mechanical pressure to dewater sludge. Conditioned sludge is fed to a gravity drainage section of the filter press where free water drains from the sludge. Pressure is then applied by squeezing the sludge between opposing cloth belts, forcing additional water from the sludge. The dewatered sludge is removed from the belts by scraper blades. Belt filter presses can produce a de-watered sludge of 15% to 30% total solids.

In centrifuge dewatering, sludge is fed at a constant flow rate into the rotating bowl of the centrifuge where it separates into a dense cake and containing low-density solids. This cake is returned to the plant head works. It is typically 20% to 30% solids and is discharged by a screw feeder from the centrifuge onto a conveyor belt.

3.6. ENERGY EFFICIENCY OPPORTUNITIES

There are various ways to improve energy efficiency in wastewater treatment facilities. The following are the most common used and those with the most potential. Implementation opportunities vary from plant to plant depending on the plant conditions and limitations.

3.6.1. Variable Frequency Drive: A variable frequency drive (VFD) is an electronic controller that adjusts the speed of an electric motor by modulating the power delivered to it. VFDs provide continuous control, allowing the speed of the motor to be adjusted according to the work being performed. VFDs help operators to fine-tune processes, at the same time reducing energy and maintenance costs.

VFD applications are increasing rapidly in the wastewater industry in which pumping and aeration are the major energy consumers. The energy consumed by pumping and aeration can be controlled by VFDs. Twenty four percent of these motors have variable load and are typically used in aeration equipment; 48% rely on VFD control [11].

Variable flow mechanical devices such as flow restricting valves or movable air vanes consume more energy. VFDs allow pumps to adjust to varying demands; yielding energy savings of nearly 50%. They are superior to single-speed motors in terms of control, torque, mechanical and electrical stress, maintenance costs, and motor life. They allow more precise control of processes such as wastewater pumping, aeration, and chemical feed. Energy saving realized through the use of the VFDs vary depending on the pump size, amount of static head and friction, and average demand flow.

The PG & E report on wastewater management with energy baseline states that “The successful application of VFD’s is also a function of the head against which the pump or blower must operate. In applications where a large static head must be overcome, VFD’s may not be effective, as a very small reduction in speed can result in an excessive reduction in flow and head” [11]. VFDs are reliable and easy to operate, and they increase control of the flow, reduce the pump noise, and help cut energy costs.

3.6.2. Premium Efficiency Motors: Premium efficiency motors use energy more effectively, and their superior design provides a higher power factor. As a result, they require less maintenance and are more reliable. They are most cost effective for applications with a high capacity factor.

Premium efficiency motors owe their higher performance to design improvements and more accurate manufacturing tolerances. Electrical losses are reduced by a longer core and the use of lower-electrical-loss steel, thinner stator laminations, and more copper in the windings. Improved bearing and more aerodynamic cooling fan further increase efficiency.

Pump and blower motors account for 80% to 90% of the energy costs in wastewater treatment, and the lifetime energy costs to run a continuous duty motor are 10 to 20 times higher than the original motor cost. Thus, premium efficiency motors can play a major role in reducing facility operating costs [11].

3.6.3. Influent Pumping: Ideally, wastewater flows by gravity to a treatment plant, which is typically located at the lowest feasible point with respect to wastewater sources. In the real world, however, complete gravity flow is often impossible. Usually, a number of wastewater lift-stations house pumps that provide the needed head for the water to reach the treatment plant. At the plant, influent pumping is sometimes necessary to convey the wastewater into the primary treatment system. These influent and lift station pumps are usually high-capacity, large-horsepower units. They usually run on level control and are typically installed in multiple units for redundancy and to accommodate the variation in diurnal flows. If the capacity factor justifies the expense, they are candidates for VFDs and premium efficiency motors [11].

3.6.4. Aeration Blowers: Two types of blowers that are commonly used in the air activated sludge process: centrifugal blowers or rotary-lobe positive-displacement blowers.

Centrifugal blowers are commonly used for higher flows, whereas positive-displacement blowers are used for lower flows, or where the discharge pressure exceeds 8 to 10 psi. Both types of blowers can have similar levels of efficiency when properly sized and operated close to the design flow rate. Centrifugal blowers are of two types: multistage or single stage. Multistage centrifugal blowers have limited turndown capability (typically 70%), and they are less efficient than single-stage units. Single-stage blowers with variable inlet vanes and variable-discharge diffusers allow flow adjustments while maintaining a constant impeller speed. They are capable of compression efficiencies ranging from 40% to 80%. They have a few disadvantages, such as like high cost, but these can be overlooked [11].

3.6.5. Dissolved Oxygen Control: Fundamental to the energy efficiency of any air-activated sludge process is the ability to vary the oxygen supply to meet diurnal changes in flow and BOD loading. The usual methods of varying the output of centrifugal blowers are inlet throttling, adjustments to inlet vanes or outlet diffusers, and variable frequency drives [11].

3.6.6. Fine Bubble Aerators: Many older plants use coarse-bubble or medium-bubble aerators because they are cheaper and less likely to foul from impurities in the air flow or exposure to wastewater. The typical oxygen transfer efficiency (pounds of oxygen used for BOD removal divided by pounds of oxygen supplied multiplied by 100) of coarse-bubble diffusers ranges of 9% to 13%. Fine bubble aerators are more expensive, require cleaner air, and must be periodically cleaned. However, they provide an oxygen transfer efficiency of 15% to 40%, and with today's higher priced energy they are cost effective. Most retrofits from coarse bubble to fine bubble will produce aeration energy savings of 20% to 40% and simple paybacks of 2 to 4 years, including the increased capital cost (for fine-bubble diffusers, piping, tankage, and gas transfer domes) and additional maintenance and cleaning costs.

3.6.7. Waste-activated Sludge (WAS) and Return-activated Sludge (RAS) Pumps: In an activated sludge plant, WAS is typically 1% to 3% of plant influent flow. At many plants, wasting is not a continuous operation; therefore, WAS flows can be as high as 10% to 15% of plant influent if wasting is carried out for only 5 minutes per hour. WAS pumps are not major energy users because of their low heads. VFD drives and premium efficiency motors are energy efficiency options for applicable to WAS pumping.

RAS flows are large, often 25% to 50% of plant influent flow. RAS pumps are not major energy users since they are also low-head applications. RAS pumps, however, are often operated continuously, and flow is paced based on the influent plant flow rate to avoid treatment disruptions from intermittent flows. Energy efficiency options for RAS pumping are VFDs and premium efficiency motors.

3.6.8. Fixed-Film and Mechanical Aeration: Fixed film treatment processes include trickling filters and rotating biological contactors. A trickling filter consists of a bed of highly permeable medium to which microorganisms are attached and through which wastewater is percolated or trickled. Generally, plastic or rocks are used. A rotating distributor distributes the liquid wastewater over the top of the bed. The organic material in the wastewater is degraded by aerobic microorganisms attached to the media, and it forms a biological film or slime layer. The treated wastewater is then clarified to remove the sludge; it is then disinfected and discharged.

Mechanical aeration typically involves the violent agitation of the wastewater to promote the dissolution of air from the atmosphere. Two common forms of mechanical aeration are surface aeration and submerged turbine aerators. Surface aerators are typically float-mounted or platform-mounted; and they may be equipped with submerged draft tubes. They can be positioned at various depths to achieve different levels of mixing, aeration, and circulation. Submerged turbine aerators include a motor and gearbox drive mounted over the aeration basin or lagoon, with one or more submerged impellers and air piped from a blower to a diffuser ring mounted below the impellers [11].

3.6.9. Tertiary Treatment: Tertiary treatment for nitrogen removal is usually an adjunct to secondary treatment, establishing an anoxic region within the secondary treatment system. Treatment using filters, activated carbon, ion exchange, and membranes is typically pump driven; therefore, VFDs and premium efficiency motors are options [11].

3.6.10. UV Disinfection: As noted above, low-pressure UV is significantly more energy efficient than medium-pressure UV. However, the higher intensity, greater penetration, and fewer lamps required with medium-pressure UV results in lower capital and maintenance costs. The reduction in energy costs with low-pressure UV can still be attractive if a plant can obtain a satisfactory return on the additional capital and maintenance costs required [11].

3.6.11. Effluent Pumping: In many instances where gravity effluent flow is not possible, effluent pumping is required. Effluent pumping can be high flow and high head, particularly if the effluent must be transported long distances, e.g., from an inland treatment plant to an ocean discharge outfall system. The effluent volume also varies widely with diurnal flow unless storage or equalization is used. As a result, energy efficiency options for effluent pumping include premium efficiency motors and VFDs.

The energy consumption of a pump is a function of the head or pressure differential against which the pump must move the liquid flow. Many treatment plants use gravity flow from process to process, with weirs and wet wells feeding pump inlets. Plant fluid levels can often be adjusted to reduce static head loss [11].

3.6.12. Sludge Processing: As noted above, sludge processing is very complex and involves a number of operations. The energy efficiency options for thickening, stabilization, and dewatering include VFD's and premium efficiency motors.

For VFDs in sludge processing, baseline design must be determined on a case-by-case basis because of the variety of processing options available. The options include belt-filter presses, centrifuges, and anaerobic or aerobic digestion. Liquids removed from the sludge are typically returned to the wastewater treatment plant head works, and they may be pumped using on/off or pressure-reducing valves that may be suitable applications for VFDs. Centrifuges and belt filter presses are usually not good applications for VFDs [11].

4. METHODOLOGY

This work combines two existing process flow models. They are presented in section 4.1.1. and 4.1.2.

4.1. PROCESS FLOW MODELS

4.1.1. Energy management systems process flow model: The steps followed in general energy management systems model are listed below [5]. Figure 4.1 shows a process flow design model.

- Identify goals and objectives to be achieved by the end of the project.
- Develop a schedule to audit energy use.
- Collect plant data.
- Perform a field inspection.
- Indentify the processes that consume the most energy.
- Note the amount of bio-solids.
- Calculate the operating capacity of the plant and the operating load.
- Calculate the amount of effluent or the daily treatment capacity of the plant.
- Determine the amount of rainfall per year.
- Calculate the distribution between energy and demand.
- Calculate the average energy consumption per month or year.
- Develop an energy consumption model.
- Identify the key issues in energy consumption.
- Choose the best alternative to improve energy efficiency and develop implementation strategies.
- Calculate energy consumption rates after the audit.
- Based on the change in the energy consumption rates, the alternatives can be varied.

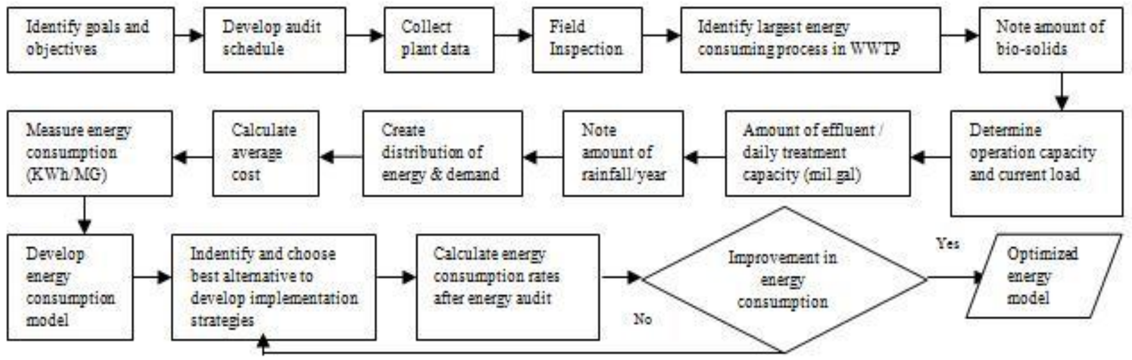

Figure 4.1. Energy management system process flow model

4.1.2. Environmental management systems process flow model: Environmental management systems models generally follow the steps listed below [5]. These steps are shown in Figure 4.2.

