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Community engagement, environmental education, and public outreach in sustainable engineering : a collaborative demonstration project for water treatment using natural processes and sustainable materials.

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COMMUNITY ENGAGEMENT, ENVIRONMENTAL EDUCATION, AND PUBLIC OUTREACH IN SUSTAINABLE ENGINEERING – A COLLABORATIVE DEMONSTRATION PROJECT FOR WATER TREATMENT USING NATURAL PROCESSES AND SUSTAINABLE MATERIALS

By

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MS, University of Louisville, 2008

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ABSTRACT

COMMUNITY ENGAGEMENT, ENVIRONMENTAL EDUCATION, AND PUBLIC OUTREACH IN SUSTAINABLE ENGINEERING – A COLLABORATIVE DEMONSTRATION PROJECT FOR WATER TREATMENT USING NATURAL PROCESSES AND SUSTAINABLE MATERIALS

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Community engagement through environmental education for the public is an important component in the link between individual citizens, their community, and local government agencies responsible for maintaining urban recreation and park areas. Streams and waterways passing through urban areas are often misunderstood by the public in terms of whether the waterway is natural, constructed, or a combination of both. Additionally, aspects of water quality or water pollution are often obscure to the community and there are limited means to provide direct information to the public. In any case, the public are often drawn to interact with urban streams through recreation activities or through environmental education interest.

It is with this concept in mind that this project was formulated and realized through collaboration between the Louisville Metro Government Metro-Council, the local water supply utility Louisville Water Company (LWC), the local stormwater and sewerage agency Metropolitan Sewer District (MSD), and the University of Louisville (UL), Kentucky Institute for the Environment and Sustainable Development (KIESD). Project collaborators include Louisville Metro-Councilwoman Tina Ward-Pugh; Mr. Greg Heitzman, LWC/MSD; Mr. Daren Thompson, MSD; and UL personnel: Mr. Daniel Carter, Dr. Deborah Yoder-Himes,

Ms. Ellen Briscoe, Mr. Jake Robertson; and Mr. Russell A. Barnett and Dr. David Wicks, KIESD.

The pilot water treatment plant consists of filters, which uses sunlight for disinfection and naturally available materials in filters. Disinfection of water by exposing it to sunlight is an age old concept. Historically containers with water were left in sunlight for hours to make it potable. Though it was a religious practice in those days. It started attracting researchers from early 80s to develop sustainable water disinfection concepts for under developed communities. Most of the research studies developed systems which involves both thermal and optical inactivation of bacteria. Researchers are working on increasing the robustness of the systems by adopting different reflective surfaces and shapes of the reflectors. Water depth, suspended solids in water are the major factors which impact the penetration of sunlight. Reduction of suspended solids can be achieved either by sedimentation or filtration. Filters comprised of naturally available material can make the system more sustainable and less expensive.

This project tests the optical disinfection capacity of sunlight. For this an open channel flow of water was adopted. Four filters were installed to reduce the amount of suspended particles entering into the solar disinfection system (SODIS). This pilot study was conducted using polluted urban stream water at 4 different water flow rates. It is observed that reduction in flow rates resulted in increased disinfection rates. And filters also contributed in reducing the bacterial concentration. SODIS is successful in achieving the minimum 30-day average *E. coli* concentrations in water accessed for recreation.

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1 INTRODUCTION

Access to pure water is essential for humans for different uses. Domestic use and recreational use are the two most water usage approaches of water. Domestic use involves using water for drinking, cooking, bathing, etc. Recreational activities involve swimming, fishing, boating, etc. Historically urban streams were used for recreational activities and educational centres. Because of the urbanization, urban streams were neglected and abused by changing the natural alignment, combined sewer overflows, polluted storm water runoff and much more. These factors made urban streams polluted and limited their usage as recreational spaces. Water has to be clean and pure to use it either for domestic or recreational purposes. The purity level that water has to achieve depends on the choice of usage. Basic example for this is limits on the bacterial concentration in drinking water (0 colony forming units (CFU)/100ml, *EPA Safe Drinking Water Act, 2009*) and recreational water (30-day average of 128 CFU/100ml, *NPDES 2012 recreational water quality report*). Various water treatment methodologies are being adopted to treat water for making it safe to drink and access it for recreation. Water is treated in different methods to make it potable. Treatment methods adoption depends on the raw water quality, accessibility to the technology, resources, and the end user size. For example, techniques used for waste water (high amount of suspended material, and in some cases high amount of chemical concentration) treatment is slightly different to the ground water (low amount of suspended solids); A community in a developed country can have better access to technology and resources than a remote community in an under developed or developing country. A water treatment plant serving an urban area has to be larger and faster than a treatment plant that serves a rural community. It may not be possible to install a modern water treatment facility in under developed communities, or treat water in an urban stream. Using natural resources to treat water where accessibility to modern technologies and/or investments are minimal to nothing can help in increasing water quality with minimal costs and less technical knowledge.

Sand and gravel are commonly available materials for water filtration. Along with them, an effective and abundant method for water disinfection is exposure to solar radiation - the radiant energy emitted by the sun. Commercially there are systems available to generate solar-type radiation for any purposes. Research has proved the use of ultraviolet (UV) radiation (electromagnetic radiation between wavelengths 280 nm – 400 nm) and infrared (IR) radiation (electromagnetic radiation between wavelengths 700 nm – 1 mm), as present in natural solar radiation, can be effectively utilized for water disinfection. Most of the research studies were carried out using still water in closed containers. Limited quantitative studies address the feasibility of water disinfection while flowing. Those results prove the concept of UV disinfection effectiveness when applied under controlled conditions. One of these conditions involve usage of transparent tubes and compound parabolic collectors (CPC) for exposing water to sunlight more effectively. This involves usage of both thermal and optical energy of sunlight for bacterial reduction in water. This project evaluated the effect of sun’s optical energy in disinfection. For this, an open channel flow is adopted for restricting water to reach the temperatures where the disinfection process starts ($38^{O}C$). Heat absorbing and light reflecting materials were used for increasing the solar radiation effect on water. Four different filters were installed prior to solar disinfection (SODIS) system for reducing suspended particles entering into the SODIS.

The goal of the project was to develop a way to connect the public with the urban stream, raise community awareness to the water quality conditions, and provide environmental education through the demonstration of viable treatment methods available to improve water quality.

The community engagement water treatment project was developed as a public demonstration of sustainable engineering methods to show how natural raw water can be processed to remove pollutants and improve water quality. The project goals included to provide a reliable and robust physical system, to apply standard water treatment practices where natural and sustainable methods are available, and to implement innovative techniques for disinfection requiring no chemical or manufactured energy. The primary water quality parameter selected to evaluate the effectiveness of the system is the concentration of a common bacteria (E.coli) typically used in evaluation of municipal drinking and waste water treatment.

To meet the project constraints, the water treatment system was constructed in a large scale with materials resistant to breakage and with low recoverable or recyclable value. The location of the project was set in a public park adjacent to an MSD primary pumping station along the main channel of the primary stream draining much of the Jefferson County Kentucky region, the Beargrass Creek watershed. Collaboration between community government agencies took the form of Louisville-Metro government permission to construct the project on the site of the Karen Lynch Park in the Butchertown neighborhood, the MSD agency providing access to the Beargrass Creek along the stream bank upstream of the pumping station, and UL

KIESD providing materials and personnel to construct the demonstration water treatment plant.

The remaining portion of this document focuses on the technical aspects of water quality evaluation performed as part of the demonstration project. In addition to that component of the effort, a number of elementary and high school student groups, and international scholar students visited the project site during the construction and water quality sampling. This project continues to provide a place for the local citizens to learn about urban streams, water quality, and water treatment processes. Figure 1.1 shows the satellite map of project location with the components marked. The map is downloaded from bing maps (*http://www.bing.com/maps/*).

Figure 1.1 Satellite Map of Project

2 LITERATURE REVIEW AND PROJECT SIGNIFICANCE

2.1 Introduction

This chapter gives detailed information about previous research in the field of water treatment (coagulation, flocculation and sedimentation, filtration, and disinfection); the hydraulics involved in slowsand filtration (SSF) and slow sand filter design procedures. Solar radiation and solar disinfection (SODIS) concepts and applications are discussed. Characteristics of *E. coli*, and its role as a biological indicator of water quality and analyses of water samples for *E. coli* concentration are discussed. Designing and testing of this project was done by considering the above concepts and the significance of this project from the previous research projects is discussed in the final section of this chapter.

2.2 Water Treatment

2.2.1 Introduction

Process that enables water to achieve the standards either for drinking (Safe drinking water act in USA) or releasing it into natural streams (National Pollution Discharge Elimination System, NPDES or State Pollution Discharge Elimination System in USA) is called water treatment. Treatment procedure that is adopted depends on the raw water quality at the source and the intended use or application of the treated water produced. Less energy is required and fewer procedural steps are typically required to treat ground water relative to any water drawn from surface sources.

In general, there is a standard series of steps in water treatment and the most common steps involved are (*EPA 832-R-12-011)**:***

1. Sedimentation, and Sedimentation with Coagulation, Flocculation
2. Filtration
3. Disinfection

2.2.2 Sedimentation, and Sedimentation with Coagulation, Flocculation

Most surface waters contain suspended and dissolved solids. Sedimentation is the process of removing suspended solids, through particles settling, while water is stationary or moving through a tank at a slow rate (World Health Organisation, *WHO, 2007*). Simple sedimentation is the process of passing water through a tank at a slow rate allowing suspended solids to fall out of suspension (*WHO 2007*). The tank is sized based on the raw water that has to be treated and also the amount of water that has to be treated (water drawn from ground water has less suspended particles, whereas water that has to be treated in wastewater treatment plants contains more suspended solids). Many simple sedimentation procedures do not remove all fine-grained particles because high design flow rates result in an insufficient retention time. To address this issue, the simple sedimentation process is enhanced through the addition of chemicals, which are called coagulants (*EPA, 2004*). Adding of coagulant chemicals is intended to thicken solids, increasing the mass and density, allowing the particles to settle more rapidly. Typically, suspended particles may be negatively charged and repel each other resulting in no coagulation (*EPA 2007*). Coagulants may be positively charged and effectively neutralize the negative charge of dissolved and suspended particles in water. The resulting reaction binds sediment particles together, or coagulates them, forming a mass called the floc (*Ayguna, A. 2010*). Once the coagulated sediment particles form a floc and flocs reach a critical mass, overcoming buoyancy, they sink to the bottom of the settle tank. Flocculation is the rapid mixing of water after the addition of a coagulant. Mixing circulates the coagulant throughout water and evenly contacts sediment particles. Most common compounds used as coagulants are ferric chloride, alum, and aluminium salts (*Amuda, O.S., 2007*). Coagulation removes suspended particles, and a large amount of organic compounds, including some dissolved organic material, which is referred to as Natural Organic Matter (NOM) or Dissolved Organic Carbon (DOC). However, there are no limits on presence of DOC, but presence of DOC can give water an unpleasant taste and odour, as well as a brown discoloration (*SDWF 2006*). Research studies show that sedimentation and coagulation remove some pathogens that are attached to suspended substances (*Kawabata, N., 2005*).

2.2.3 Filtration

Filtration is the next step in water treatment process. Some small water treatment plants that cannot afford the coagulation unit, because of the investment that involves in setting up coagulation tanks, will directly go for filtration (*Pernitsky, D.J., 2006).* The purpose of filtration is to remove fine-grained suspended particles from water by passing water through a medium. Filtration is usually the final step in the removal of solids that began with sedimentation and coagulation/flocculation. Most commonly used filters in small communities and remote communities (communities that do not have access to technology and low income) are slow sand filters (*Huisman, L., 1974*). They are good for serving small communities, because of their less filtration rate and economic viability (*Huisman, L., 1974).*

2.2.3.1 Slow Sand Filtration

Slow sand filtration process is one of the oldest and widely used method for small communities to filter water. The treatment process is simple, reliable and an inexpensive way for water filtration. It requires minimal to zero power for operation and no chemicals are required. Slow sand filtration reduces bacteria, cloudiness, and organic contaminant levels in water (*Huisman, L., 1974*). Particle removal process in sand filters is categorized into three mechanisms. They are transport, attachment, and detachment.

Transport

Transport is the process of bringing impurities into contact with the sand grain in filter media material. Physical properties of the suspended particles influence these mechanisms (*Thames Water and University of Surrey 2005*). The transport mechanisms include:

- Interception

    Interception is the contact of a suspended particle to a sand grain in filter media. This depends on the diameter of the suspended particle and the pore size of the filter media. This can be achieved only if the particle is carried by one of the streamlines closest to the media grain (a distance of 0.05 mm or less between the sand grain and streamline) (*Ives, K. J., et al., 1975*). Streamlines are those that are drawn to visualize the flow, they are tangential to the velocity field. Rates of interception increases as the diameter of the suspended particle increases and the pore size between the media grains decreases.

- Inertial Flow

When water flowing in straight-line flows between the media grains, suspended particles in water with sufficient inertia may swerve off the line of flow that they are supposed to follow. Due to this, a particle may come in contact with the sand grain as a result, and attach. Transport via inertia increases as the surface loading rate (hydraulic loading (flow rate, m^3/h) per unit cross-sectional area of the filter bed (m^2)) increases (*Ives, K.J., et al., 1975*).