- Identify goals and objectives.
- Develop project schedule.
- Collect plant performance data.
- Note COD and BOD levels.
- Collect data on energy consumption of plant.
- Identify data filters.
- Create regression model.
- Test model.
- Identify dependent and independent variables.
- Analyze regression model results.
- Calculate efficiency ratio.
- Calculate energy star rating.

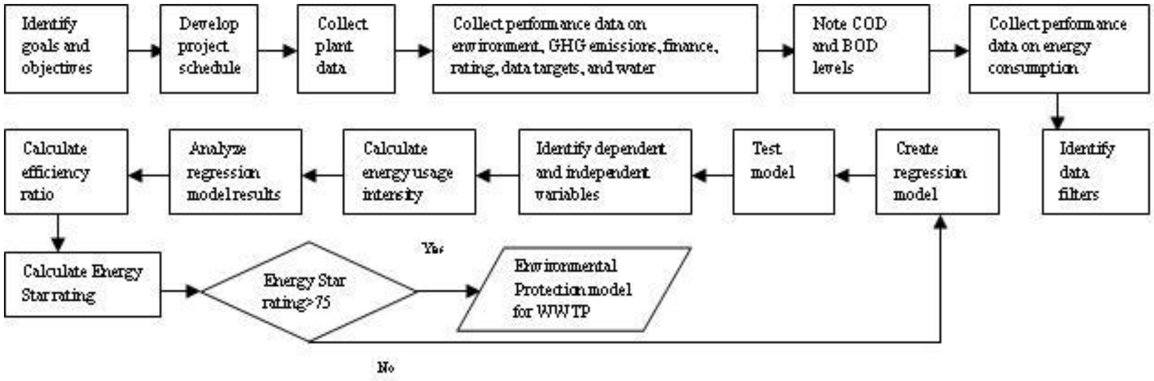

Figure 4.2. Environmental Management System process flow model

4.1.3. Strategic Process Integration: Research thus far has concentrated energy management and environmental management separately. In an energy management model, an energy audit is preferred. Based on the results, measures are taken to reduce the energy consumption at specified points in the process; however, no care is taken to control environmental effects. Energy reduction, therefore, can be achieved at the cost of environmental considerations. Similarly, in an environmental management model, the primary focus is on controlling the environmental effects, although energy consumption is also considered. A proper balance is needed between energy and environmental factors so that both energy efficiency and environmental outcomes can be improved simultaneously. This work uses strategic process integration (SPI) to combine the two systems. The SPI model presented here is a holistic approach to process design that considers the interaction among various steps in the process flow and takes advantages of the benefits of each individual process design model. The main objective of this SPI model is to integrate and optimize each process by conducting a detailed study of the benefits of each approach. A study conducted by the EPA and Siemens Building Technologies, Inc., has shown that most water and wastewater treatment plants operate far below their efficiency capacity. The cross functional model developed in this research can guide a plant manager in developing strategies, scheduling operations, and implementing optimization techniques to increase efficiency while following the environmental policies. [5]

4.2. APPROACH

To use this model, the processes and factors that contribute to the energy consumption must first be identified. By analyzing data collected over a period of time, the process or factor most significant to energy consumption is found. The amount of rainfall and average flow per day is measured. Rainfall has a direct impact on energy consumption, decreasing the BOD level in the influent water. Given significant rainfall, the influent requires little filtration; therefore, energy consumption comes down automatically reduced. Influent flow also has an effect on energy consumption; with an increase in the flow; energy consumption also increases. The integrated model requires that distribution be created between the demand and the energy consumption. Thus this work has developed an energy consumption model that considers energy factors. Energy efficiency improvement techniques are then applied based on the plant conditions. Energy consumption is monitored to evaluate the success of these techniques. If there is no significant improvement, an alternate technique can be applied. This process is repeated until considerable energy efficiency is achieved.

Environmental management systems identify the main factors affecting the environment. This is accomplished by collecting plant performance data and evaluating the chemical composition of the discharged water. The GHG emissions are measured along with BOD and COD levels, nutrients, chlorine, odor, and the suspended solids in effluent. The results are compared to ISO 14001 norms, required discharge characteristics, and EPA standards. The various factors identified are separated into dependent and independent variables and are subjected to regression analysis. The energy usage intensity per environmental impact is then calculated, the results are analyzed, and the most significant factors are identified. The energy efficiency ratio is calculated and used to determine energy star rating. The primary objective is to increase the energy star rating of the facility.

The integrated model combines the steps taken in energy and environmental management systems. Data on the various factors affecting the two systems are collected. The significant factors are then divided into dependent and independent variables, and correlations among them are identified. Factors that correlate are not considered for analysis since they produce more errors. A multi-variate regression analysis is conducted to identify the significant factors and determine the effect of one variable on another. This analysis is repeated, changing the dependent and independent variable and, thus the effect of one factor on another. Based on the results of each multi-variate regression model, factors most significant to both energy and environmental systems are identified. By controlling these factors, a balance can be maintained between energy and environmental management models. Once these factors are identified; techniques that improve energy efficiency while simultaneously conforming to environmental norms can be applied. This is shown in Figure 4.3.

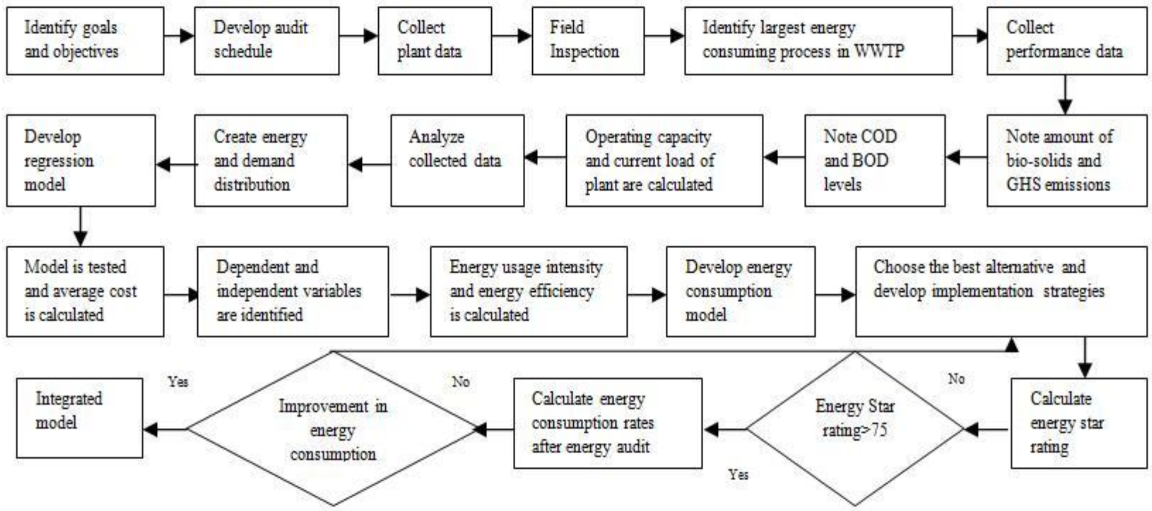

Figure 4.3. Integrated energy and environmental management system process flow model

4.3. REGRESSION ANALYSIS

Regression analysis is a tool for exploring the relationship between one variable referred to as a response variable or dependent variable, and one or more other variables, called predictor or independent variables. Regression analysis is distinguished from other statistical tools in that the primary objective is to express the dependent variable as a function of independent variables. Once such an expression is obtained, the relationship can be used to predict the values of dependent variable, identify the significant variables, or verify the cause of the results, and errors in the data.

All applications of linear regression methodology use the relationship between the dependent and independent variables. The term Y represents the dependent variable and n represents the number of independent variables $X_1, X_2, X_3, \ldots X_n$. The linear relationship between Y and other independent variables takes the form

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots\ldots\ldots + \beta_n X_n + \varepsilon. \qquad (1)$$

In the above expression α, β_1, β_2, $\beta_3 \ldots\ldots \beta_n$ are unknown model parameters called *regression coefficients*. The term ε represents the error, because the observed variables are subject to variability and cannot be expressed exactly as the linear combination of independent variables.

4.3.1. Simple linear Regression [12]:

Regression between one dependent variable and one independent variable is considered as a simple linear regression. If ‘Y’ is the dependent variable and ‘X’ is the independent variable; then

$$Y = \alpha + \beta_1 X_1 + \varepsilon \qquad (2)$$

where α and β_1 the unknown model parameters and ε represents the error.

4.3.2. Multilinear Regression:

A multi-linear regression model is a model has one dependent variable and two or more independent variables. Most practical applications use multilinear regression which yields more accurate results than simple linear regression.

4.4. ASSUMPTIONS IN REGRESSION ANALYSIS [13]

The accuracy of a regression model depends mainly on the assumptions made about the data and its properties. The following are a few assumptions that ensure that a regression estimate will have good properties:

- Error term follow a normal distribution and they are identically independent
- Independent variables are nonrandom, i.e., they are independent of the disturbance and have finite variances.
- Independent variables are linearly independent. That is, no independent variable can be expressed as a linear combination of the other independent variables. In other words, there is no multi-collinearity in the data.

4.5. CORRELATION OF THE VARIABLES

Correlation and regression analyses are related in the sense that both deal with relationships among variables. Correlation refers to the interdependence among the variables, and the correlation coefficient is a measure of the linear association between two variables. It reflects the closeness of the dependent and independent variables. Values of the correlation coefficient vary between -1 and +1. If the correlation coefficient is +1, the two variables are perfectly related in a positive linear manner; if the correlation coefficient is -1 then the two variables are perfectly related in a negative linear manner. A correlation coefficient of 0 indicates that there is no linear relationship between the two variables.

"Neither regression nor correlation analyses can be interpreted as establishing cause-and-effect relationships. They only indicate how or to what extent variables are associated with each other. The correlation coefficient measures only the degree of linear association between two variables. Any conclusions about a cause-and-effect relationship will purely depend on the judgment of the analyst." [14]

4.6. USES OF REGRESSION ANALYSIS [12]

Most uses of regression analysis can be divided into three broad categories: they are prediction, parameter estimation, and model specification.

Prediction: By constructing a prediction equation and subjecting it to regression analysis, future outcomes of the variables can be forecasted. Regression analysis shows the effects of one variable on another, the degree of these effects and their significance can be determined, facilitating effective future planning.

Model Specification: A critically important benefit of regression analysis, model specification assesses the relative value of individual predictor variables in response prediction. It requires that all the variables are contained in the database and that the prediction equation be defined with the correct functional form for all predictor variables.

Parameter Estimation: For regression analysis to yield good results, it must meet certain criteria. For example, the model should be correctly specified, prediction should be accurate, and the characteristic of the database should permit accurate estimation. Certain characteristics of the database, such as multi-collinearity and correlation, affect the accuracy of the model. If there is correlation or multi-collinearity among the variables, the results are bound to be biased and inaccurate.

4.7. LINEAR LEAST SQUARES [15]

Linear least squares regression is the most often used method to fit a model to the data. Linear least squares regression can be used to fit the data to any function of the form

$$Y= \alpha+\beta_1X_1+\beta_2X_2+\beta_3X_3+\ldots\ldots\ldots.+\beta_nX_n+\varepsilon \tag{3}$$

In the least squares method, the unknown parameters are estimated by minimizing the sum of the squared deviations between the data and the model. The differences between the predicted values of Y and the observed values of Y are called residuals. If the sum of the squares of the residuals is high, then the model is said to have more noise. Thus, the residual sum of squares should me as minimum as possible. The method of least squares minimizes the squares of the residuals.

One very simple example which we will treat in some detail in order to illustrate the more general problem is that of fitting a straight line to a collection of pairs of observations (xi, yi) where i = 1, 2, . . . , n. We suppose that a reasonable model is of the form

$$Y = \alpha + \beta_1 X_{1.} \tag{4}$$

This is a special case of more general form of fitting a polynomial of order ‘p’, for which we should find p+1 coefficients and it is generally done by the method of least squares. The problem is to find the values of α and β_1 that minimize the residual sum of squares (S).

$$S(\alpha, \beta_1) = \sum_{i=1}^{n} (Y_i - \alpha - \beta_1 X_1)^2 \tag{5}$$

This operation involves the minimization of the vertical deviations from the line; therefore it is not symmetrical in Y and X. In other words; if X is treated as the dependent variable instead of Y, one can expect a different result. The minimizing values of β_i we just solve the equations resulting by setting $(dS / d\alpha)$ and $(dS / d\beta_1)$ equal to 0. The least square parameter estimates are the calculated by

$$\alpha = \frac{\Sigma Xi^2 \Sigma i\mathrm{Y}i - \Sigma \mathrm{X}i \Sigma \mathrm{X}i\mathrm{Y}i}{n\Sigma Xi^2 - (\Sigma Xi)^2} \quad \text{and} \tag{6}$$

$$\beta 1 = \frac{n\Sigma XiYi - \Sigma Xi\Sigma Yi}{n\Sigma Xi^2 - (\Sigma Xi)^2} \tag{7}$$

where $\sum$ is taken to be from i = 1 to n in each case.

5. ROLLA SOUTHEAST WWTP

Rolla is a small rural community located in south central Missouri. The Rolla Southeast Wastewater Treatment Plant processes an average of 3 million gallons of wastewater every day. The main step in the treatment process is the separation of solids, which account for about 2% of wastewater. Wastes are separated and filtered by various processes such as aeration, trickling filter, sand filter, primary and secondary clarifier, and oxidation. Figure 5.1 shows the aerial view of the Rolla Southeast WWTP. Figure 5.2 illustrates the various processes used at the plant, the flow of influent through various filters, and capacity of each process. Initially, the influent flows from mechanical filtration tanks where solids are separated. It is then allowed to flow through clarifiers where it loses most of the solid wastes. The oxidation process reduces the odor and maintains COD and BOD levels. This plant runs no disinfection process; after oxidation, the effluent is directly discharged into water bodies. [5]

Figure 5.1. Aerial View of Rolla Southeast WWTP

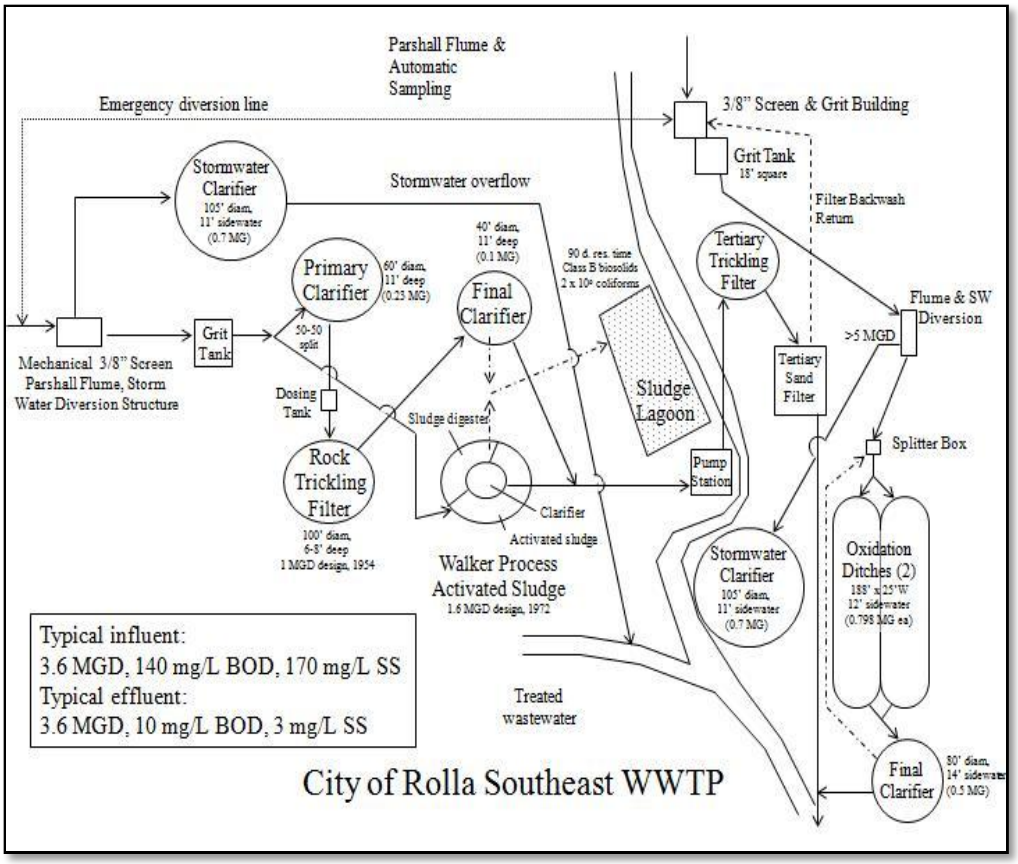

Figure 5.2. Flow of influent in Rolla Southeast WWTP

5.1. PERFORMANCE DATA AND COMPARISON

The monthly performance data for the plant was collected over a period of two years. The energy consumed by the plant per month was determined and the energy consumed by each process was then estimated based on the specifications for equipment run at the facility and on run time. Three processes that consume majority of the energy used at Rolla Southeast WWTP are blower and oxidation ditch, pump and trickling filter, and clarifier. Based on the literature review, specifications, operating time, and capacity, the blower and oxidation ditch were estimated to consume 75% of the total energy, the pump and trickling filter 10% and the clarifier the remaining 15%. In this analysis, the energy consumption values were estimated based on BOD, suspended solids, average flow, and observations of the other plant with similar conditions. The BOD level of the influent was noted for every month, and the change in the BOD level of the influent in each process was estimated based on the purification process. BOD level is determined primarily mainly affected in the oxidation ditch; the dissolved oxygen brings down the BOD level in the influent. Based on the literature review, and on the capacity and specifications of the equipment, the clarifier was estimated to reduce the BOD level by 10%, the pump and trickling filter by 25%, and the blower and oxidation ditch by the remaining 65%. Suspended solids are separated initially by the clarifier; most solids are removed by this process. The amount of suspended solids in each process was measured and noted. An estimated 86% of suspended solids are reduced by clarifier, 9% by trickling filter, and remaining 5% by the oxidation ditch. The amount of rainfall per each month was also collected because this Figure has great influence on BOD and eventually on the energy consumption. Since rain water is fresh water, when there is more rainfall the BOD level in the influent is reduced. Thus, less energy is required to reduce for reducing the BOD to desired levels. Average flow is directly proportional to the energy consumption since energy consumption increases as average flow increases. The daily flow rate of the waste water was also measured and an average monthly flow rate is calculated.

This analysis took energy as the dependent variable; and BOD, suspended solids, flow rate, and rainfall are taken as the independent variables. The change in the dependent variable energy with the change in the independent variables such as BOD, Suspended solids, average flow and rainfall was observed; out of these variables the significant variables affecting the energy and its severity were calculated.

6. RESULTS AND DISCUSSION

Multilinear regression analysis was conducted with energy as a dependent variable and BOD, suspended solids, average flow, and rainfall as independent variables. Energy consumption is divided among the three main processes clarifying, filtering, and oxidation. Similarly, BOD and suspended solids values for each process were estimated. The results of the multilinear regression gives are shown in Tables 6.1, 6.2, 6.3.

Table 6.1. Analysis of variance (clarifier)

Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr>F**
Model	5	727073147	14541629	79.58	<.0001
Error	34	62131087	1827385		
Corrected Total	39	789204234			

In Table 6.2 we can see that the value of adjustable R-square is 0.9097 indicating that this model explains the 90.97% of the variation, i.e., it gives us the 90.97% of information, thus the results are reliable. A variance inflation factor was used to verify the multi-collinearity between the variables, if it its value was >10 then we can say that multi-collinearity exists among the variables. If multi-collinearity exists between the variables then we get biased and non-reliable results.

Table 6.2. R-Square and Adjustable R-Square - Clarifier

Root MSE	1351.80802	**R-Square**	0.9213
Dependent Mean	24587	**Adjustable R-Square**	0.9097
Coeff Var	5.49809		

Table 6.3 demonstrates that the variance inflation factor for all the variables was less that 10; thus, there was no multi-collinearity among the factors. Parameter estimates are the values of the coefficient of each variable; however, they could not be compared as

the units of measure were different for each variable. Standardized estimates are the values of the coefficients of the variables as expressed in common units; these values were β1, β2, and β3 (from Equation (3)). The value of Pr>|t| was less than .0001, indicating that suspended solids are the most significant factor for energy consumption during clarification and its effect on BOD primarily depends on the amount of suspended solids. This is predicted with a with a 99.99% confidence level based on Pr>|t| value from Table 6.3.

Table 6.3. Parameter estimates (Clarifier)

Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**Standardized Estimate**	**Variance Inflation**
Intercept	1	14569	1388.23391	10.49	<.0001	0	0
BOD	1	71.32068	99.59280	0.72	0.4788	0.04816	1.95316
SS	1	93.90135	6.88790	13.63	<.0001	0.88174	1.80665
Rainfall	1	151.33299	87.92586	1.72	0.0943	0.08639	1.08798
Wet	1	0.07620	0.06964	1.09	0.2186	0.05369	1.03984
Dry	1	-18.90375	9.07498	-2.02	0.0516	-0.10717	1.21856

We assumed that the error terms follow a normal distribution. The bell shaped curve with the peak at the mean helps us to identify the correctness of the data. If the peak does not occur at the mean then the data and results are not reliable. Error terms follow normal distribution and they are identically independent from the plot we can identify the deviation of the error terms from normality. Figure 6.1 shows the distribution of residuals for energy, it is a perfect curve with the peak at the mean and all the error terms follow the normal distribution, hence we can rely on the data. If the residuals by predicted follow a defined pattern like club, parabola or a regular curve, etc; then the model and data are not suitable for study. In Figure 6.2 we can see from the plot that these is no regular pattern followed by the data, thus the model and data are suitable for the study.