- Diffusion

Diffusion is used to describe mass transport via Brownian motion. Brownian motion is defined as the movement of suspended particles in fluid or gas medium due to their bombardment by molecules of that fluid or gas. Thus, there is a transfer of thermodynamic energy to kinetic energy, from the media molecules to the particles suspended in it (*Huisman. L. & Wood W. E., 1974*). In this case, media is raw water flowing into the filters. A suspended particle will take discrete steps as a result of its collision with water molecules (*Hendricks, D.,, 1991*). This results in suspended particle achieving Brownian motion. The particle will move from one streamline to another, until eventually it may collide with a media grain. Diffusion is independent of the surface loading rate.

- Sedimentation

This is similar to the process that happens in sedimentation phase of water treatment process. Gravitational forces can move particles across streamlines into quiescent areas on upward-facing surfaces of bed grains. Larger, denser particles will settle first. Sedimentation efficiency is the function of the ratio between the surface loading and the settling velocity of the suspended particles.

Attachment

Once the suspended particles in water come in contact with a sand particle, there must be a force present to hold particles in place and achieve removal of the particles. Process of holding of suspended particles by sand particles is attachment. The main forces involved in this mechanism are:

- Electrostatic Attraction

  Particles in suspension and the surfaces of the media grains attract to each other, if they are oppositely charged. This depends on the age of the sand. A clean crystal sand grain has a negative charge and is able to attract positively charged particles. This accumulates positively charged particles to such an extent that oversaturation may occur with reversal of the charge, and starts attracting negatively charged particles (*Huismans, L et. al. 1974*).

- Van der Waal's Forces

  Forces present between molecules are Van der Waals forces. These forces include attraction and repulsion forces present between molecules. The attractive forces happens when the material in water are at a distance of 0.05 mm or less (*Ives and Gregory, 1967*). The attractive force between two water molecules have minor effect in drawing suspended particles together.

However, when the particles (Sand grain and suspended particle) get in contact with each other the attractive forces between water molecules will play a significant role in ensuring attachment of one to other.

- Adhesion

  Deposited organic particles quickly become the breeding grounds for bacteria and other microorganisms that results in creating microbial colonies. This situation results in the development of a biofilm called *Schmutzdecke* (*Law, S. P., et al., 2001*). This layer helps in trapping the bacteria and reducing the bacterial concentration leaving the filters. However, this takes a while to achieve depending on the impurities that flow into the filters.

Detachment

The mechanism of losing attached material to the sand grain is detachment. It is required to maintain the equilibrium between the factors that help in operating the sand filters. In addition, this mechanism is largely influenced by the physical characteristics of the media, and type and growth of microorganisms in biofilm (*van Loosdrecht et al 1995*). If not maintained, detachment of the particles that are attached to sand gains, playing key role in water purification happens and this results in degraded performance of the filter. Factors that make detachment happen are:

- Flow Rate Change

  High flow rates or sudden changes in flow, combined with deposit instability may result in detachment. To minimize this, excessive run lengths and improper flow rates into filters should be avoided. This minimizes deposit instability and erosion.

- Grazing

Biofilm may be removed by grazing by macro-fauna and/or predation of smaller organisms by protozoa (*Bryers, J. D., 1987*).

- Shedding of Biofilm

  This happens because of improper cleaning activities and this detaches microorganisms from biofilm and opens place for a new habitat for microbiological colonization.

2.2.4 Disinfection

Disinfection is the final step in water treatment process and is done just before distribution. This step clears the bacterial concentration in water. Disinfection rates are dependent on the source of water. Most commonly used disinfection methods are heat, chlorination, ozonisation, UV light and micro-filtration. The disinfection methods are categorized into two methods, chemical and non-chemical.

2.2.4.1 Chemical Disinfection

Adding of chemicals to water for killing the bacteria or virus in water is called chemical disinfection. Most commonly used chemicals for disinfection are chlorine and ozone. In order for chemical disinfection to be effective, water must be filtered. Chemical disinfection often leaves an undesirable taste in water, which an activated carbon filter can remove post-treatment.

Chlorination

Chlorination is the process of adding chlorine to water as a method of water disinfection that makes it fit for human consumption. Water treated with chlorine is effective in preventing the spread of disease (*EPA, 1986*). Chlorine may be used in gas, liquid or solid form to disinfect water because chlorine gas is highly toxic and can be dangerous if released into the atmosphere, this form of disinfection must be done in controlled environment. Otherwise, the danger is avoided by the use of chlorine in liquid form (sodium hypochlorite) or solid form (calcium hypochlorite). Chlorine when added to water releases hypochlorous acid (HOCl), and hydrochloric acid (HCl). Depending on the pH, HCl may further breakdown into Hydrogen (H^+) and Hypochlorite (OCl^-) ions. The concentration of hypochlorous acid and hypochlorite ions in chlorinated water will depend on water's pH. A higher pH facilitates the formation of more hypochlorite ions and results in less hypochlorous acid in water. Hypochlorous acid is the most effective form of free chlorine residual, which is chlorine available to kill microorganisms in water. Hypochlorite ions are much less efficient disinfectants. So, disinfection is more efficient at a low pH than at a high pH.

$$Cl_2 + H_2O \rightarrow HCl + HOCl$$

$$HCl \leftrightarrow H^+ + Cl^-$$

Water utilities are moving from using free chlorine to chloramine in their drinking water disinfection (*EPA 1999*). Chloramines are made when ammonia is added to water containing chlorine, or when water-containing ammonia is chlorinated. Even though chloramines are weaker disinfectants than chlorine, they are used as disinfectants because; they are more stable and extend disinfection benefits throughout a water utility's distribution system. Chloramines are not used as the primary disinfectant for water; but are used for maintaining a higher-level disinfectant residual in the distribution system for a longer period relative to chlorine.

While chlorine is a highly effective and widely used method of water disinfection, it reacts with organic compounds in water, forming trihalomethanes (THMs) and haloacetic acids, which are carcinogenic in large quantities. The best way to avoid this is to remove as many organics as possible, prior to disinfection. Chloramines do not form THMs or haloacetic acid as chlorine does.

Ozone

Ozone disinfection is gaining popularity because of its better performance than chlorination in disinfecting water (*EPA 1999*). Being a powerful oxidizing agent, ozone is toxic to most waterborne organisms. When ozone is decomposed into water, hydrogen peroxy (HO2) and hydroxyl (HO) are formed. These have great oxidizing capacity and results in cell wall disintegration in bacteria. Ozone is often accompanied by a secondary disinfectant, such as chlorine. Post-treatment, it leaves few residuals to prevent the future growth of microorganisms in water. Due to its highly unstable nature, ozone cannot be transported. Therefore, ozone has to be generated at the site of water treatment. This requires lots of investment. Though the contact time required is less when compared to other chemicals and no harmful residuals are left after treatment, ozonisation has been less used because of its complex technology and greater power usage. Research is going for making the technology more viable and adoptable.

2.2.4.2 Non-Chemical Disinfection

Disinfecting techniques of water without usage of chemicals falls in this category.

Boiling

Boiling of water to kill bacteria is an age-old technique that is used in present days when water may be from a primitive source with unknown treatment or there is a boil-water emergency (*CDC, 2013*). Heating water to the boiling point kills disease-causing microorganisms and is the surest way to make otherwise-clean water safe for drinking. To ensure that all microorganisms are killed, water must boil vigorously for one minute (*CDC 2013*).

Membrane Filtration

Membrane filtration is recognized widely as a superior water and wastewater treatment technique. Membranes provide a physical barrier that effectively removes solids, viruses, bacteria and other unwanted molecules. Researchers are developing a variety of membranes for different industries and some are even smart. For example *Lewis, S. R., et al., 2011* developed a membrane that have nano-pores which opens and closes according to the impurities present in water flowing through the membrane. Primary advantages of membranes are less space requirement and the treatment process can be automated. For example, conventional filter cleaning practices takes lots of human effort and time to carryout depending on the size of filter, where as in case of membrane filtration cleaning can be scheduled based on the filter usage and filter pore clogging. With the advent of technology, advancing research in this field is making the membranes more efficient and economical over the time. Ultrafiltration is a type of membrane filtration that is a pressure-driven process, which removes particles by pushing water through a filter medium. Any particles larger than the filter pore opening are blocked and removed from water. Ultrafiltration is majorly used for clearing suspended solids, removal of viruses and bacteria or high concentration of macromolecules in water. This technology is being applied in many industries like oil, food processing, chemical process, and water treatment, where separation is required at micro or nano-level (*lenntech, web reference*).

UV Disinfection

Use of UV based disinfection systems has experienced rapid growth over the last 2-3 decades (*Mbonimpa E.G., et al., 2012*), because of low by-products release and less space for construction. The UV spectrum covers the wavelength range from 100-400 nano-meters (nm), and lies between x-rays and visible light in the electromagnetic spectrum. UV light with wavelengths between 200-300 nm (UVC) inactivates most microorganisms. Studies prove a maximum disinfection capacity for most microorganisms with exposure to UV at 260 nm (*EPA 2006*). Most of the synthetic UV light generators contain an inert gas and a small amount of liquid mercury. The mechanism involved in generating synthetic UV light is by exciting the mercury atoms to higher energy state. This is done by the collision of free electrons and ions with the gaseous mercury atoms. Energy that is in the form of UV light that is in the range of germicidal wavelength (200 – 300 nm) is discharged when the excited mercury atoms return to their ground, or normal, energy state. The amount of UV light produced by a synthetic UV lamp is influenced by the concentration of mercury atoms in the lamp (*Clarke, S. H., 2006*).

When UV light is transferred from a source (most of the times source is mercury arc lamp) to an organism's genetic material, UV penetrates through the cell wall of an organism and destroys the cells' ability to reproduce. Microorganisms that cannot reproduce cannot infect and are thereby inactivated. Limitations to UV water disinfection include presence of high turbidity, particulate matter, and natural organic matter (*EPA 832-F-99-064*).

The advantages of UV disinfection include no significant toxic by-products. Over dosing, is not an issue as with chemical treatments. Storage or development of harmful chemicals are not required other than proper disposal of UV lamps after useful life. The contact time for disinfection is much less when compared to chemical disinfection processes. However, one considerable disadvantage includes the absence of a disinfection residual to maintain disinfection in a distribution or storage system. Organism may reverse the inactivation either by "photoreactivation" or by "dark repair" mechanisms. Photoreactivation is the recovery from biological DNA damage caused by UVC or UVB radiation by simultaneous or subsequent treatment with light of longer wavelength (>300nm), a similar mechanism that happens in the absence of light is called dark repair.

2.3 Hydraulics and Design of Slow Sand Filter

2.3.1 Introduction

Hydraulics involved in slow sand filtration and its design procedures are discussed in this section. Hydraulic analysis influences the design decisions and plays key role in a slow sand filter design. Major hydraulic functions involved in a slow sand filter design are (*Huisman, L., et al., 1974*):

1. Raw water distribution on the filter without erosion (inflow)
2. Head loss through the filter bed
3. Water collection from filter (Outflow)
4. Control water flow through sand bed
5. Water draining from filter for sand bed maintenance
6. Over flow of filter

2.3.2 *Hydraulics and Design*

Function 1 is about finding the volume of water (m^3) that has to be flown into filter per unit time (hr) per unit area (m^2). The amount of water a slow sand filter filters depends on the Hydraulic Loading Rate (HLR). It is defined as the rate of flow per unit area. Here, area is the surface area of sand bed and flow is the raw water flowing into the filter. The ideal HLR values range between 0.1 m/hr to 0.4 m/hr. Equation 2.1 is for calculating the HLR value.

$$\mathrm{HLR} = \frac{\mathrm{Q}}{\mathrm{A}} \qquad (2.1)$$

Where,

HLR = Hydraulic loading rate ($m^3/m^2/s$)

Q = Flow of water (m^3/s)

A = Plan area of filter bed (m^2)

Once water is made to flow into the filter, flow through the filter bed is assumed to be laminar. A flow is said to be laminar, when the molecules (water molecules) are flowing in straight and parallel lines. In other words the flow is said laminar in pipe flow when the Reynolds number (ratio of inertial force to viscous force, and it is dimension less) of the flow is less than 2000. In general, Reynolds number (R) is expressed as shown in equation 2.2.

$$\mathrm{R} = \frac{\rho \mathrm{VL}}{\mu} \qquad (2.2)$$

Where,

R = Reynolds number

ρ = Fluid density (kg/m^3)

V = Mean velocity of the object relative to fluid (m/s)

L = Characteristic length (m)

μ = Dynamic viscosity of the fluid (kg/(m·s))

Consideration of characteristic length value depends on the flow: for example, pipe diameter is considered as characteristic length for pipe flow, it is hydraulic radius in open channel flow. However, for porous media flow it changes because of the particle size distribution and non-uniform flow paths. *Ward (1964)* simplified the characteristic length value in porous media as square root of intrinsic permeability. Where, intrinsic permeability is the property of the porous media, and basically a measure of the surface area of the grains in a porous medium.