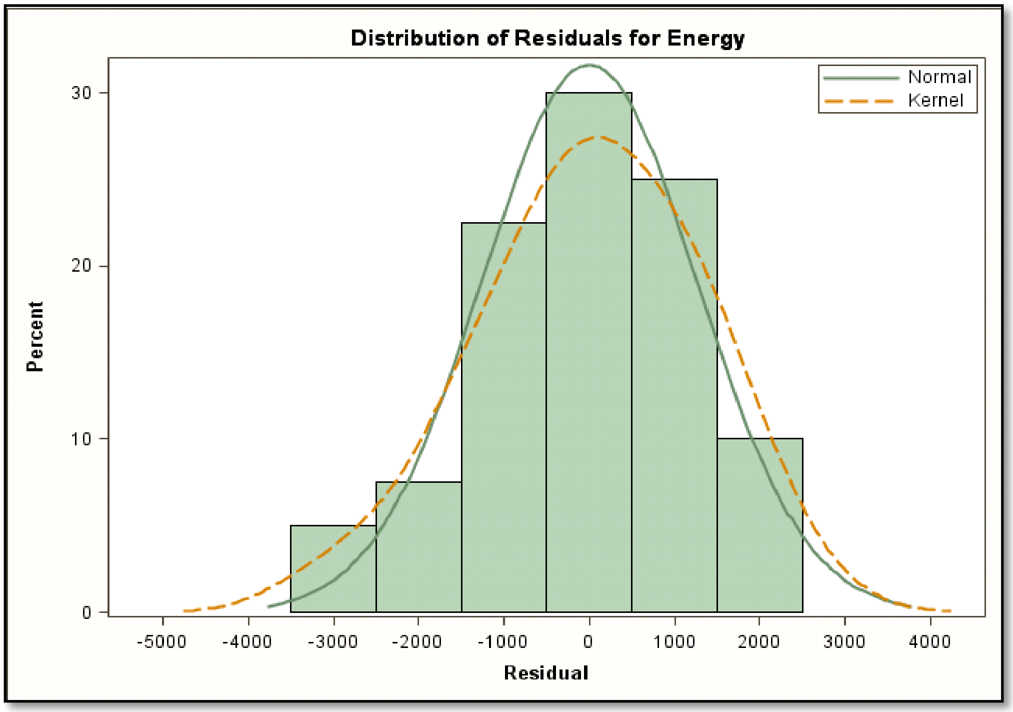

Figure 6.1. Normal distribution residual plot for clarifier process

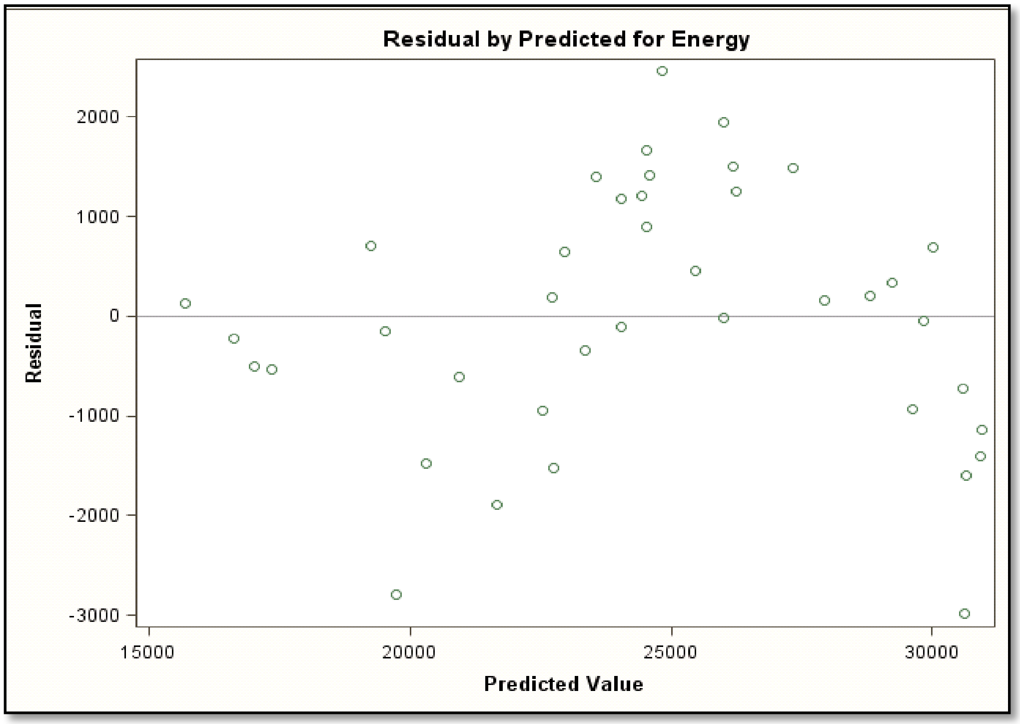

Figure 6.2. Residual predicted for energy (Clarifier)

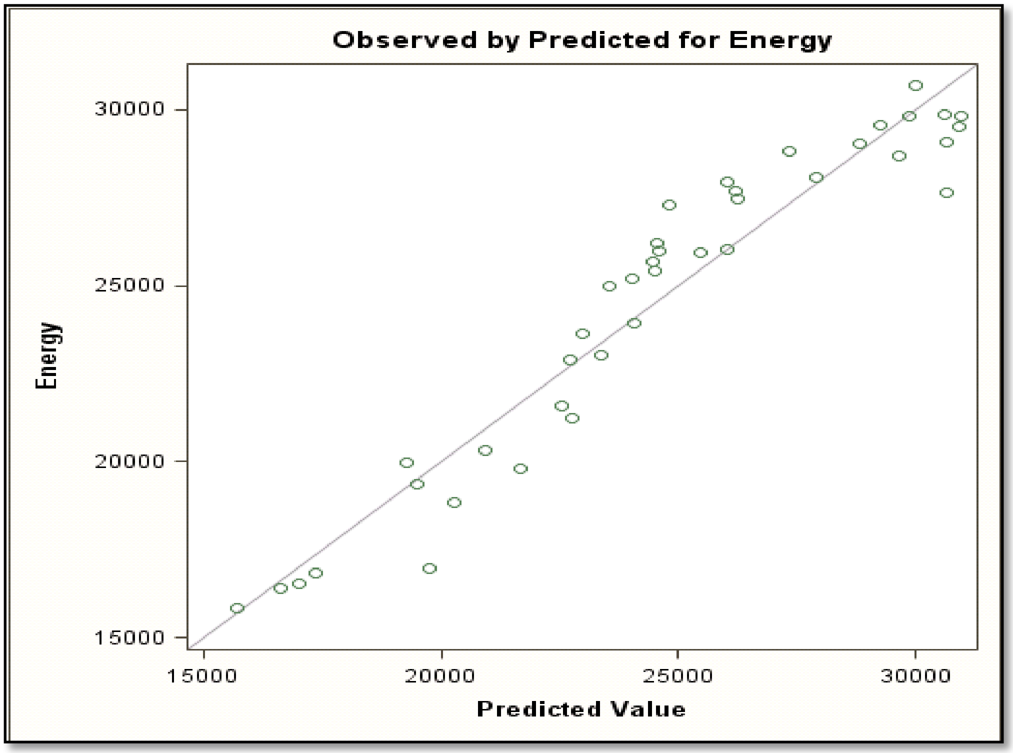

Figure 6.3. Predicted vs. Observed values of energy for clarifier

The closeness of the predicted values to the observed values defines the error and goodness of fit. Figure 6.3 demonstrates the closeness of the predicted and observed values indicating that it is a good fit.

Outliers are the extreme values in the data which are distant from the rest of the data. They are often an indicative of the measurement error. If there are many outliers in the data, then the chance of occurrence of error is high. Outliers change the results of model, and lead to wrong conclusions. An RStudent value between -3 and +3 indicates the results to be accurate and error free. In Figure 6.4 we can see that RStudent values here lay between -2 and +2, thus the model is accurate. A Q-Q plot is similar to a residual curve; it is used to check whether the data follow a normal distribution. The proximity of the data points to the line shows that the data follows a normal distribution (from Figure 6.5).

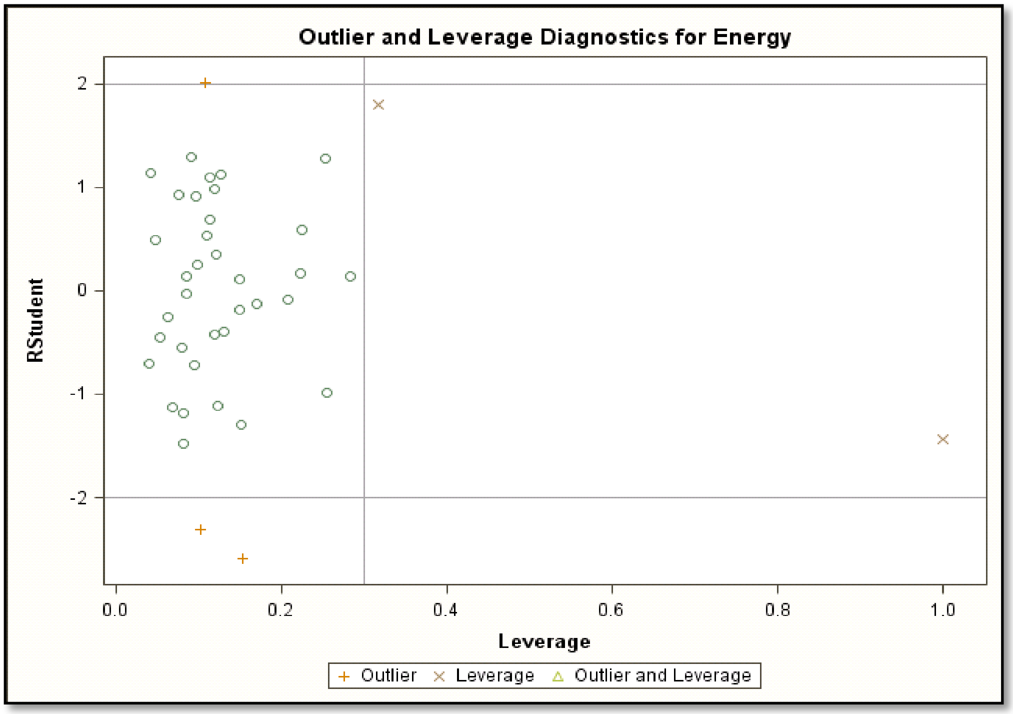

Figure 6.4. Outlier and leverage values (Clarifier)

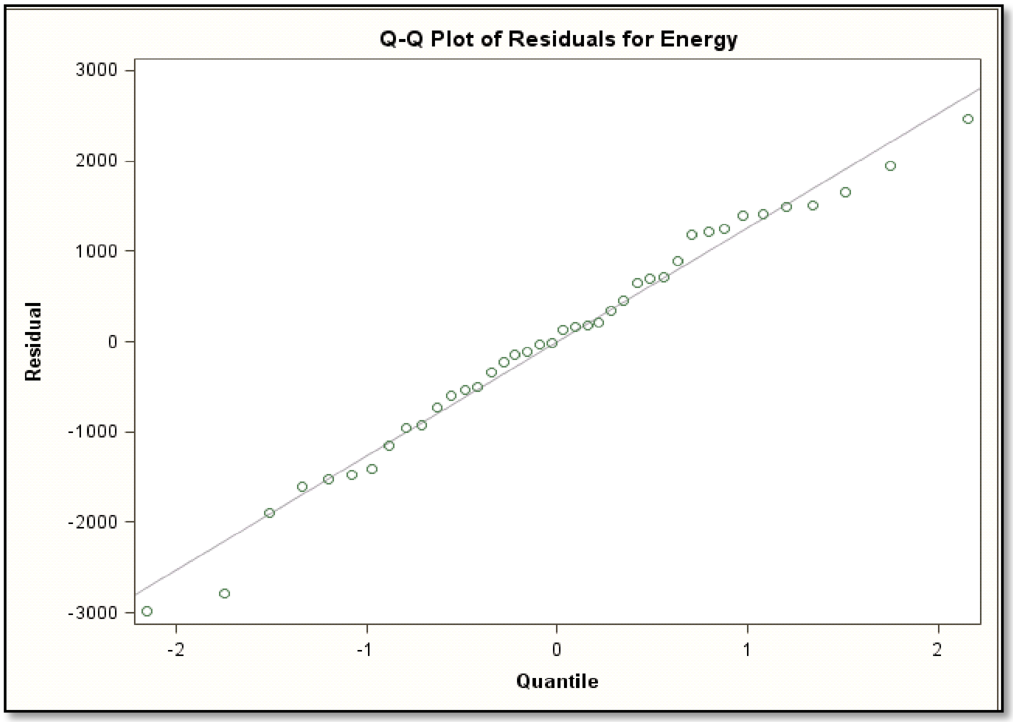

Figure 6.5. Q-Q plot of residuals for energy (Clarifier)

Tables 6.4, 6.5 and 6.6 show the results of multilinear regression with energy consumed by blower and oxidation as the dependent variable and BOD, suspended solids, rainfall, and average flow as independent variables. As explained above in the case of the clarifier this model also explains 90.97% of variation. In this case also the suspended solids are the significant factor; therefore to reduce energy consumption at the blower and the oxidation ditch, the influent from the clarifier must contain minimal amounts of suspended solids. Pr>F is less than .0001 from Table 6.4 this signifies the goodness of the fit for the given data.

Table 6.4. Analysis of variance (Blower and Oxidation)

Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr>F**
Model	5	18176828679	3635365736	79.58	<.0001
Error	34	1553277180	45684623		
Corrected Total	39	19730105859			

Table 6.5. R-Square and Adjustable R-Square (Blower and Oxidation)

Root MSE	6759.04009	**R-Square**	0.9213
Dependent Mean	122934	**Adjustable R-Square**	0.9097
Coeff Var	5.49809		

From Table 6.6, we can see that variance inflation factor is less than 10 hence no multi-collinearity exists between the variables.