Equation 2.3 gives the general equation created by *Ward (1964)* for the Reynolds number (R_{pm}) in porous media. In the case of a packed bed, Reynolds number has to be less than 10 to state the flow as Laminar (*Ziolkowska, I. et al., 1988*).

$$R_{pm} = \frac{\mathrm{v}\,\mathrm{k}^{\frac{1}{2}}\rho}{\mu} \qquad (2.3)$$

Where,

R_{pm} = Reynolds number through porous media

v = Superficial velocity synonymous to HLR or specific discharge (q = Q/A) (m^3/m^2/hr) standard value between 0.1 – 0.4 m^3/m^2/hr = 2.78 e-5 – 1.11 e-4 m^3/m^2/s

k = Intrinsic permeability (m^2)

$$k = \frac{K\mu}{\rho g} \quad (2.3\ a)$$

K = Hydraulic conductivity (m/s) – 2 e-7 to 2 e-4 (value for fine sand, *Domenico and Schwartz 1990*)

g = Acceleration due to gravity (m/s^2) -- 9.81 m/s^2

ρ = Fluid density (kg/m^3) – 999.8 kg/m^3 for water at 0^0C; 998.2 kg/m^3 at 20^0C

μ = Dynamic viscosity of the fluid (kg/(m˙s)) – 0.001792 kg/(m˙s) for water at 0^0C; 0.001003 at 20^0C

Equations 2.3.1 and 2.3.2 are example calculations of Reynolds number for a flow through sand bed at 0^0C and 20^0C. Substituting the standard values from above the Reynolds number for a flow through fine sand bed will be:

$$R_{pm} \text{ at } 0^0\text{C} = \frac{(2.78\ e{-5})\sqrt{\frac{(2e{-7})(1.79)(e{-3})}{(9.81)(999.8)}}}{(1.792e{-3})}\ (1000) \quad (2.3.1)$$

R_{pm} = 2.97 e-6 < 10

$$R_{pm} \text{ at } 20^0\text{C} = \frac{(2.78\ e{-5})\sqrt{\frac{(2e{-7})(1.03)(e{-3})}{(9.81)(998.2)}}}{(1.003e{-3})}\ (1000)\ (2.3.2)$$

R_{pm} = 3.973 e-6 < 10

This condition satisfies Laminar flow conditions. Laminar flows typically occur when the fluid is highly viscous or the flow velocity is too low. In slow sand filters the sand bed is expected to have equally distributed pores and pore sizes because of the uniform sand (particle size) used in it. When water flows through the sand bed there will be a constant change in direction as the flow leaves one sand grain and meets the next. In majority of the cases, this satisfies the condition of laminar flow (water molecules flowing in parallel to each other). With this assumption, Darcy's law describes the head loss in the sand medium. The HLR value from equation 2.1 is used to calculate the head loss using the equation 2.3 b.

$$h_L = \mathrm{v}\frac{\mathrm{z}}{-\mathrm{K}} \qquad (2.3\text{ b})$$

h_L = Headloss across sand bed (m)

z = Depth of filter bed (m)

Head loss calculated from above equation is for the initial stages of filter. This value increases over the period because of the clogging of pores and development of biofilm called *Schmutzdecke*. However, helps in removing bacteria from water, *Schmutzdecke* may result in improper passage of water into sand bed. This results in head loss increase and flow not meeting laminar flow conditions. Laminar flow conditions help in controlling sand erosion and indicates uniformity of flow through sand bed, which means no blockages in the sand bed. Not satisfying laminar flow conditions also results in improper outflow volumes. Headloss across filter bed is measured by using piezometers. An increase in headloss shows the accumulation of suspended particles or formation and thickening of *Schmutzdecke*.

2.3.3 Maximum Surface Area of Sand Bed

Flow rate (Q) is determined by water supply demand (average volume of water required per unit end user per day), this value changes based on the climatic conditions, and influenced by the type of end user (humans, factories, and irrigation, etc.) and equation 2.1 is used to determine the area of sand bed required for operation. The acceptable range of HLR is 0.1 m/hr to 0.4 m/hr (*AWWA, 1990*).

2.3.4 Depth of Sand Bed

Depth of sand bed depends on the desired number of years of operation before re-sanding. Re-sanding is the process of refilling the sand to replace the sand bed that is lost because of scrapping (removal of certain depth of top portion of sand bed (few inches) along with *Schmutzdecke* to make the filter perform better after clogging). In addition, researches proved that the deeper the sand beds results in the longer the filter operations (*EPA 1995*). However, to have a deeper sand bed it requires huge construction.

2.3.5 Particle size

The granular fill material used in the filter must have a range of grain sizes. The filter is constructed in layers of generally similar grain sizes. The filter layers are ordered by grain size with finer grain layers at top and coarser at bottom. The coarser bottom layers restrict finer particles from entering into the plumbing. Gradual increase of particle size from top to bottom achieves the desired mitigation of finer material entering into plumbing. From their studies, *Huisman and Wood (1974*), have suggested five rules for design of the gravel support and AWWA (American Water Works Association) made those rules as benchmark for the particle size in slow sand filtration (*AWWA 1990*). The rules are:

1. d90 (given layer)/d10(given layer) $\leq$ 1.4
2. d10 (lower layer)/d10(upper layer) $\leq$ 4
3. d10 (top layer)/d15(sand) $\geq$ 4
4. d10 (top layer)/d85(sand) $\leq$ 4
5. d10 (bottom layer)/2 X d (drain orifice diameter) $\leq$ 1.4

AWWA slow sand filtration manual (*AWWA 1990*) recommends to design and test a pilot filtration system before designing a full-size system. This helps in learning about the raw water quality that has to be treated and allows evaluation of locally available filter materials.

Advantages of slow sand filtration

- Effective in improving the bacterial and physical qualities (turbidity) of water
- Easy to operate and maintain
- No chemicals required
- Can achieve 4 log reduction of bacteria at its peak performance

Disadvantages of slow sand filtration

- Requires larger space to construct
- Vulnerable to clogging if incoming water have high turbidity

Rapid sand filters (RSFs) have the same core mechanism as slow sand filters (SSF). However, they are more advanced. Some RSFs are multi-media filters, which include usage of anthracite, granular activated charcoal along with sand and gravel. Back washing can be done in RSFs for cleaning the filters. Back washing is the process of passing pure water in the reverse order of filtration. Because of advantages over slow sand filters, many slowsand filters are being replaced with rapid sand filters.

2.4 Filter Media

While there are wide variety of filter media available following are materials used in the potable water industry.

2.4.1 ***Sand***

Sand is the most common available filter material. Moreover, it is good to test the local available sand first as filter bed, because it can be a viable financial option to use local material than importing it from other places. Sand should be washed prior to use, and different grades of sand improve the long-term operation of the system.

2.4.2 Activated Carbon

Activated carbon (AC) has been in use in home water purification systems for removing odour and taste. They are also effective in removing chlorine, sediment, and volatile organic compounds (VOCs). Activated carbon filtration is an adsorptive process in which the contaminant is adsorbed onto the surface of the carbon particles. The efficiency of the adsorption process is influenced by particle and pore size, surface area, density and hardness of the carbon particle. AC medium used can be petroleum coke, bituminous coal, lignite, wood products, coconut shell, or peanut shells. The carbon medium is “activated” by subjecting it to steam and high temperature (2300°F) without oxygen (*Dvorak, B. I. et al. 2013*). It is then crushed to produce a granular or pulverized carbon product. This creates small particles with more outside surface area available to which compounds can adsorb, which results in greater contaminant removal. The source of the carbon and the activation method determine the effectiveness of removal for specific contaminants. A filter reaches its capacity when all adsorption sites on the activated carbon become full of contaminants (*EPA 2013*).

2.4.3 Anthracite

Anthracite coal is a hard coal with more fixed carbon and less volatile matter (*EPA 1996*). Anthracite promotes higher service flow rates and longer filter runs with less head loss than single media filter beds. This reduces the backwashing rates. Backwashing of filters is a regular process of cleaning filters for cleaning the filter and make them perform better; this involves flushing water in reverse path to the regular water filtration path. Low uniformity coefficient anthracite filter media extends the life of filter. Because of its high carbon content, Anthracite is the most common media used in rapid multimedia filters along with sand.

2.5 Solar Radiation

Solar radiation is the electromagnetic radiation emitted by the sun. Solar radiation has many bands in it. However, the significant band of radiation is divided into five regions in ascending order of wavelengths (*Naylor, M. F., et al., 1995*). These band regions are UVC (100 – 280 nm), UVB (280 – 315 nm), UVA (315 – 400 nm), Visible Light (380 – 780 nm), IR (700 - 106 nm). Visible light or visible range is that visible to human eye and that is not visible to naked eye is non-visible range or light. In nature UVC is blocked by stratospheric oxygen and no amount of UVC radiation reaches the earth's surface, mechanism involved behind this is, an oxygen (O_2) molecule is split into two oxygen (O) atoms being hit by high frequency UV light (UVC and UVB). These atoms then combine with O_2 molecules to form ozone molecule (O_3) (*Newman, P.A 1999*). Figure 2.1 shows the atmospheric Ozone-Oxygen cycle (*Newman, P.A 1999*). More than 90% of the UVB radiation is absorbed by ozone (*Amaro-Ortiz A., et al., 2014*). Infrared radiation in solar radiation is the primary cause for temperature increase in the atmosphere. The temperature increase depends on the Carbon dioxide (CO_2) concentration in atmosphere.

Clouds reduce the amount of solar irradiance reaching the Earth's surface although changes in the ultraviolet region are not as great as those of total intensity (*Diffey, B. L., 1991*). The effect of cloud cover on solar radiation reaching earth's surface depends on the cloud layers and cloud types. Huge storm clouds can almost eliminate terrestrial UVR (Ultra Violet Radiation) even in summer time (*Diffey, B. L., 1 991*).

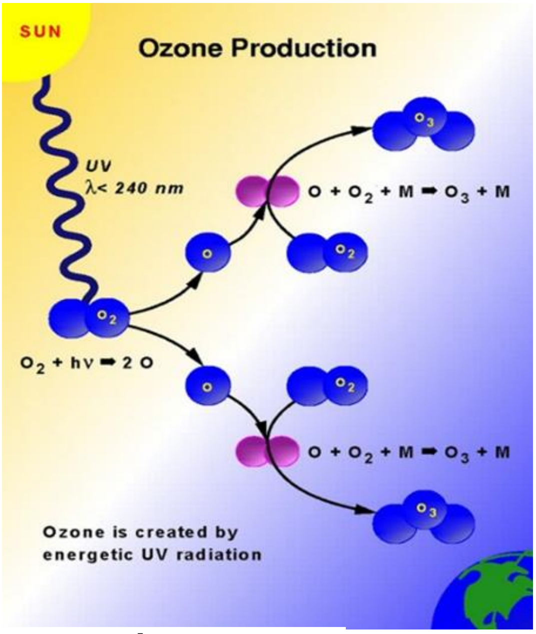

Figure 2.1 Oxygen-Ozone cycle

Reflection of solar radiation from ground surfaces, including the sea, is normally low (<7%) and is high for fresh snow (fresh snow can reflect up to 80 per cent of incident solar radiation). This proves that more than 7% of solar radiation cannot be reflected from water surface and it can be absorbed by water. Penetration of solar radiation is dependent on the turbidity levels of water. Altitude is another factor that affects the solar radiation, each 1 km increase in altitude increases the ultraviolet flux by about 6%, i.e. places on the Earth's surface below sea level are relatively poorer in receiving solar radiation than sites that are at sea level or higher elevation (*Cutchis, P., 1991*). Louisville region's elevation ranges from a high of about 761 feet and to a low of 382 feet above sea level (*elevations and distances in the United States, USGS*) and so suffices as a suitable location for utilization of natural UV irradiance for water disinfection.

2.6 Solar Disinfection (SODIS)

Solar disinfection (SODIS) is the process of disinfecting water by exposing it to sunlight. Descriptions of solar disinfection of water have existed in communities on the Indian sub-continent for nearly 2000 years. In the distant past, drinking water was placed outside in open containers to be “blessed” by the sun (*Baker, M.N.T.M., 1981*). *Downes and Blunt (1877)* proved that sunlight is effective in reducing or killing the bacteria. Disinfection by sunlight happens because of the UV radiation and infrared radiation present in solar radiation (*Mbonimpa, E. G., et al., 2012*). The shorter the wavelength the stronger is its disinfection capacity, based on this UVC is considered as the strongest disinfectant. Stratospheric oxygen absorbs all the UVC and 90% of the UVB radiation and 5-10 % of UVA reaching earth’s surface. This creates a situation that UVA and UVB are available for disinfection.

2.6.1 Bacterial Inactivation Mechanism by UV

The inactivation mechanism involved in artificial UV (UVC is generated and used from vapor lamps) and natural UV (UVB and UVA) are slightly different (*Caslake, L. F., et al., 2004*). The basic mechanism involved in UVB and UVC disinfection is formation of pyrimidine dimers. When bacterial DNA absorbs UVB or UVC radiation thymine base pairs in genetic sequences bond to each other and forms pyrimidine dimers. This is a disruption in the strand, which reproductive enzymes cannot copy (*Goodsell D.S., 2001*). Figure 2.2 (http://www.bath.ac.uk/) shows the pyrimidine dimers formation before and after absorption of UV by DNA. Formation of Pyrimidine dimers results in making the bacteria incapable to reproduce and this reduces infection capacity of the bacteria. Unable to multiply, pathogens no longer pose a health risk and soon die. UVB (wavelength of 280-315 nm) being in the germicidal range (200-300 nm) is capable of causing DNA damage.

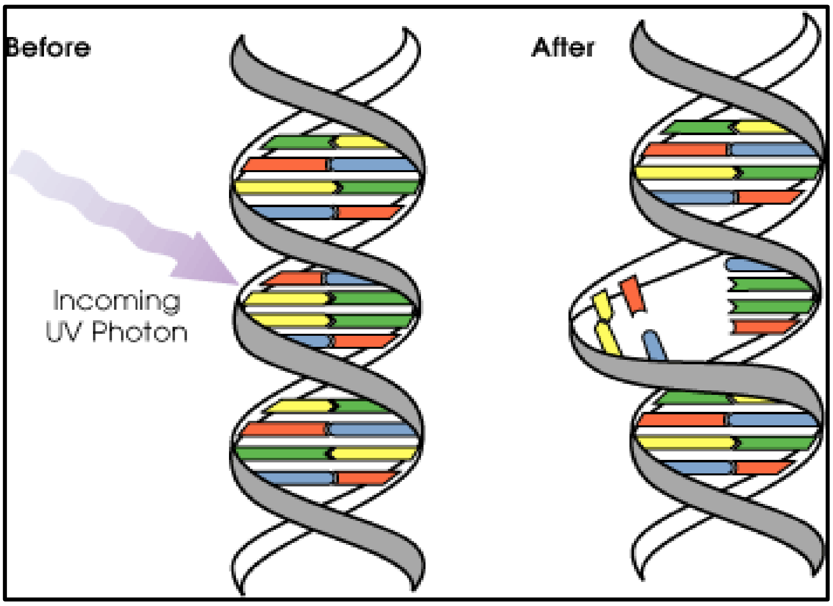

Figure 2.2 Formation of Pyrimidine Dimers

Although the UVA wavelengths (315-400 nm) are not sufficiently energetic to directly modify DNA bases, they play an important role in formation of reactive oxygen species (ROS) such as singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radical (*Jagger, J 1981*; *Eisenstark, A 1987; Lloyd, R. E. et. al. 1990; Sammartano, L.J., 1987; Tuveson, R. W. et al. 1986*). Once formed, these ROS can cause damage to DNA. Additionally, sunlight can be absorbed by natural exogenous photosensitizers present in surface waters (humic acids and chlorophyls), which in turn can react with oxygen to produce ROS (B*lough,N.V. et al. 1995; Schwartzenbach, R.P., et. al., 2003*) which can exert a disinfecting effect. *Berney (2006) and Bosshard (2010)* studied damaging effects of sunlight on cell protein.

They pointed out that solar photons attack proteins, directly or indirectly via ROS, and this could be the main mechanism of action during solar disinfection. *Hamamoto A. et. al. 2007* developed a water disinfection system using UVA light-emitting diodes, discovered that UVA radiation is effective in reducing and inactivating the bacteria.

Several SODIS systems, or reactors, are developed considering UVB or UVA radiation and IR. When using the solar radiation as source for disinfection, UVA is abundantly available in natural sunlight and is able to penetrate deeply (*Lee, Z et. al. 2013*).

2.6.2 Bacterial Inactivation in Solar Disinfection Reactors

Inactivation of the bacteria under solar radiation occurs in three ways.

1) Thermal inactivation.

2) Optical inactivation.

3) Combined thermal and optical inactivation.

2.6.2.1 Thermal Inactivation

Thermal inactivation is a process of inactivating the bacteria by application of heat. This is one of the oldest techniques for water disinfection. This significantly improves the microbiological quality of water, but does not fully remove the potential risk of waterborne pathogens if water temperatures do not reach boiling point (*Rosa et al. 2010*). Infrared radiation is another region in solar radiation and not visible to naked eye, but the heat produced by radiation in wavelengths beyond 700nm is sensed as heat. The infrared radiation absorbed by water is responsible for increasing its temperature. Microorganisms are sensitive to heat, and water can experience a bacterial reduction of 99.9% prior to reaching a boil temperature. This can be achieved by heating up water to 50-60°C for one hour (*SANDEC, 2002*).

In solar disinfection, water is retained in airtight containers to increase the water temperature. A number of enhancement methods have been attempted by accelerating the rate of thermal inactivation of organisms using absorptive materials and painting the containers black (*Sommer, B. et. al., 1997*) in order to aid in the absorption of solar radiation. Thermal enhancement has been achieved by: (i) painting sections of the bottles with black paint (Martin-Dominguez, A. et al. 2005); (ii) circulating water over a black surface in an enclosed casing that was transparent to UVA light (Rijal, G.K et al. 2003); (iii) using a solar collector attached to a double glass envelope container (Saitoh, T.S., El-Ghetany, H.H. 2002). Solar reflectors can also increase the temperature of water but not to the same extent as the use of absorptive materials or blackening of bottles (Mani, S.K. et al. 2006).

2.6.2.2 Optical Inactivation

Optical inactivation of bacteria is a process of inactivating bacteria by application of optical irradiation. In this case, solar irradiance is the optical irradiation. The incident solar irradiance on the outer Earth atmosphere has an intensity of approximately 1360 W/m^2. This value varies with position within the elliptical sidereal orbit of the Earth (the path that earth follows to revolve around the sun during a day or month or season) as it orbits the Sun. The irradiance intensity on a horizontal surface at ground level on the equator is reduced to roughly 1120 W/m^2 (averaged over the period of hours during which sunlight is available) after it gets absorbed by atmospheric components including water vapour, ozone, oxygen, and others. Thus, 1.12 kJ/m^2 (1.12 kj/m^2 = 1120 W/m^2 X 1sec, here 1120 w/m^2 is the average solar irradiance intensity reaching earth surface during sunny time and 1 sec is the unit exposure time, otherwise 1.12 kWs/m^2) of optical energy is available in each second to inactivate microbial. This value reduces in a cosine fashion as latitude increases away from the equator (*McGuigan, K.G., et. al 2012)*.

UVA, and UVB reaching the earth surface plays a major role in optical inactivation of the bacterial population. This concept is good when applied to zero turbid water, and can help the sunlight pass through deeper levels of water and can effectively reduce the bacterial count.

2.6.2.3 Combined Thermal and Optical Inactivation

Inactivation of bacteria by applying both thermal (heat) and optical irradiance is called combined thermal and optical inactivation. The Combined thermal and optical inactivation is the mechanism involved in most solar disinfection systems. These systems help in effective usage of both solar UV and IR for disinfection.

2.6.3 SODIS Systems

Systems that use solar radiation for disinfection are called SODIS systems. These involve a combination of thermal and optical inactivation of bacteria. Compound parabolic collector (CPC) reflectors are widely used solar disinfection systems. Figure 2.3 (*Alternative Energy Tutorials*) shows the reflection mechanism involved in compound parabolic collector (CPC) reflectors. The walls of the CPC act as reflectors and water containing tube act as a receiver. This has been proven as the successful solar water disinfection system so far (*Mbonimpa E. G. et al. 2012*). Research studies have proven that usage of reflective materials gives better disinfection rates rather than usage of heat absorbent materials because of the effective usage of sunlight in both direct (radiation from sun) and indirect (radiation from reflectors) means. The material used for reflecting radiation depends on the pricing of the material available in market. Researchers are working for developing the most viable reflection material. *Mani, S.K., et. al. 2006* conducted a comparative study between reactors with reflective, absorptive and transmissive rear surfaces. This study concluded that reactor with a reflective rear surface performed better in reducing *E. coli* than others. *Mani, S.K. et al. 2006* conducted some of their studies in sub-optimal sunlight conditions where thermal effects are minimal and optical effects is maximized by the return of solar radiation through water under treatment. This is because of the availability of UVA on cloudy days for reflectors to enhance the optical inactivation of solar disinfection unlike blackened surfaces that are unable to raise the temperature of water as required on cloudy days. Figure 2.4 (*Plataforma Solar de Almería, 2006*) shows a conventional solar flow reactor unit. This contains transparent tubes and reflectors. Transparent tubes transmit sunlight through them and helps in optical inactivation of bacteria. Reflectors used in this system are compound parabolic collectors (CPC), which are considered as best reflective shape, reflect the sunlight and concentrate the reflected light on to the tubes. This helps in increasing the optical inactivation rate. In addition, the infrared radiation warms up water and results in thermal inactivation.

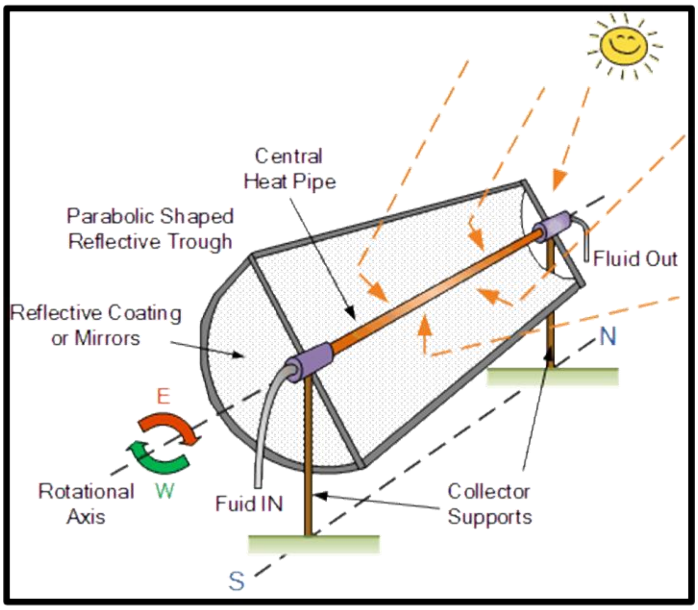

Figure 2.3 CPC Reflector

Figure 2.4 Conventional Solar Flow reactor

2.7 SODIS Projects Review

PET bottles are the WHO recognized way for solar disinfection in under developed countries. PET bottles do not transmit UVB, their thin wall thickness allows them to efficiently transmit 85–90% in the UVA region if the bottles are not old or scratched (*McGuigan, K, G. et al 1998*). Main concern involved in using plastic bottles is that they may have the potential to leach compounds into water after exposure to strong sunlight conditions. However, research results so far show that in some cases photoproducts such as terephthalate compounds remain on the surface of the container but do not migrate into water (*Wegelin, M. et al. 2001*). Carbonyls and plasticizers are found in water but are well below the limits set for drinking water quality (*Reed, R. H., 2000*). SODIS bags maximize the area for photon collection and minimize the path length for light penetration through water to be treated. Main drawback in PET bottle SODIS is the low batches they treat. And availability of the bottles in rural areas and limitations on useful lifetime.

Flow reactors use several reactor designs to enhance solar disinfection and increase batch size. Some flow reactors have focused on increasing the optical inactivation component of sunlight inactivation using solar collectors and reflectors. *Caslake et al. 2004* developed a solar disinfection system based on a PVC circuit covered by an acrylic layer transparent to the UV range for drinking water disinfection. The disinfection capacity of this system is 1 liter in 30 minutes, and in spite of high turbidity, the system obtained a 4-log reduction for total coliforms. *Ubomba-Jaswa et al. 2009* observed that increasing flow rate has a negative effect on inactivation of bacteria, irrespective of the exposure duration. It seems that at a given time-point there needs to be maximum exposure of bacteria to UV to ensure complete inactivation rather than having bacteria repeatedly exposed to sub-lethal doses over a long period of time. The authors determined that inactivation of bacteria is dependent on the UV dose rather than UV irradiance. *Gill et al. 2010* designed a continuous flow SODIS reactor capable of delivering 10 L min^{-1} of treated water and they tested it in a Kenyan rural village to treat surface waters from a small collection dam. The reactor used 120 m of 47 mm diameter pyrex tubing at the focus of a CPC reflector, assembled in eight panels. While only preliminary measurements were made soon after the reactor was completed, these indicated that coliform populations were being reduced from 10^2 to 0 CFU/mL after a 20 min single pass residence time. No details of the cost of manufacture or construction were available. *Polo-López et al. 2011* proposed a continuous single pass flow reactor, which would deliver solar disinfected water in the outlet of the reactor. This is a sequential batch photo-reactor which decreased the treatment time required for complete bacterial (*E. coli*) inactivation and increased the total output of water treated per day, reducing user-dependency. For this, the authors incorporated a CPC reflector of concentration factor 1.89 which reduced the residence time needed for disinfection and therefore, treated a higher volume of polluted water in the same time. The system also incorporated an electronic UVA sensor which controlled the discharge of the treated water into a clean reservoir tank following receipt of the pre-defined UVA dose. If this reactor could be constructed with six modules, it would produce at least 90 L of potable water per day, and approximately 31,500 L during a typical year. Table 2-1 gives information about the projects that developed SODIS systems and their capacities. The batch volume given is the amount of water that the system can disinfect in a single run. The systems given are both dynamic systems in which water flows continuously through the system and static systems in which water does not flow and most of the times static systems are PET bottles and bags. Only projects with information on the volume of water are considered in developing the table. The data is organized based on the batch volume of water treated, in descending order.