Table 6.6. Parameter Estimates – Blower and Oxidation

Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**Standardized Estimate**	**Variance Inflation**
Intercept	1	72846	6941.16956	10.49	<.0001	0	0
BOD	1	54.86206	76.60985	0.72	0.4788	0.04914	1.95316
SS	1	8075.5160	592.35902	13.63	<.0001	0.89162	1.80665
Rainfall	1	756.66495	439.62929	1.72	0.0943	0.08749	1.08798
Wet	1	0.38099	0.34822	1.09	0.2186	0.05369	1.03984
Dry	1	-91.54874	45.37488	-2.02	0.0516	-0.10617	1.21856

In Figure 6.6 residual plot shows that the data follows a normal distribution and the error terms are identically independent. It is a smooth curve with the peat the mean. Hence the data is reliable.

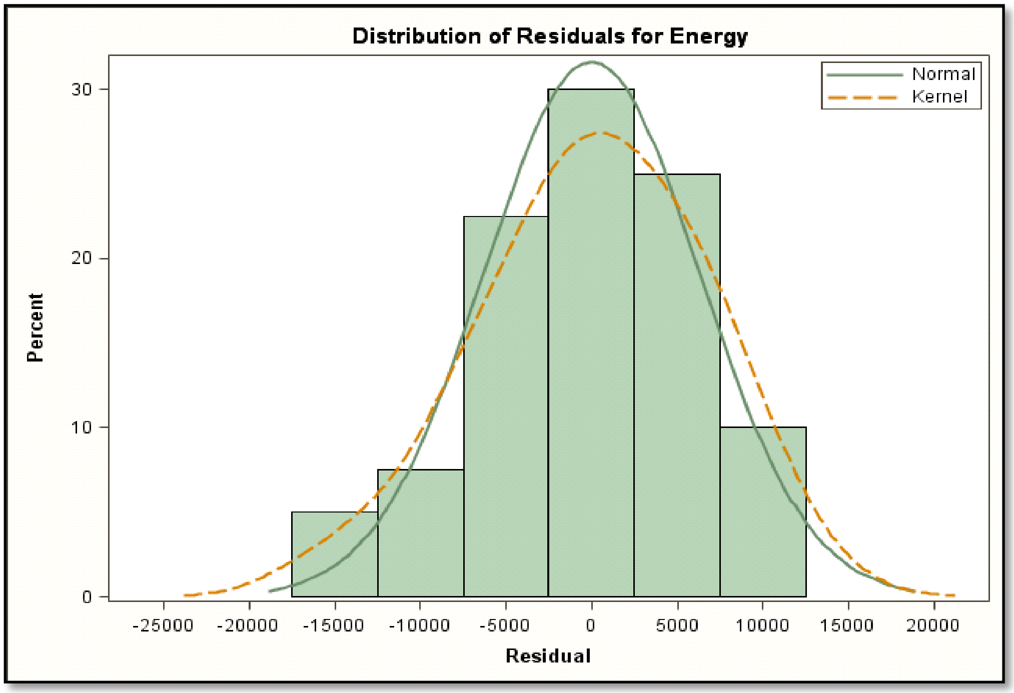

Figure 6.6. Normal distribution residual plot for blower and oxidation process

The plot of the residual by predicted is scattered and does not follow any pattern as shown in Figure 6.7, thus the model and data are good and suitable for study.

From Figure 6.8 we observe that the predicted and observed values are almost same, hence it is a good fit for the model. The outlier values are also within the allowable limit as shown in the Figure 6.9. Hence the model is accurate and reliable.

The closeness of the points on the Q-Q plot with the line in Figure 6.10 shows that the data follows a normal distribution. Hence the error terms follow the normal distribution and there is no deviation from the normality.

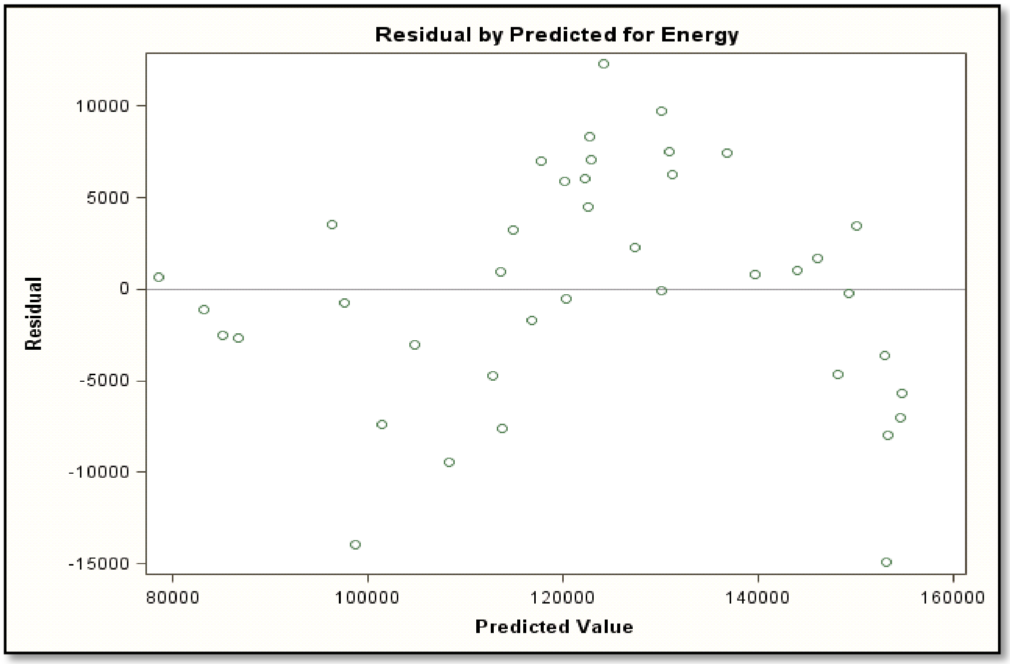

Figure 6.7. Residual predicted for energy (blower and oxidation)

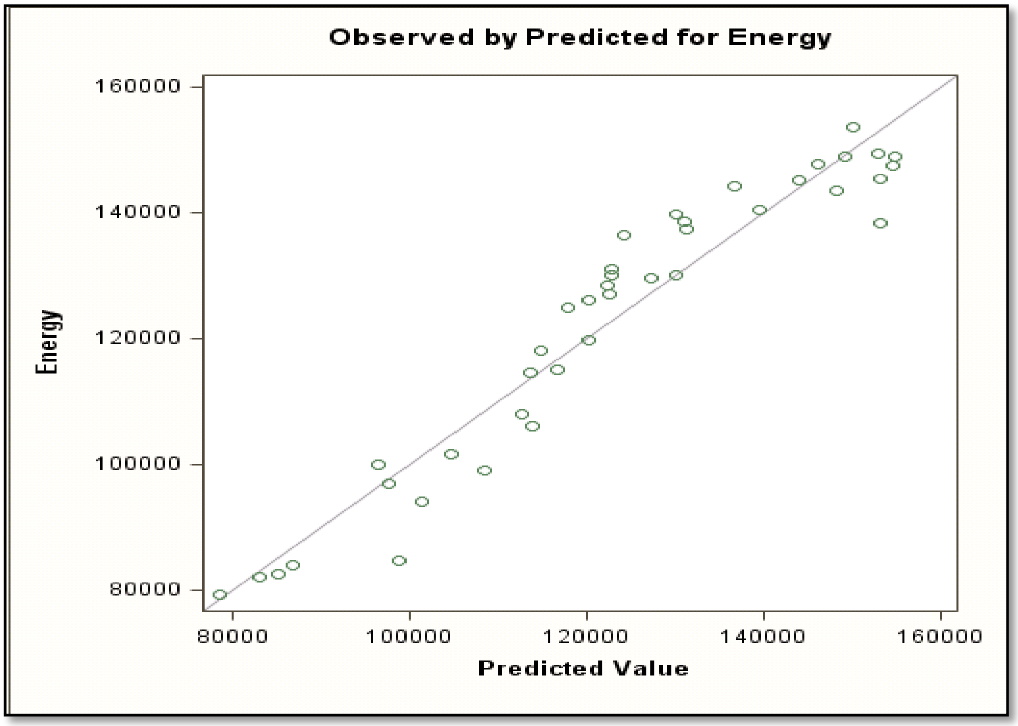

Figure 6.8. Predicted vs. Observed values of energy for blower and oxidation

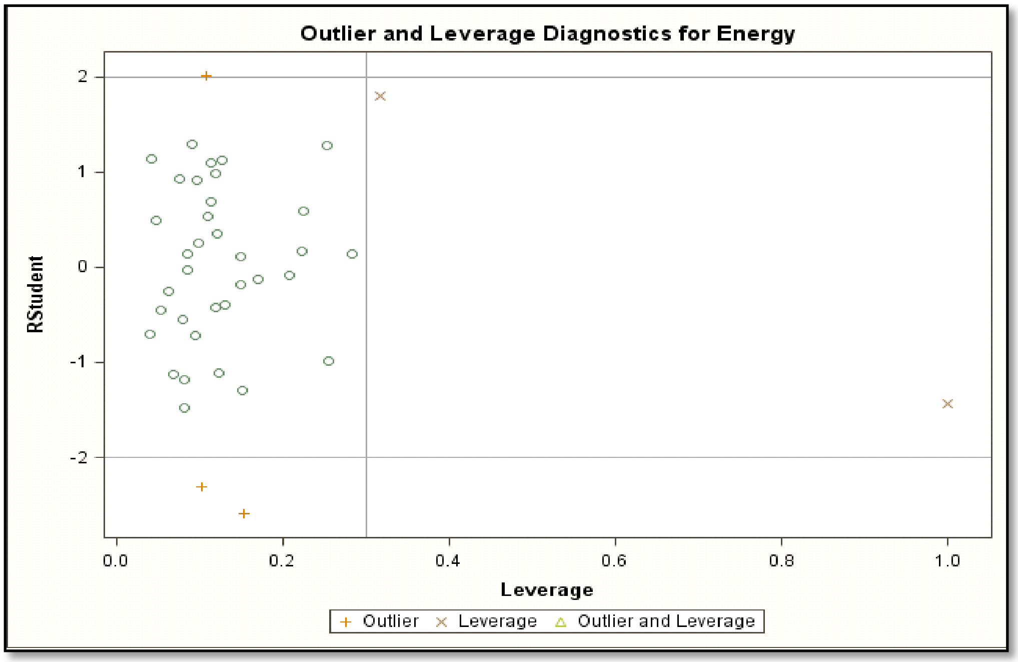

Figure 6.9. Outlier and leverage values (Blower and oxidation)

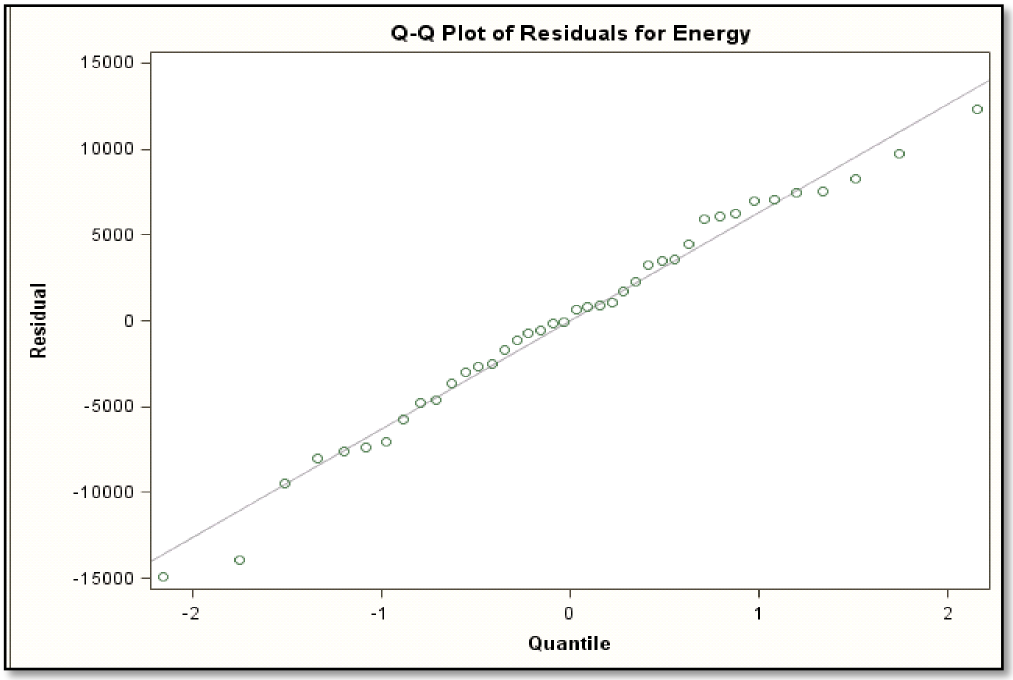

Figure 6.10. Q-Q plot of residuals for energy (Blower and oxidation)

The multilinear regression with energy consumed by pumping and trickling filter as dependent variable and BOD, Suspended Solids, rainfall, and average flow as independent variables gives the results as shown in Table 6.7, Table 6.8, and Table 6.9. As explained earlier in the case of Clarifier this model also explains 90.97% of variation, i.e., we can get 90.97% of the reliable information from the model. In this case also the suspended solids is the significant factor, it means that for reduced consumption of energy at blower and oxidation ditch the influent must get rid of maximum amount of suspended solids from previous process (i.e., Clarifier).The residual plot as shown in Figure 6.11 shows that the data follows a normal distribution and the error terms are identically independent. Pr>F is <.0001 from Table 6.7, this signifies the goodness of the fit for the given data. The plot of the residual by predicted is scattered and does not follow any pattern as shown in Figure 6.12, thus the model and data are good. From Table 6.9, we can see that variance inflation factor is <10 hence no multi-collinearity exists between the variables. From Figure 6.13 we observe that the predicted and observed values are almost same, hence it is a good fit for the model. The outlier values are also within the limit from Figure 6.14.