Table 2-1 SODIS systems and Their Capacity

Authors	Batch Volume	Title Of The Project	Year
L.W. Gill, C. Price	500 Liters	Preliminary Observations Of A Continuous Flow Solar Disinfection System For A Rural Community In Kenya	2010
Sommer, B., Marino, A., Solarte, Y., Salas, M. L., Dierolf, C., Valiente, C., Wegelin, M.	100 Liters	Sodis An Emerging Water Treatment Process	1997
Anthony Amsberry, Clayton Tyler, William Steinhauff, Justin Pommerenck, Alexandre T. F. Yokochi	55 Liters	Simple Continuous-Flow Device For Combined Solar Thermal Pasteurization And Solar Disinfection For Water Sterilization	2014
Pansonato N, Afonso Mv, Salles Ca, Boncz Ma, Paulo Pl.	51 Liters	Solar Disinfection For The Post-Treatment Of Greywater By Means Of A Continuous Flow Reactor.	2011
A.J. Fjendbo Jorgensen, K. Nohr, H. Sorensen, F. Boisen	50 Liters	Decontamination Of Drinking Water By Direct Heating In Solar Panels	1998

O.A. Mcloughlina, P. Fernández Ibáñezb, W. Gernjakb, S. Malato Rodríguezb, L.W. Gilla	35 Liters	Photocatalytic Disinfection Of Water Using Low Cost Compound Parabolic Collectors	2004
Peter Kalt, Cristian Birzer, , Harrison Evans, Anthony Liew, Mark Padovan, Michael Watchman	34 Liters	A Solar Disinfection Water Treatment System For Remote Communities	2014
Sadek Igoud, Fatiha Souahi, Chems Eddine Chitour, Lynda Amrouche, Chahinez Lamaa, Nadia Chekir & Amar Chouikh	30 Liters	Wastewater Disinfection Using Ultraviolet (Uva, Uvc) And Solar Radiation	2014
Eunice Ubomba-Jaswa,A, Pilar Fernandez-Ib, Nez, Christian Navntoft,C M. Inmaculada Polo-Lopez And Kevin G. Mcguigana	25 Liters	Investigating The Microbial Inactivation Efficiency Of A 25 L Batch Solar Disinfection (Sodis) Reactor Enhanced With A Compound Parabolic Collector (Cpc) For Household Use	2010
M.I. Polo-Lópeza, P. Fernández-Ibáñeza, E. Ubomba-Jaswab, C. Navntoftc, D, I. García-Fernándeza, P.S.M. Dunlopf, M. Schmidf, J.A. Byrnef, K.G. Mcguigan	25 Liter	Elimination Of Water Pathogens With Solar Radiation Using An Automated Sequential Batch Cpc Reactor	2011
R.H. Reed, S.K. Mani, V. Meyer	25 Liters	Solar Photo-Oxidative Disinfection Of Drinking Water: Preliminary Field Observations	2000

P. Fernández-Ibáñeza, C. Sichela, M.I. Polo-Lópeza, M. De Cara-Garcíab, J.C. Tellob	14 Liters	Photocatalytic Disinfection Of Natural Well Water Contaminated By Fusarium Solani Using Tio2 Slurry In Solar Cpc Photo-Reactors	2009
P. Fernández, , J. Blanco, C. Sichel, S. Malato	11 Liters	Water Disinfection By Solar Photocatalysis Using Compound Parabolic Collectors	2005
Takeo S Saitoh, Hamdy H El-Ghetany	8 – 10 Liters	A Pilot Solar Water Disinfecting System: Performance Analysis And Testing	2002
Takeo S. Saitoh And Hamdy H. El-Ghetany	3 – 5 Liters	A Pilot Solar Water Disinfecting System: Performance Analysis And Testing	2001
C. Navntofta, D, E. Ubomba-Jaswab, K.G. Mcguiganb, P. Fernández-Ibáñezc,	2.5 Liters	Effectiveness Of Solar Disinfection Using Batch Reactors With Non-Imaging Aluminium Reflectors Under Real Conditions: Natural Well-Water And Solar Light	2008
P.S.M. Dunlop, M. Ciavola B, L. Rizzo, J.A. Byrne A	2.5 Liters	Inactivation And Injury Assessment Of Escherichia Coli During Solar And Photocatalytic Disinfection In Ldpe Bags	2011
Alejandra Martín-Domíngueza, Ma. Teresa Alarcón-Herrerab, Ignacio R. Martín-Domínguezb, Arturo González-Herrerac	2 Liters	Efficiency In The Disinfection Of Water For Human Consumption In Rural Communities Using Solar Radiation	2005

Silvia Gelover, , Luis A. Gómez, Karina Reyes, Ma. Teresa Leal	2 Liters	A Practical Demonstration Of Water Disinfection Using Tio2 Films And Sunlight	2006
Laurie F. Caslake, Daniel J. Connolly, Vilas Menon, Catriona M. Duncanson, Ricardo Rojas, Javad Tavakoli	2 Liters	Disinfection Of Contaminated Water By Using Solar Irradiation	2004
S.C. Kehoe, T.M. Joyce, P. Ibrahim, J.B. Gillespie, R.A. Shahar, K.G. Mcguigan	1.5 Liters	Effect Of Agitation, Turbidity, Aluminium Foil Reflectors And Container Volume On The Inactivation Efficiency Of Batch-Process Solar Disinfectors	2001
J. Ndounlaa, E, D. Spuhlerb, S. Kenfackc, J. Wéthéd, C. Pulgarina,	1 – 1.5 Liters	Inactivation By Solar Photo-Fenton In Pet Bottles Of Wild Enteric Bacteria Of Natural Well Water: Absence Of Re-Growth After One Week Of Subsequent Storage	2013
D. Carey Walker, Soo-Voon Len, Brita Sheehan1	1 Liter	Development And Evaluation Of A Reflective Solar Disinfection Pouch For Treatment Of Drinking Water	2004

2.8 E. coli

Escherichia coli is a gram-negative, non-spore forming bacillar bacteria which is a facultative anaerobe and ferments simple sugars like glucose (*Unc, A. and Goss, M. J. 2000)*. It is a common inhabitant of the intestinal tract of man and other warm blooded animals. Most of the strains of E. coli live as endo commensals in the intestinal tract along with other gut-inhabitant bacteria and are harmless. However, some strains are virulent and cause diarrhoeal illnesses. The four main virulent/ pathogenic strains are enteropathogenic *E. coli*, enteroinvasive *E. coli*, enterotoxigenic, *E. coli* and enterohemorrhagic *E. coli*. *E.coli* being gram-negative bacteria, produces endotoxins which when released lead to diarrhoeal symptoms.

E. coli is known to be a good biological indicator of water treatment safety for decades (*Edberg, S.C. et al. 2000*). The bacterium fulfils several essential conditions required for an ideal biological indicator. Firstly, it is present in copious amounts in mammalian (human) fecal matter and also it does not multiply adequately outside the host. World Health Organization (WHO) states that the presence of fecal bacteria in drinking water is an important factor in the assessment of water quality. The bacteria are known to survive in drinking water for over 4-12 weeks depending on several weather conditions indicated by temperature, pH, microflora and others. Studies have reported that *E. coli* can be expected to survive in the river water for approximately 30 days. This is a huge advantage as a cost effective protocol can be used. After testing several other enterogenic bacteria, it has been suggested by several studies that *E. coli* is a single best biological indicator. The methods available for the detection of *E. coli* are sensitive (sensitivity in testing is perfect identification of the required bacteria without any influence of other bacteria present in the sample); inexpensive (some detection techniques require lots of infrastructure when compared to others, an inexpensive method can save money and resources); specific (specificity is defined as the identification of a required or particular strain of bacteria in a bacterial group (for example: there are testing procedures for finding out the E. coli O157:H7, which are present in low concentrations) and less technique sensitive (this is reduction of standard operation procedural steps involved in analyzing a sample for bacteria. This saves time.).

E. coli contamination poses a huge threat to the safety of drinking water. The presence of *E. coli* in drinking water is considered unsafe. This occurs by the fecal contamination of humans or animals into water resources. Studies have demonstrated that public health threat comes from sewage intrusion, which is expected to have high concentration of *E. coli* (108-109 colonies/100ml). Many studies have signified *E. coli* had higher or at least equal survival rate to several other bacteria on disinfection.

As stated by WHO, that water contamination should be tested often to avoid water borne diseases, therefore, the method to detect the contamination should be sensitive yet economical and accessible. Although several other bacteria have been tested for biological indicators of safe drinking water like *Enterococci*, *Clostridium perfringens*, somatic phages etc. However, *E. coli* still stands above all in its application as a biological indicator due to the presence of simple methods. Methods that involve testing *E. coli* concentration in water range from qualitative analysis to quantitative analysis.

*2.8.1 **Qualitative Analysis of water for E. coli***

This analysis used as verification means to indicate whether there is any *E. coli* contamination in the collected samples or not. There are many onsite, home based water analysis kits for qualitative analysis of bacteria. H2S paper strip method is the most used or tested for its performance, because of its implementation and pricing. *Pillai, J. et al 1999* proved that H2S paper strip method is the most reliable method for qualitative analysis for fecal coliforms and this method do not require access to incubators, freezers and other lab equipment that used for testing fecal coliform presence in water samples. This method can be performed at room temperatures. *Manja et al., (1982)* developed this on-site microbial water testing method. H2S paper strip method works based on the detection of hydrogen sulphide producing bacteria, and there are high concentrations of sulphate reducing bacteria that are present in human faeces. The method is less expensive, and can give a faster result. Previous research studies (*Grant, and Ziel, 1996; Hewison et al., 1988; Sivaborvorn, and Dutka, 1989*) show that this method do not required technical personnel to conduct it and have a good correlation with the standard methods. *Pillai, J et al. 1999* conducted this method at different temperatures and concluded that this procedures work better between temperatures 20 – 44^0C. Research study conducted by *Anwar, M. S, et al. 1998* in Pakistan proved that H2S paper strip method is a good qualitative indicator test for fecal coliform. *Wright, J. A. et. al., 2012* compared alternative methods for bacterial analysis and concluded that H2S is best available onsite method based on accuracy, pricing and implementation.

2.8.2 Quantitative analysis of water for E. coli

This analysis gives the number of bacterial colony forming units (CFU) present in water samples. CFU is defined as the rough estimate of the number of viable bacteria or fungal cells in a sample, who have an ability to multiply via binary fission under the controlled conditions. There are many methods available for analyzing the *E. coli* concentration in water samples. EPA (United States of America

Environmental Protection Agency) has approved ten enzyme-based total coliform and *E. coli* detection tests for examination of drinking water (*Olstadt, J. S., et al., 2007*). They are, Colilertw, Colilert-18w, Colisurew, m-Coli Blue 24w, Readycultw Coliforms 100, Chromocultw, Coliscanw, E p Colitew, ColitagY and MI Agar. All these tests detect the enzymes β-D galactosidase and β-D glucuronidase which are uniquely associated with total coliforms and *E. coli*, respectively. This includes addition of buffers, salts and micro-nutrients to enhance enzyme expression. Antibiotics are added to suppress the activity of non-coliforms. MI Agar, an EPA suggested technique is used for quantitative analysis of water samples in this project

2.8.2.1 MI Agar method

EPA suggested method (*Method 1604, EPA*) MI Agar method is a combination of media and membrane filtration. This method gives the Total Coliform and E. coli concentrations in the samples. The substrates involved with this method are MUGal (4-methylumbelliferyl-ß-D-galactopyranoside) for detection of total coliform and IBDG (Indoxyl-ß-D-glucuronide) for detection of *E. coli* (*Olstadt, J et al., 2007*).

MI agar medium in form of powder are available and the plating procedure involves addition of 36.5 gms of MI agar to 1000 ml of double distilled water and autoclaved for 15 minutes at 121^0C at 15lb pressure. Then the solution is transferred to water-bath maintained at 50^0C for tempering agar. A 5ml of antibiotic Cefsulodin solution (concentration of 1mg/ml) is filtered through a 0.22 µm pore size, 25mm diameter sterile syringe filter. This filtered antibiotic is then added to the agar right before pouring of plates. The plates are then allowed for settling down. Once settled plates are tested for any bacterial growth in them. The plates with any bacterial growth must be discarded and the rest should be stored at 4^0C for usage.

An appropriate volume of a water sample (10, 25, 50 or 100 ml) is filtered through a 47-mm, 0.45-µm (The size of fecal coliforms is between 0.5 to 2 µm in diameter and 1 to 4 µm in length, *Unc, A. and Goss, M. J. 2000*) pore size cellulose ester membrane filter that retains the bacteria present in the sample (*Method 1604, EPA*). Then the filter is placed on the plate of MI agar and the plate is incubated at 35°C for up to 24 hours. The blue colour bacterial colonies that grow on the plate are *E. coli* and colonies that are fluorescent under long-wave ultraviolet light (366 nm) are total coliforms other than *E. coli*. When water sample used is not 100 ml, equation 2.4 gives the estimation of *E. coli* concentration in 100 ml.

$$\frac{E.coli}{100ml} = \frac{N_{BC}}{V}\ (100) \qquad (2.4)$$

Where,

N_{BC} = Number of blue colonies

V = Volume of water sample (ml)

Equation 2.5 gives the total coliforms (TC) in water sample.

$$\frac{\text{TC}}{100\text{ml}} = \frac{N_{BC}+N_{FC}}{\text{V}}\ (100) \qquad (2.5)$$

TC = Total Coliforms

N_{BC} = Number of blue colonies

N_{FC} = Number of fluorescent colonies

V = Volume of water samples (ml)

2.9 Project Significance

From the previous discussions about past research projects, it can be concluded that UVB or UVA, along with infrared radiation plays a significant role in water disinfection by using solar irradiance. This happens because of optical inactivation and thermal inactivation. In most of the cases the material (transparent pipes) used for exposing water to sunlight either filters UVA or UVB in the solar spectrum, but increases water temperature. Unlike these previous projects, this project adopts the open channel flow concept to test the effective ness of UVB and UVA radiations in bacterial inactivation. Effect of infrared radiation was not significant, as water temperature never exceeded the thermal inactivation threshold of 38^0C.

3 MATERIALS AND METHODS

3.1 Introduction

All materials to construct and methods for developing the project are discussed in this chapter. Effort was taken to keep this project as sustainable as possible by using solar panels for generating electricity, non-chemical disinfection of water, and gravitational circulation of water throughout the system. Following sections will give a clear picture of the components used in this project and methods implemented in this. The raw water for this project is drawn from Beargrass Creek, an urban stream in Louisville metro area because of high bacterial concentration in water. The reason behind using this water as raw water is explained in detail.

3.2 Project Setup

The pilot water treatment project have four components:

1. Pumping water into storage tank
    a. Photo voltaic (PV) panels
    b. Solar powered submersible pump
2. Filtration
    a. Sand
    b. Gravel
    c. Activated charcoal
    d. Crushed oyster shells
3. Disinfection

a. Solar radiation

4. Aeration

a. Water fall

No chemicals or fossil fuels were used in this system. Major portion of materials were bought local or in 500miles radius. Figure 3.1 shows the project setup. Solar panels are to power the pump for pumping water in to water tank. The four filters are for water filtration, filled with different filter material. SODIS troughs are for exposing water to sunlight. Overflow from tank takes out the surplus water from tank and this water flows back into the stream through water fall for increasing the dissolved oxygen (DO) concentration in water.

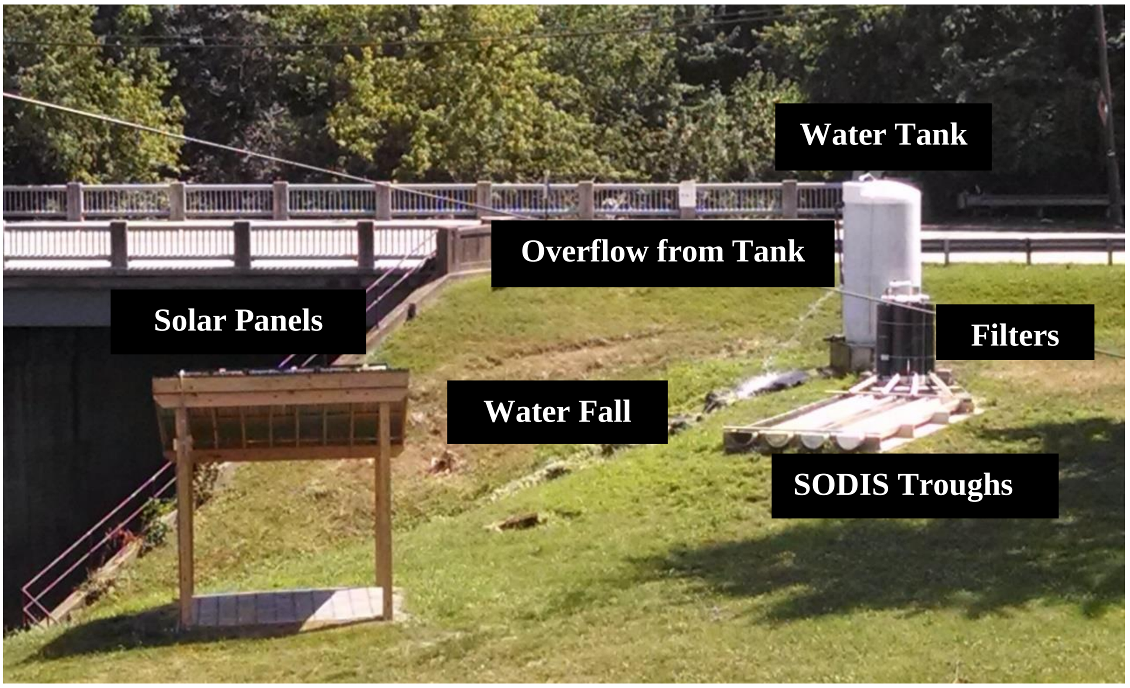

Figure 3.1 Project Setup

3.2.1 Water Pump, PV Panels, and Storage Tank

Six solar panels are installed to power the submersible pump that is installed in the creek. This pump pumps water into a storage tank that is about 35 feet above water level in the creek. The over flow water flows back into the creek through a concrete water fall, this water fall creates ripple effect and helps in increasing the Dissolved Oxygen (DO) concentration in water. The storage tank helps in reducing settling down the sediment in water. Figure 3.2 shows the PV panels setup for powering the pump.

Figure 3.2 Panels for Powering Water Pump

3.2.2 Filtration

American Water Works Association's manual of design of slow sand filtration was followed in designing slow sand filters. Filters are designed to reduce the suspended solids in water for increased penetration of sunlight into water. Mechanism involved in setting up a filter is using coarser material in the bottom and gradually decreasing the grain size to finer material in the top. This helps in controlling the finer particles entering into the plumbing and clogging them (*Hendricks, D., et al., 1992*).

3.2.2.1 Sand

Sand filters are good in reducing the suspended particles and bacterial concentrations in water over the course of time because of the development of a biofilm called *Schmutzdecke* in the top few millimetres of the fine sand layer. *Schmutzdecke* is formed in the few days of filter operation depending on the flow into the filters and consists of different species ranging from bacteria to protozoa (*Huisman, L 1974*). A fine particulate sand is used in this pilot study to reduce as much of total suspended solids (TSS) as possible.

3.2.2.2 Oyster Shells

Oyster shells, because of the rich calcium content in them are being used as the calcium supplement in chicken industry. In addition, they are good in reducing the NH3-N (Ammonical nitrogen) concentrations in water (*Liuin, Yao-Xing 2010*). Commercially available crushed oyster shells because of their size can also be used as a coarser particle in the filter eliminating a portion of gravel used in filters. Gravel in filters do not have any significance in water purification (*Collins, M. R 1998*). Replacing a portion of gravel with some material of similar particle size and a better water treating agent can help in improving the filter performance. But total replacement of gravel with Oyster shells can't be a better option because it takes long time to dissolve a pebble than an oyster shell. Crushed oyster shells can best fit in this zone because of three reasons 1) Particle size similar to gravel; 2) Price, a 50lbs bag of shells costs only $10; 3) They are proven as good reducing agents of NH3-N compounds in water and also performs better if pre-processed in reducing Total Phosphorus concentrations in water (*Liuin, Yao-Xing 2010*).

3.2.2.3 Activated Charcoal

Activated charcoal has been used as a filter material for increasing odour and taste of the potable water (EPA). The mechanism involved in activated charcoal filtrating is adsorption, because of its high porosity and provides large surface area to which contaminants may absorb. Granular activated charcoal, derived from burning of coconut shells is used in this project. In the beginning, activated charcoal was used as a filter for adsorbing wide range of chemicals (EPA). However, research studies show that it can effectively adsorb E. coli bacteria depending on the retention time (*Katsumi, N 2000*). In addition, their particle size makes it as a perfect match to be applied in the filter in between coarse to finer material.

A 1 foot diameter 20 feet long schedule 80 PVC pipe was cut into four 5 feet long pipes and are filled with filter materials in different proportions. Table 3-1 shows the filter specifications. Figure 3.3 shows the Filter arrangement. Figure 3.4 show the inflow controls into filters. Figure 3.5 shows the outflow control from the filters and inflow into the solar troughs. Water flow is gravitational into the filters and controlled individually at the inflow of each filter.

Table 3-1 Filter Specifications

Filter	Filter Media
1	Gravel – 11”; Oyster Shells – 7”; Sand – 3.5”
2	Gravel – 11”; Oyster Shells – 6” Activated Charcoal – 3.5”
3	Gravel – 11”; Activated Charcoal – 7”
4	Gravel – 11”; Oyster Shells – 7”

Figure 3.3 Filter Arrangement Showing Inflow and Outflow Controls

Figure 3.4 Inflow Control into Filters

Figure 3.5 Outflow Control from Filters

3.2.3 Solar Disinfection (SODIS)

CPC reflector systems collect and illuminate the pipe in regular SODIS applications. The pipes used are transparent, and these materials range from Pyrex, polyethylene, acrylic... etc. Most of these materials don't transmit 100% of the UV radiation from sun. Moreover, because of the closed system, oxygen levels may not be raised. Circular shape of the pipes will have a minimal area of exposure to direct sunlight. *Caslake et al. 2004* developed a system with semi-circular exposure surface. The system used is serpentine shape grooved on a PVC sheet and is covered by acrylic layer. This system has successfully obtained a 4-log reduction in spite of high turbidity. However, it is a small system, which has a capacity of 1 litre. Most of the projects apply the combination of Thermal and optical inactivation of bacteria by sunlight. In addition, majority of studies have concentrated on UVB radiation in sunlight for disinfection. Few studies have concentrated on UVA radiation for disinfection. UVA is also proven as a potential disinfecting radiation. There are limited number of studies addressed the effectiveness of both radiations in disinfection that is optical inactivation.

This project studies the effectiveness of solar radiation in just optical inactivation of bacteria. For that, this project adopted the open channel concept. Infrared radiation of solar radiation helps in increasing the temperatures and when water temperatures reaches 50^0 C disinfection rate reaches maximum and that situation will reduce the choice of studying only optical inactivation process. Open channel also helped in to achieve the maximum water surface exposure to sunlight. Open channel helps in increasing oxygen levels and when hit by UV transforms into ROS and increases the disinfection rate. The introduction of different filtration materials help in reducing the TSS, nutrient levels in water and reduces the load on

UV chamber. Reduction of nutrient levels help in cutting down the food chain to bacteria. This project used the fundamental expressions in hydraulics and SODIS at design phase and system is altered over the course of time depending on the performance.

In this study, 18-inch pvc pipes are cut into half to create semi-circular channels. Equation 3.1 below defines removal percentage of Escherichia coli (*E. coli*) (cdc.gov/ecoli) from water using a first-order decay relation. Simulated results with exposure time required for 10 percent to 99.9 percent removal of *E. coli* over a ten percent increment is presented in Table 3-2.

$$\frac{N}{N_0} = e^{-K_i I T} \qquad (3.1)$$

N - Final *E. coli* concentration (CFU/ml)

N_0 - Initial *E. coli* concentration (CFU/ml)

K_i - Inactivation rate constant ($cm^2/(\mu W\ min)$)

I - Intensity of solar radiation ($\mu W/cm^2$)

T - Time of exposure (min)

I - 94 (average of solar irradiance) for Louisville area (ref: http://www.nrel.gov)

Table 3-2 Exposure time summary

% Removal	N/N_0	K	F = I*T	I	T (hrs)	T (mins.)
99.9	0.001	0.03	230.25	94	2.44	146.97
90	0.1	0.03	76.75	94	0.81	48.99
80	0.2	0.03	53.64	94	0.57	34.24
70	0.3	0.03	40.13	94	0.42	25.61
60	0.4	0.03	30.54	94	0.32	19.49
50	0.5	0.03	23.10	94	0.24	14.74
40	0.6	0.03	17.02	94	0.18	10.86
30	0.7	0.03	11.88	94	0.12	7.58
20	0.8	0.03	7.43	94	0.08	4.74
10	0.9	0.03	3.51	94	0.04	2.24
hrs = hours; mins. = minutes						

A simulation was carried out using controlled flow values of 75, 85 and 100 gallons/hour was used to estimate flow travel length required to achieve exposure duration for disinfection. Those results are presented in table 3-3. Exposure time and flow area are constant and velocity varies with respect to the flows and with flow lengths. Equations 3.2, 3.3 and 3.4 define flow velocity (V), wetted area (A) of a horizontal cylinder and flow length (L), respectively,

$$\mathrm{V} = \frac{\mathrm{Q}}{\mathrm{A}} \qquad (3.2)$$

V = Velocity of flow (feet/hour, meter/hour)

A = Wetted area of the horizontal cylinder (feet^2)

$$A = r^2 \cos^{-1}\left(\frac{r-h}{r}\right) - (r-h)\sqrt{2rh - h^2} \qquad (3.3)$$

r = radius of the cylinder (inches)

h = water depth or wetted depth (inches)

Q = Volumetric flow rate (gallon/hour (gph) = 0.134 ft^3/hour = 3.785 liter/hr (lph))

L = Flow length (inches)

$$\mathrm{L} = (\mathrm{V})(\mathrm{T}) \qquad (3.4)$$

Table 3-3 Flow lengths from volume flow values

	Q = 75		**Q = 85**		**Q = 100**	
	75 gph	283.91 lph	85 gph	321.76 lph	100 gph	378.54 lph
	Velocity		**Velocity**		**Velocity**	
	6.36 fph	1.94 m/h	7.18 fph	4.31 m/h	8.45 fph	5.07 m/h
Exposure Time (mins.)	**Flow Length**		**Flow Length**		**Flow Length**	
	feet	meters	feet	meters	feet	meters
146.97	15.50	4.73	17.50	5.34	20.59	6.28
48.99	5.17	1.58	5.83	1.78	6.86	2.09
34.24	3.61	1.10	4.07	1.24	4.79	1.46
25.61	2.70	0.82	3.05	0.93	3.58	1.09
19.49	2.06	0.63	2.32	0.71	2.73	0.83
14.74	1.56	0.48	1.75	0.53	2.06	0.63
10.86	1.15	0.35	1.29	0.39	1.52	0.46
7.58	0.80	0.24	0.90	0.27	1.06	0.32
4.74	0.50	0.15	0.56	0.17	0.66	0.20
2.24	0.24	0.07	0.26	0.08	0.31	0.09
gph = gallons/hour; lph = liters/hour; fph = feet/hour; m/h = meters/hour						

3.3 Construction

Two 18” X 10 feet long pvc pipes are cut into two half cylinders with rectangular base and semi-circular ends. Each half cylinder is painted with different colour either with reflective paint or with heat absorbing paint. Figure 3.6 shows the semi-circular troughs painted in different colours. Water flowing out of the filters flows into separate troughs and filled up to the designed depth. Water then flows out by opening the valve shown in figure 3.6a. Table 3-4 gives details about the painted surfaces and why they are applied.