Table 6.7. Analysis of Variance (Pumping and trickling filter)

Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr>F**
Model	5	323143621	64628724	79.58	<.0001
Error	34	27613817	8128171		
Corrected Total	39	350757438			

Table 6.8. R-Square and Adjustable R-Square (Pumping and trickling filter)

Root MSE	901.20535	**R-Square**	0.9213
Dependent Mean	16391	**Adjustable R-Square**	0.9097
Coeff Var	5.49809		

Table 6.9. Parameter Estimates (Pumping and trickling filter)

Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**Standardized Estimate**	**Variance Inflation**
Intercept	1	9712.84762	925.48928	10.49	<.0001	0	0
BOD	1	19.01885	26.55808	0.72	0.4788	0.04715	1.95316
SS	1	598.18637	43.87845	13.63	<.0001	0.87144	1.80665
Rainfall	1	100.88866	58.61724	1.72	0.0943	0.08534	1.08798
Wet	1	0.05080	0.04643	1.09	0.2186	0.05269	1.03984
Dry	1	-12.20650	6.04998	-2.02	0.0516	-0.10214	1.21856

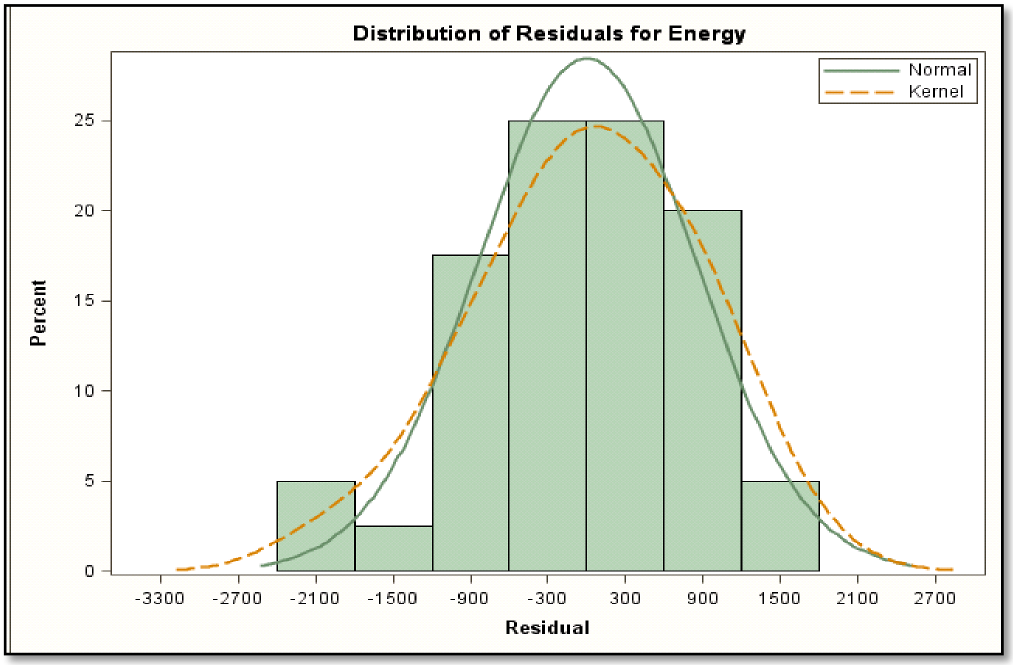

Figure 6.11. Normal distribution residual plot for pumping and trickling filter

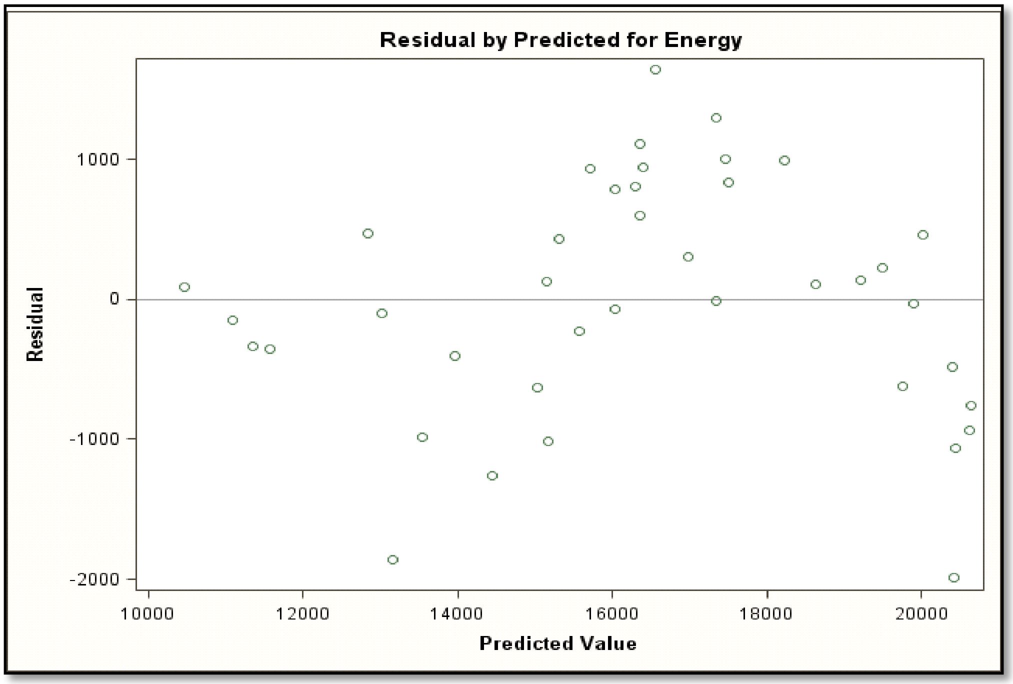

Figure 6.12. Residual predicted for energy – pumping and trickling filter

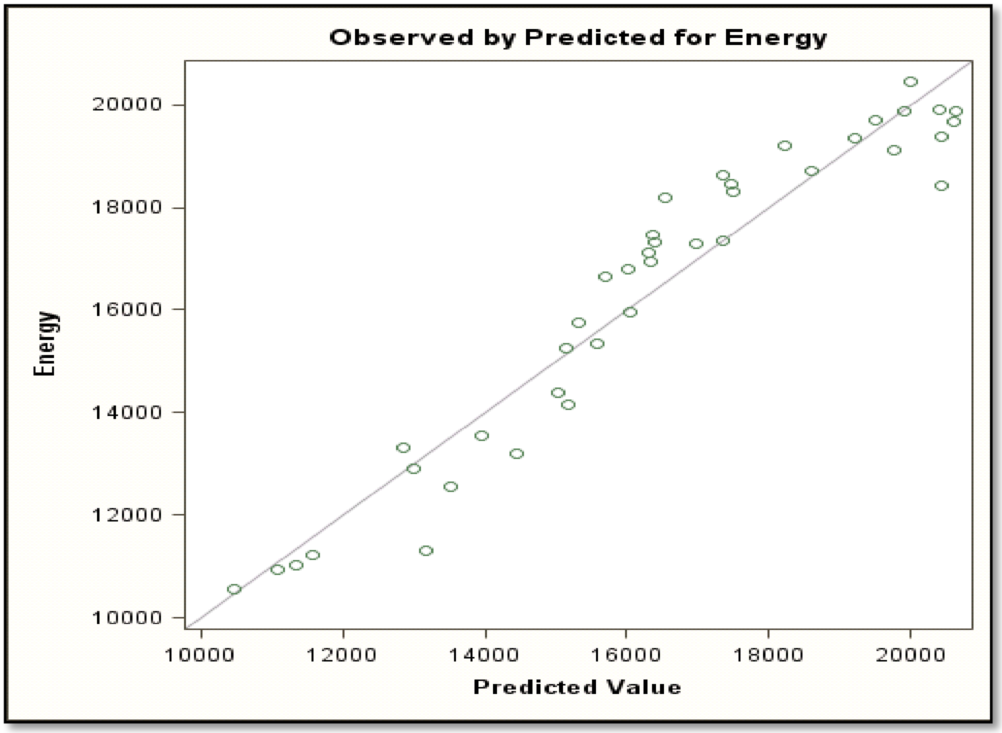

Figure 6.13. Predicted vs. Observed values of energy for blower and oxidation

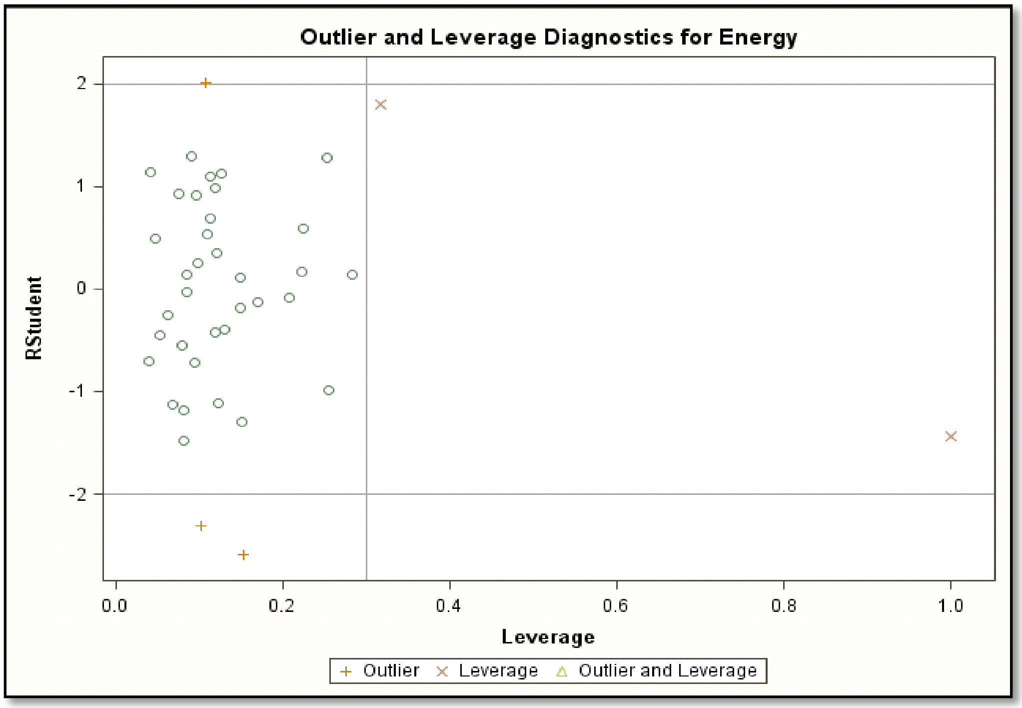

Figure 6.14. Outlier and leverage values- Pumping and trickling filter

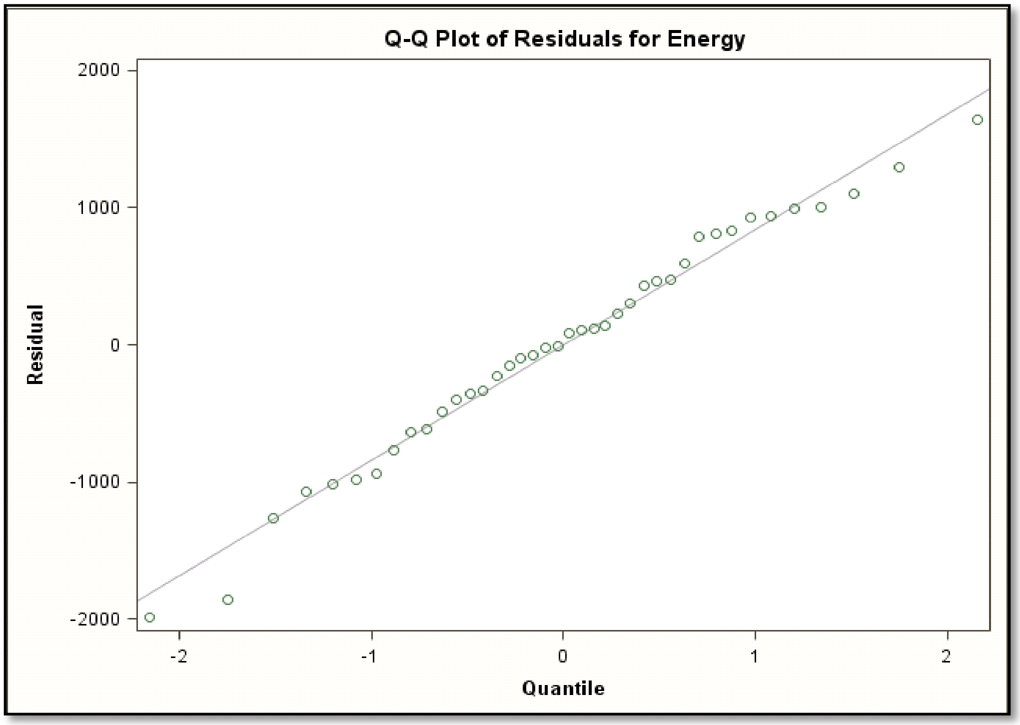

Figure 6.15. Q-Q plot of residuals for energy- Pumping and trickling filter

When we plot the variation of BOD and Suspended solids against the average flow then we can see as shown in Figure 6.16 and 6.17 that variation in BOD and SS is almost the same. But there is no exact relationship between average flow and BOD or SS, i.e., we cannot predict the BOD and SS level with the help of average flow.

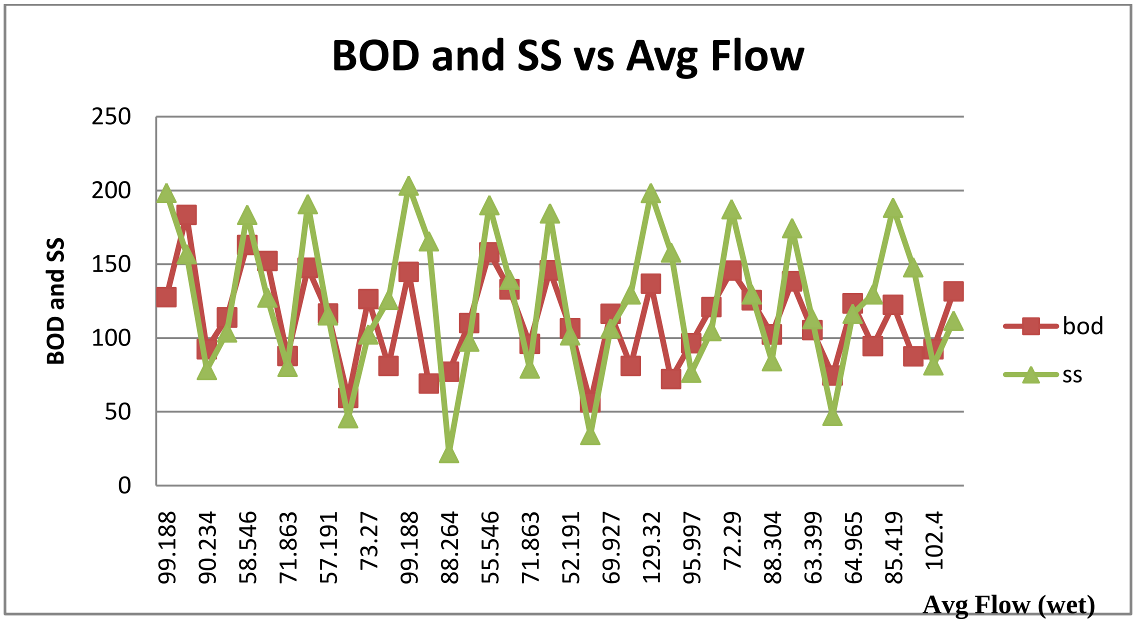

Figure 6.16. BOD and SS vs. Avg Flow (wet)

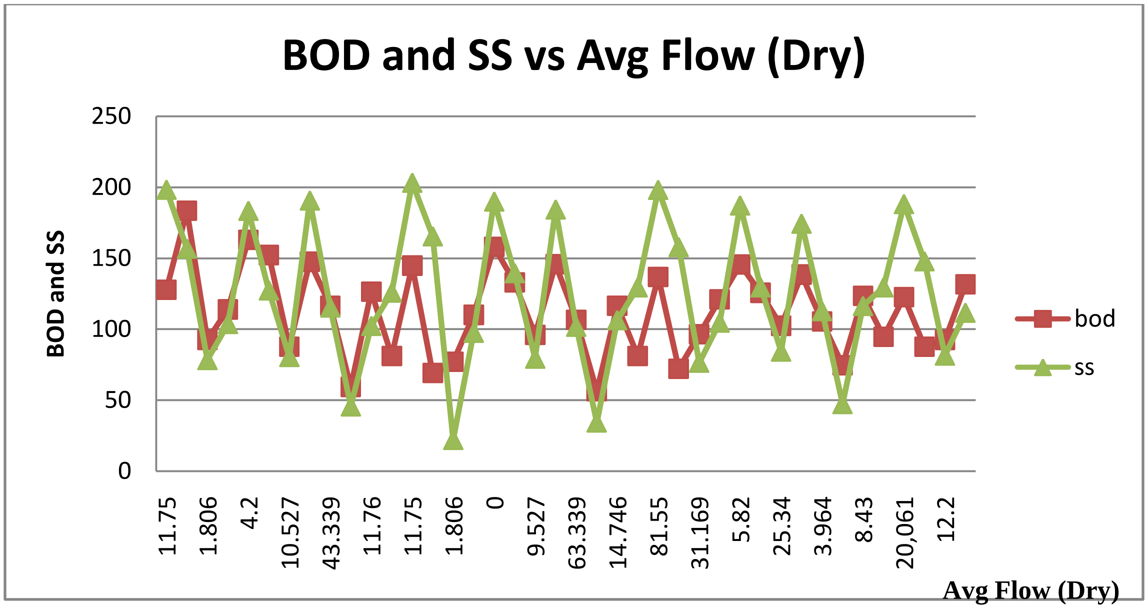

Figure 6.17. BOD and SS vs. Avg Flow (dry)

BOD and SS when plotted against the average rainfall we see that variation in BOD and SS is almost as shown in Figure 6.18. As the rainfall increases BOD and SS level decreases.

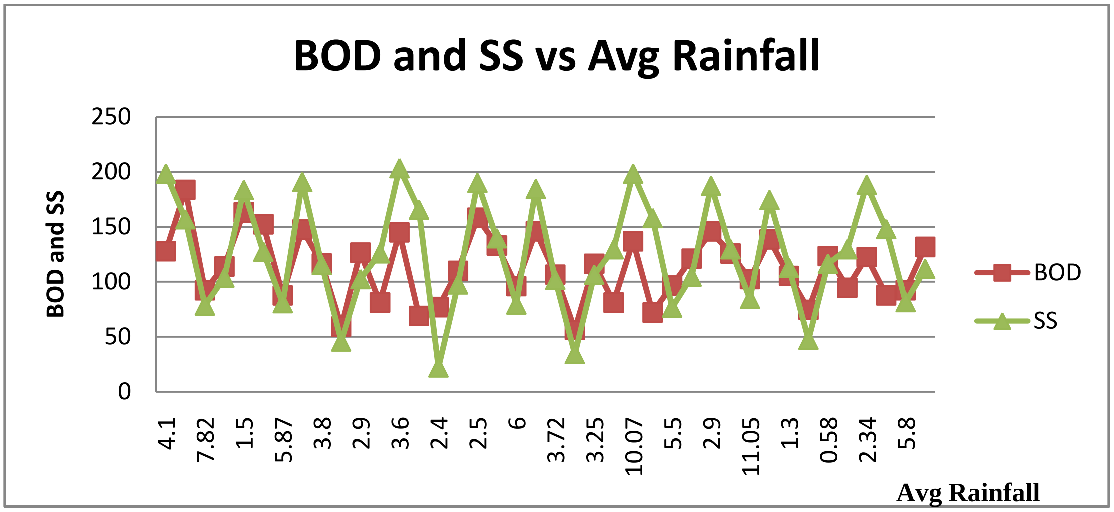

Figure 6.18. BOD and SS vs. Avg Rainfall

7. CONCLUSION

This research demonstrates that there exists a relationship between environmental and energy factors, and that there is, therefore, a need to maintain a balance between the two. The solution is to develop an integrated energy and environmental management model. This work investigated the various possibilities for increasing the energy efficiency while maintaining the environmental standards. Based on the results, one suitable technique is developed. The results of a case study on the Rolla Southeast WWTP show that among BOD, suspended solids, rainfall, and average flow, the suspended solids is the most significant factor for the energy consumption. Thus, if the amount of suspended solids can be minimized then the energy consumption can be reduced. The Rolla plant uses clarification, pumping, a trickling filter and oxidation. Clarification mainly reduces the suspended solids. The oxidation ditch reduces BOD, but energy consumption during this process is high. If the suspended solids are reduced at the clarifier therefore the energy consumed at the subsequent processes will be reduced. If contrary to this model, energy consumption at the blower is reduced using VFDs or any other method, however the BOD and suspended solids levels in the effluent which would ultimately affect the environment. By integrating energy and environmental models, both energy consumption and environmental conditions are considered and a balance is maintained.

Following the preliminary research and analysis based on the data available, this work identified valuable information on a range of potential options to address both energy and environmental concerns. This model cannot be generalized to all WWTPs since the conditions and facilities at the Rolla Southeast WWTP are unique. The purification processes for example are very specific; the discharged water is not disinfected and the plant capacity is very small. Much of the data collected for the model and analyses presented here were the estimated, therefore, the results may not be reliable. Implementing the same model with the actual data, however, will yield improved results to provide stronger conclusions.

8. FUTURE WORK

Future work will evaluate the strategic industrial partnership options that could allow a WWTP to improve its performance and quality and to reduce pollution levels. Such work will also introduce more accurate implementations.

The effectiveness of the integrated model will be tested by implementing it in a WWTP and constantly monitoring its effect on plant performance. The sustainability and sensitivity of the integrated model will be analyzed in greater detail. By including more factors such as cost and time and by applying linear programming techniques the results will be optimized. Energy conservation techniques will also be explored in greater detail in future studies.