Table 3-4 Painted Troughs

Trough	Paint	Purpose
1	White	Best reflector, Cheap reflecting agent
2	Spray Painted Aluminum Finish	Better reflector than White but expensive
3	None	Left unpainted for control
4	Black	Absorbs more heat than other materials

Figure 3.6 SODIS Troughs Setup and Out Flow Control

Figure 3.6 a Trough out Flow Valve

3.4 Operation

The pilot project is operated in two phases with respect to flow. Phase I is a static batch system. In which troughs were filled and allowed water to expose to sunlight for 2 hours. Each trough is capable of holding 113 gallons with a water depth of 8”. Phase II is a continuous flow system in which water flow is continuous into the troughs at a constant flow rate and the event ends with water reaching targeted depth in targeted time. Two flow depths are tested at three different targeted times.

Scenario I

Water flowing out of filters is made to achieve 8” depth over the period of 3.5 hours (113 gallons in 3.5 hrs). But the trough painted white that is attached to the filter 1 can’t attain the desired flow depth because of the fine grained sand used in the filter created low pore size and not allowed water pass through as the other filters. Trough 1 is able to attain the desired flow depth of 8” in 6.0 hrs. Flow rate input into water for this is 32.3 gal/hr.

Scenario II

Water flowing out of filters is made to achieve 8” depth over the period of 6.0 hours (113 gallons in 6.0 hrs). In this case, trough painted white is able to attain the targeted depth of 8” in 6.0 hrs. Flow rate input into water for this is 18.8 gal/hr.

Scenario III

Water flowing out of filters is made to achieve 3.5” depth over the period of 5.0 hours (36.15 gallons in 5.0 hrs). Flow rate input into water for this is 7.3 gal/hr.

All flows are measured using a measure jar of known volume over time. Each flow is measured up to 5 times and averaged. Calibration continued until averaged flow values are equal to the desired flow rate.

3.5 Raw Water for Experiments

The raw water for this project is water drawn from the Beargrass creek. Water drawn from a natural source is due to the presence of organic and inorganic matter present in water during disinfection has an important effect on both the kinetics and the final disinfection result (*McGuigan, K.G 2012*). Using a natural source of water gives a better prediction of microbial inactivation under real conditions. Using natural water avoids weakening of bacterial cells due to an unfavourable osmotic environment (lack of ions).

3.6 Sampling and Testing

3.6.1 Sample Collection

Water samples for microbial testing were collected by following grab sampling. Samples are collected using 150 ml bottles with leak proof lids. Sample containers were opened just before taking water sample. Inside of the containers was never touched. Sample containers were never reused. Containers with sodium thiosulfate tablets were used to reduce the chlorine concentration in water if present. Samples were stored in ice bag without immersing them into the ice. A temperature of 1-4°C was maintained during transit to the laboratory. It used to take around 30-45 mins to reach the lab and start the analysis. Figures 3.7 and 3.8 show water sample collection bottle and cooler bag for transporting water samples to lab. Care was taken that the sample bottles never sunk into the ice. Water samples for physical parameter analysis was done at the site by using the probes. Analysis of water in troughs is done by introducing the probe in water. Water sample analysis for water coming out of tank and filters are collected in water sample collection bottle and probes are introduced into the bottle.

Figure 3.7 Sampling Bottles Closed, Opened and Labelled

Figure 3.8 Cooler Bag for Transporting Water Samples

3.6.2 Microbial Analysis

EPA's Method 1604 was used for conducting the quantitative analysis of *E. coli* in water. This method uses the MI agar medium for growing colonies. A known volume of water sample (10, 25, 50ml) is diluted with double distilled water and is filtered through a 0.45µm filter membrane. Figures 3.9 and 3.10 show the 0.45 µm cellulose ester membrane filter and the filtration system. Then the membrane is plated on the MI agar medium. Figure 3.11 shows an example of the plate loaded with the membrane and the plates are incubated at 35^0 C for 24 hours. The plates are then taken out of the incubator and colonies are counted manually. Figure 3.12 shows an example of the incubated plate with bacterial growth on it. The results were then expressed in colonies/100ml using the equation 3.5 Bacterial change at different stages are analysed and bacterial reduction is calculated on percentage and logarithmic scales.

$$E.\ Coli\ Concentration\ in\ 100ml\ = \frac{Number\ of\ blue\ colonies}{Volume\ of\ water\ simple\ analysed}\ 100 \quad (3.5)$$

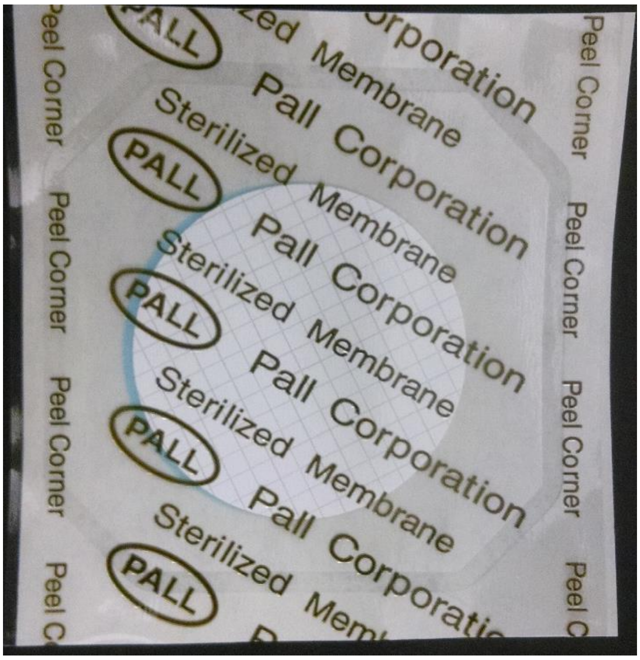

Figure 3.9 0.45 µm Pore Size Cellulose Ester Membrane

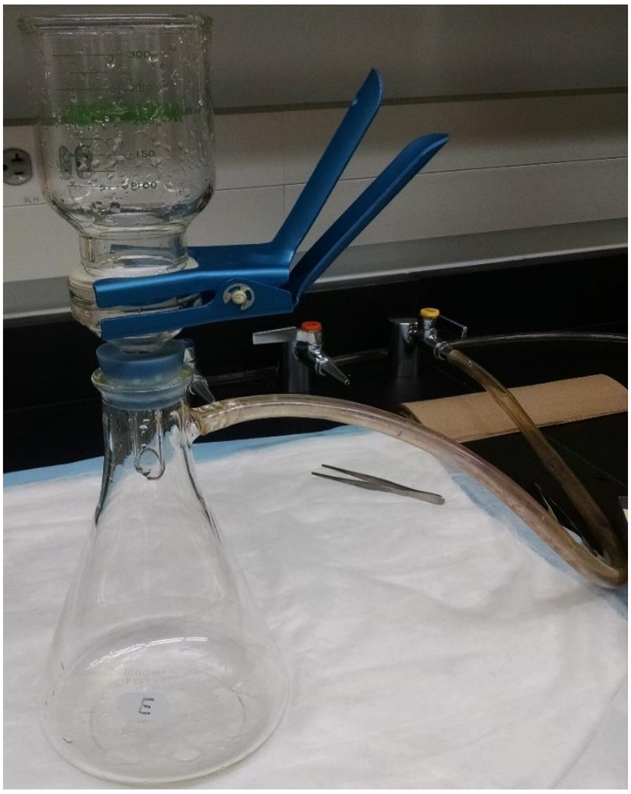

Figure 3.10 Filtration Assembly

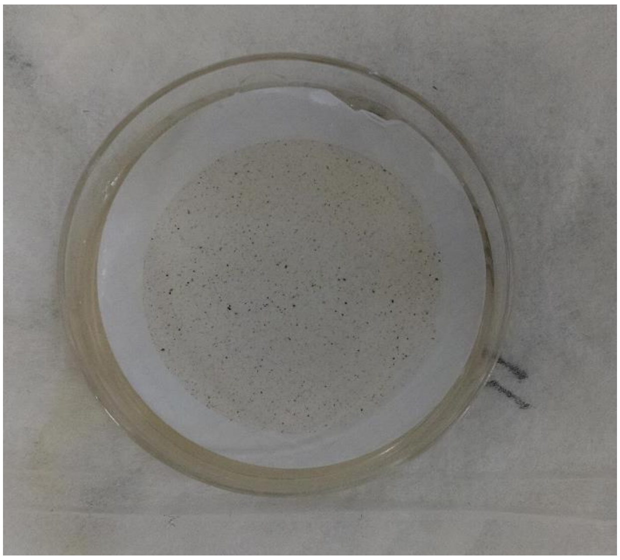

Figure 3.11 Plate Loaded with the Membrane

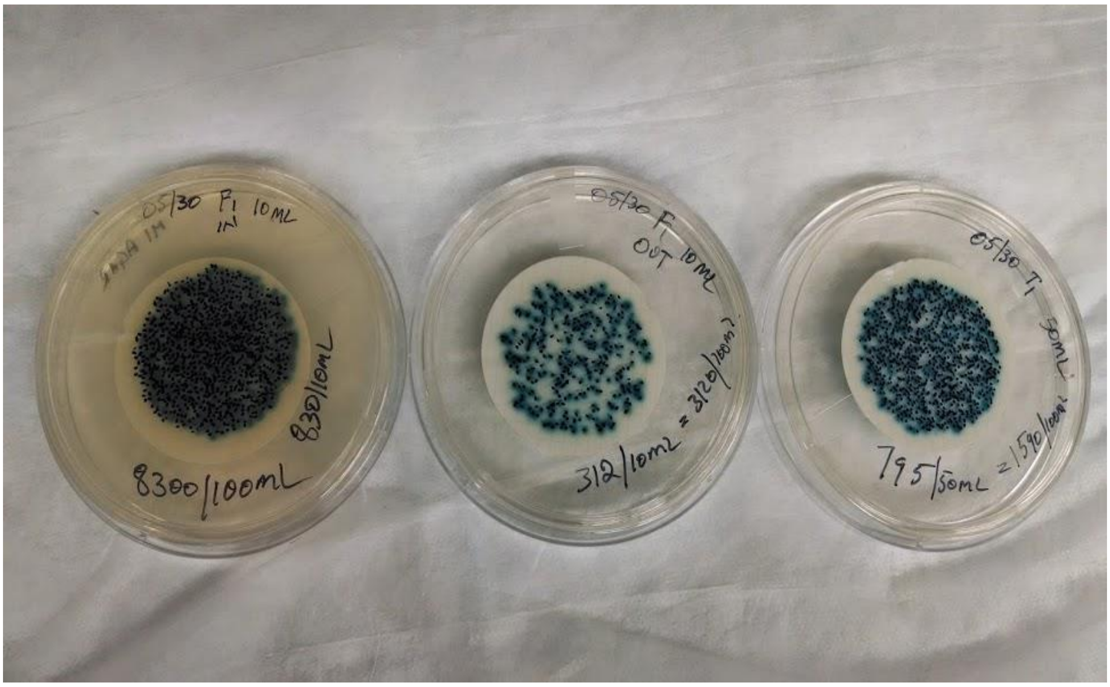

Figure 3.12 Incubated Plates with Bacterial Growth

3.6.3 Physical Water Analysis

Water samples are analysed for pH, temperature, Dissolved Oxygen (DO), and conductivity using the probes "Extech DO610 ExStik II DO/pH Conductivity Kit".

Figure 3.13 shows the probes used for sampling. Stream water parameter values are downloaded from USGS website. Stream water quality data is downloaded from USGS website (*USGS water quality data).*

Figure 3.13 Extech DO610 ExStik II DO/pH Conductivity Kit

3.7 Meteorological Data

Meteorological data accessed for this project is, solar irradiance (watts/m^2), air temperature (^{0}C or ^{0}F), previous hour precipitation (inches, or cms), humidity (%), solar azimuth angle (in degrees), and cloud cover (%).

The hourly data of the above parameters is bought from the weather analytics website. All the data provided for a Weather Analytics station comes from the Climate Forecast System Reanalysis (CFSR) data set. The CFSR data set was created by The National Centres for Environmental Prediction (NCEP). The CFSR data set was constructed with the combination of a full atmospheric model, satellite observations, upper air balloon observations, aircraft observations and ground observations (*Weather Anlytics website*). This data is collected from the sensors installed at Standiford field, Louisville international airport, which is 5.65 miles (9.09 km) from the pilot project site (straight line). Figure 3.14 shows the straight-line distance between the pilot project site and Standiford field.