APPENDIX

ROLLA SOUTHEAST WASTEWATER PLANT PERFORMANCE DATA

Energy consumption data for the whole plant and for individual process

Energy				
month and year	usage in kWh	blower and oxidation ditch	pump and trickling filter	clarifier
Mar-06	141700	106275	14170	21255
Apr-06	186200	139650	18620	27930
May-06	125500	94125	12550	18825
Jun-06	132400	99300	13240	19860
Jul-06	188700	141525	18870	28305
Aug-06	155800	116850	15580	23370
Sep-06	203200	152400	20320	30480
Oct-06	183100	137325	18310	27465
Nov-06	201100	150825	20110	30165
Dec-06	183100	137325	18310	27465
Jan-07	235700	176775	23570	35355
Feb-07	192400	144300	19240	28860
Mar-07	180300	135225	18030	27045
Apr-07	187200	140400	18720	28080
May-07	165600	124200	16560	24840
Jun-07	201600	151200	20160	30240
Jul-07	194700	146025	19470	29205
Aug-07	186600	139950	18660	27990
Sep-07	194100	145575	19410	29115
Oct-07	170100	127575	17010	25515
Nov-07	174000	130500	17400	26100
Dec-07	177300	132975	17730	26595
Jan-08	210600	157950	21060	31590
Feb-08	165300	123975	16530	24795
Mar-08	137700	103275	13770	20655
Apr-08	176400	132300	17640	26460
May-08	165300	123975	16530	24795
Jun-08	142400	106800	14240	21360
Jul-08	218700	164025	21870	32805
Aug-08	159900	119925	15990	23985
Sep-08	201900	151425	20190	30285
Oct-08	185400	139050	18540	27810

Nov-08	200100	150075	20010	30015
Dec-08	176100	132075	17610	26415
Jan-09	224700	168525	22470	33705
Feb-09	188400	141300	18840	28260
Mar-09	180300	135225	18030	27045
Apr-09	187200	140400	18720	28080
May-09	165600	124200	16560	24840
Jun-09	179400	134550	17940	26910

Average flow of influent in wet and dry conditions

Average Flow		
month and year	wet (mil.gal)	dry (mil.gal)
Mar-06	99.188	11.75
Apr-06	114.532	6.962
May-06	90.234	1.806
Jun-06	84.891	7.492
Jul-06	58.546	4.2
Aug-06	68.627	5.29
Sep-06	71.863	10.527
Oct-06	80.465	7.831
Nov-06	57.191	43.339
Dec-06	89.015	7.85
Jan-07	73.27	11.76
Feb-07	143.41	45.836
Mar-07	99.188	11.75
Apr-07	124.512	4.968
May-07	88.264	1.806
Jun-07	74.891	6.492
Jul-07	55.546	0
Aug-07	65.627	5.29
Sep-07	71.863	9.527
Oct-07	80.465	7.831
Nov-07	52.191	63.339
Dec-07	92.015	6.385
Jan-08	69.927	14.746
Feb-08	153.414	45.836

Mar-08	129.32	81.55
Apr-08	128.449	38.34
May-08	95.997	31.169
Jun-08	116.924	21.898
Jul-08	72.29	5.82
Aug-08	76.3	8.3
Sep-08	88.304	25.34
Oct-08	69.339	3.694
Nov-08	63.399	3.964
Dec-08	102.932	9.891
Jan-09	64.965	8.43
Feb-09	73.498	14.275
Mar-09	85.419	20,061
Apr-09	93.38	0
May-09	102.4	12.2
Jun-09	153.43	14.46

BOD level in the influent and its change in each process

BOD				
month and year	BOD level (mg/l)	blower and oxidation ditch (mg/l)	pump and trickling filter (mg/l)	clarifier (mg/l)
Mar-06	127.682	82.9933	31.9205	12.7682
Apr-06	183.43	119.2295	45.8575	18.343
May-06	92.4	60.06	23.1	9.24
Jun-06	113.87	74.0155	28.4675	11.387
Jul-06	163	105.95	40.75	16.3
Aug-06	152.23	98.9495	38.0575	15.223
Sep-06	87.63	56.9595	21.9075	8.763
Oct-06	147.5	95.875	36.875	14.75
Nov-06	116.5	75.725	29.125	11.65
Dec-06	59.25	38.5125	14.8125	5.925
Jan-07	126.4	82.16	31.6	12.64
Feb-07	81	52.65	20.25	8.1
Mar-07	144.75	94.0875	36.1875	14.475
Apr-07	69	44.85	17.25	6.9
May-07	77	50.05	19.25	7.7
Jun-07	110	71.5	27.5	11
Jul-07	158	102.7	39.5	15.8

Aug-07	133	86.45	33.25	13.3
Sep-07	96	62.4	24	9.6
Oct-07	145.8	94.77	36.45	14.58
Nov-07	106.5	69.225	26.625	10.65
Dec-07	56.25	36.5625	14.0625	5.625
Jan-08	116.4	75.66	29.1	11.64
Feb-08	81	52.65	20.25	8.1
Mar-08	136.72	88.868	34.18	13.672
Apr-08	72	46.8	18	7.2
May-08	96.39	62.6535	24.0975	9.639
Jun-08	121	78.65	30.25	12.1
Jul-08	145.64	94.666	36.41	14.564
Aug-08	125.57	81.6205	31.3925	12.557
Sep-08	102.36	66.534	25.59	10.236
Oct-08	138.43	89.9795	34.6075	13.843
Nov-08	105.37	68.4905	26.3425	10.537
Dec-08	74.45	48.3925	18.6125	7.445
Jan-09	123.4	80.21	30.85	12.34
Feb-09	94.5	61.425	23.625	9.45
Mar-09	122.49	79.6185	30.6225	12.249
Apr-09	87.55	56.9075	21.8875	8.755
May-09	92.4	60.06	23.1	9.24
Jun-09	131.58	85.527	32.895	13.158

Suspended solids level in the influent and its change in each process

Suspended Solids				
month and year	Suspended Solids (mg/l)	blower and oxidation ditch (mg/l)	pump and trickling filter (mg/l)	clarifier (mg/l)
Mar-06	198.34	9.917	17.8506	170.5724
Apr-06	156.76	7.838	14.1084	134.8136
May-06	78.3	3.915	7.047	67.338
Jun-06	103.72	5.186	9.3348	89.1992
Jul-06	183.46	9.173	16.5114	157.7756
Aug-06	127.35	6.3675	11.4615	109.521
Sep-06	80.45	4.0225	7.2405	69.187
Oct-06	190.71	9.5355	17.1639	164.0106
Nov-06	115.3	5.765	10.377	99.158
Dec-06	45.6	2.28	4.104	39.216
Jan-07	102.34	5.117	9.2106	88.0124

Feb-07	125.8	6.29	11.322	108.188
Mar-07	203.25	10.1625	18.2925	174.795
Apr-07	165.5	8.275	14.895	142.33
May-07	22	1.1	1.98	18.92
Jun-07	97.5	4.875	8.775	83.85
Jul-07	190	9.5	17.1	163.4
Aug-07	139.5	6.975	12.555	119.97
Sep-07	79.25	3.9625	7.1325	68.155
Oct-07	184.4	9.22	16.596	158.584
Nov-07	101.75	5.0875	9.1575	87.505
Dec-07	34.25	1.7125	3.0825	29.455
Jan-08	106.4	5.32	9.576	91.504
Feb-08	129.5	6.475	11.655	111.37
Mar-08	198.24	9.912	17.8416	170.4864
Apr-08	157.89	7.8945	14.2101	135.7854
May-08	76.43	3.8215	6.8787	65.7298
Jun-08	104.65	5.2325	9.4185	89.999
Jul-08	187.24	9.362	16.8516	161.0264
Aug-08	129.5	6.475	11.655	111.37
Sep-08	84.25	4.2125	7.5825	72.455
Oct-08	174.4	8.72	15.696	149.984
Nov-08	112.75	5.6375	10.1475	96.965
Dec-08	47.25	2.3625	4.2525	40.635
Jan-09	116.4	5.82	10.476	100.104
Feb-09	129.5	6.475	11.655	111.37
Mar-09	188.24	9.412	16.9416	161.8864
Apr-09	147.89	7.3945	13.3101	127.1854
May-09	81.43	4.0715	7.3287	70.0298
Jun-09	111.65	5.5825	10.0485	96.019

Amount of rainfall

Rain fall	
month and year	rainfall (inches)
Mar-06	4.1
Apr-06	4.7
May-06	7.82
Jun-06	8.25
Jul-06	1.5

Aug-06	5.47
Sep-06	5.87
Oct-06	2.93
Nov-06	3.8
Dec-06	3.4
Jan-07	2.9
Feb-07	3.2
Mar-07	3.6
Apr-07	4.1
May-07	2.4
Jun-07	7.35
Jul-07	2.5
Aug-07	4.6
Sep-07	6
Oct-07	3
Nov-07	3.72
Dec-07	3.25
Jan-08	3.25
Feb-08	2.52
Mar-08	10.07
Apr-08	5.2
May-08	5.5
Jun-08	7.35
Jul-08	2.9
Aug-08	5.3
Sep-08	11.05
Oct-08	11.05
Nov-08	1.3
Dec-08	1.3
Jan-09	0.58
Feb-09	2.18
Mar-09	2.34
Apr-09	5.6
May-09	5.8
Jun-09	6.5

BIBLIOGRAPHY

[1] Richard Brown, “Energy Efficiency and Renewable Energy Technologies in Wastewater Management”, *testimony on Sustainable Wastewater management, subcommittee on Water Resources and Environment House committee on Transportation and Infrastructure (*February 4, 2009)

[2] EPRI, “Energy audit manual for water/wastewater facilities”, (July, 1994)

[3] EPA, “Ensuring a sustainable future: An energy management guidebook for wastewater and water utilities”, (January, 2008)

[4] EPA, “Effective utility management: A primer for Water and Wastewater Utilities”, *EPA* (Jun 2008)

[5] Gangichetty, B and Long, S. October 2009. Strategic Process Integration: Creating a Unified Energy and Environmental Management Systems Model for Wastewater Treatment Plants. *Conference proceedings of the ASEM 2009 Annual Conference, Springfield, MO*

[6] Dae-Hyun Koo and Samuel T. Ariaratnam, “Application of Sustainability Model for Assessing Water Main Replacement Options”, *Journal of Construction Engineering and Management,* ASCE (August 2008)

[7] Jennifer Baumert, laura Blood Good, “Private Sector Participation in the Water and Wastewater Services Industry”, *Office of Industries U.S. International Trade Commission* (April 2004)

[8] Wei Deng Solvang, “Increasing Eco-efficiency through Holistic Green Supply Chain Management”, *IEEE international conference, April 2008*

[9] Henan province wastewater management and water supply project in the people’s republic of china, Environmental management plan, (February, 2005)

[10] EPA, “Achieving environmental excellence: An environmental management systems (EMS) handbook for wastewater utilities”, (August, 2004)

[11] PG&E new construction energy management program, “Municipal wastewater treatment plant energy baseline study”, (June, 2003)

[12] Richard F. Gunst, Robert L. Mason, “Regression Analysis and its application: A data-oriented approach”, Markel Dekker Inc (1980)

[13] Econometrics laboratory software archive, University of California, Berkeley. “Regression Analysis, http://elsa.berkeley.edu/sst/regression.html .

[14] Dept. of Physics, university of Oregon. "http://abyss.uoregon.edu/~js/glossary/correlation.html"

[15] D.C. Angew, C. Constable, "Chapter 7: Least Squares estimation", University of California system wide institute of geophysics and planetary physics (IGPP), (2004)

VITA

Bharath Kumar Gangichetty was born on April 21, 1987 at Hyderabad, Andhra Pradesh in the southern part of India. He completed his Bachelor of Engineering in Industrial Production Engineering (Mechanical) from M.V.S.R. Engineering College, Hyderabad, India. He started his Master of Science program from Engineering Management Department at Missouri University of Science and Technology in August 2008. His primary areas of interest are Supply chain and Logistics, Production Management, Business Marketing, Project Management, and Strategic Management. He received a Master’s Degree in Engineering Management from Missouri University of Science and Technology.