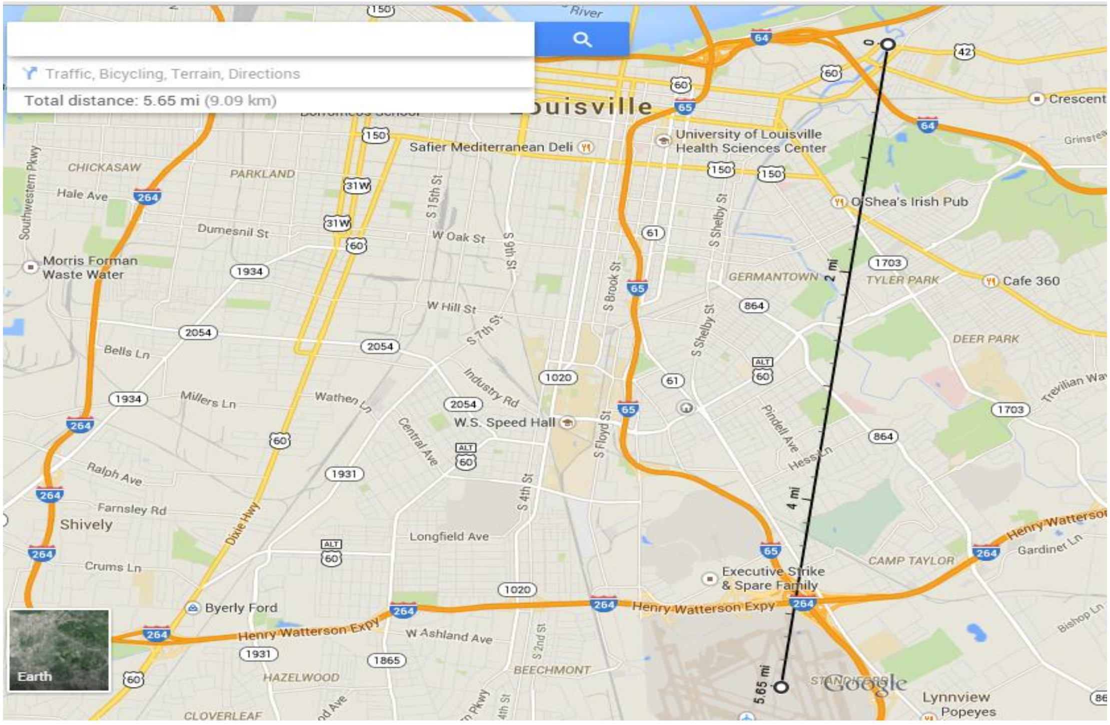

Figure 3.14 Straight Line Distance between SDF and Beargrass Falls

4 METEOROLOGICAL DATA

4.1 Introduction

This chapter gives detailed information about the measurement of solar radiation reaching earth's surface. Factors that affect solar radiation and effects of solar radiation on temperature variations during a day are discussed. Discussion is done by using the past research and the graphical illustration of the discussion is done by using the data acquired for this project from the weather analytics website. Data chosen for this discussion is the average of the data values between sunrise and sun set times in a day is considered as daily average. The data used for analysis is from weather analytics. Weather Analytics uses the meteorological data from the ground-installed stations

4.2 Solar Radiation Measurement

The electromagnetic radiation emitted by sun is called solar radiation. Extraterrestrial radiation (ETR) is the amount of solar radiation at the top of the earth's atmosphere. Earth revolves around the sun in an elliptical orbit and this result in the variation of distance between Earth and Sun. This affects the amount of solar radiation reaching Earth's outer atmosphere. The ETR value varies between 1412 W/m^2 and 1321 W/m^2 (*Paulescu, M. et al. 2013*). Measurement of solar irradiation at Earth's surface is done in different ways. Three commonly measured solar radiation quantities are: direct normal or beam irradiance; diffuse horizontal irradiance; global horizontal irradiance.

4.2.1 Direct Normal or Beam Irradiance

Direct normal irradiance (DNI) is the amount of the solar radiation from the direction of the sun. This is measured in the surface that is held perpendicular to the straight line from the direction of sun.

4.2.2 Diffuse Horizontal Irradiance

Diffuse horizontal irradiance (DHI) is defined as the amount of radiation received per unit area on earth's surface that has been scattered by molecules and particles. The absence of atmosphere results in no diffuse radiation recorded.

4.2.3 Global Horizontal Irradiance

Global horizontal irradiance (GHI) is the sum of direct normal irradiance, diffuse horizontal irradiance, and ground-reflected radiation. Ground reflected radiation is insignificant compared to DHI, and DNI. Therefore, excluding the ground reflected radiation DHI and DNI are considered for calculating GHI. Equation 4.1 gives the estimation of GHI.

$$GHI = DHI + DNI\ [Cos\ (solar\ zenith\ angle)] \qquad (4.1)$$

Figure 4.1 shows the GHI, DHI, and DNI measurements (*Texas State Energy Conservation office, 2008*).

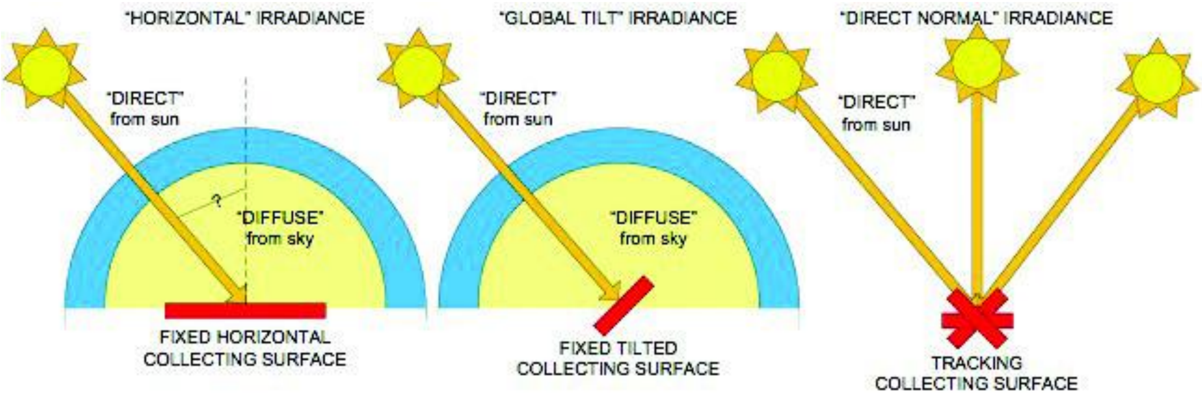

Figure 4.1 Measurement of GHI, DHI, and DNI

Solar zenith angle is the angle between the sun and the overhead point of the location where the irradiation. This angle is useful in determining the sunrise and sunset. Figure 4.2 (*City University of New York 2013*) shows the solar azimuth angle measurement.

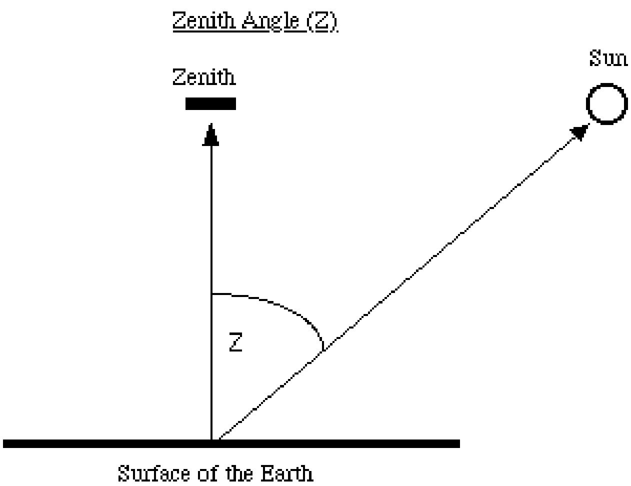

Figure 4.2 Solar Zenith Angle

4.3 Seasonal Variations of the Solar Radiation

Seasons are caused because of the tilt of earth on its axis. This controls the daylight length and solar irradiance reaching earth surface. Figure 4.3 (*National Oceanic and Atmospheric Administration, NOAA*) shows the tilted earth's elliptical orbit around the sun and cause of seasons. Duration of sunlight in summer is more than other seasons and the intensity is high because of the earth's tilt towards the sun. Figure 4.4 shows the chart developed for average solar irradiance during the second and first full months of spring (April), summer (July), fall (September), and winter (January) in Louisville. Meteorological data used to develop the chart is from weather analytics website. This website acquire the data from the weather station installed at Louisville international airport. This chart shows that solar radiation reaching earth's surface is high in summer and low in winter.

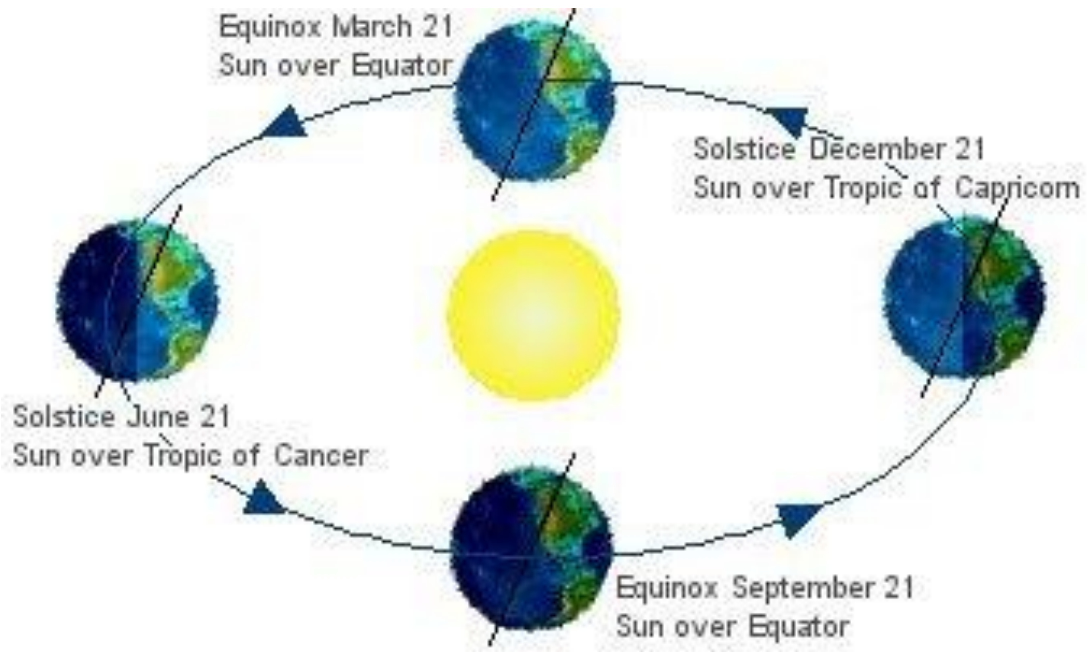

Figure 4.3 Earth's Tilt Cause of Season

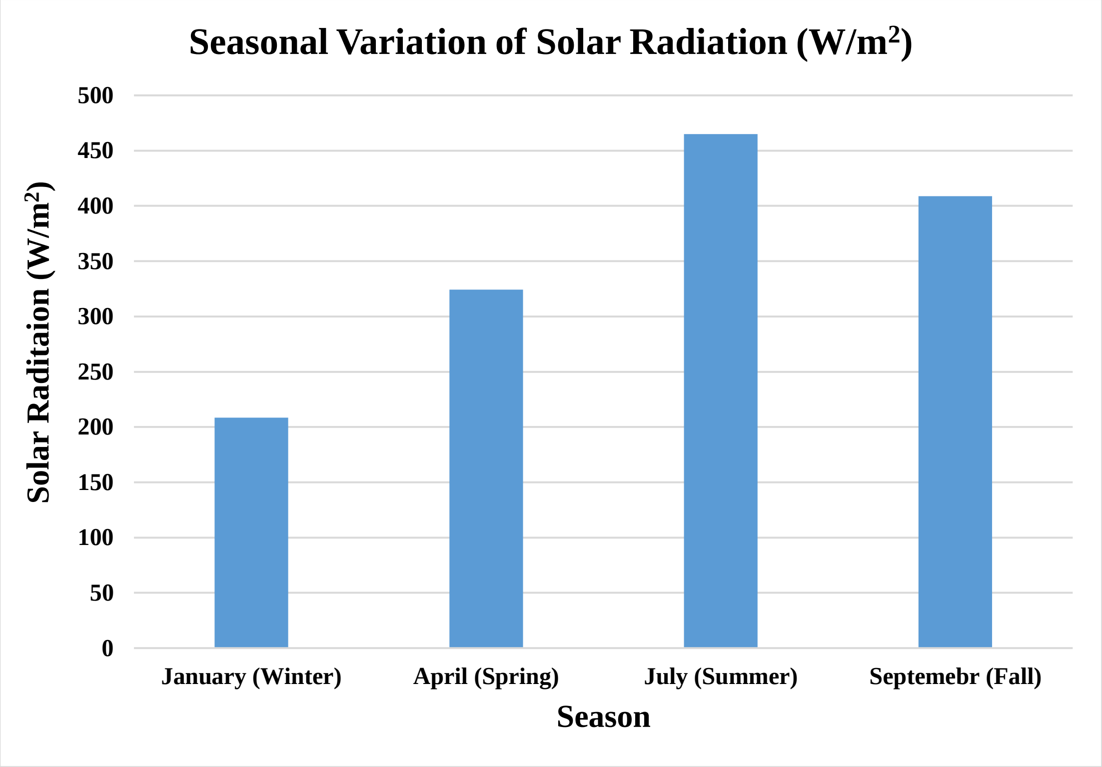

Figure 4.4 Seasonal Variation of Solar Radiation

4.4 Hourly Variations of Solar Radiation during the Day

Sunrise and sunset times varies based on the seasons. This occurs because of the earth's tilt. The variation of solar radiation during the day is due to the change of the solar zenith angle. Figure 4.5 (*International network for sustainable energy, INFORSE*) shows the seasonal variation of path of sun for the months June, December, March, and September. This shows the path of sun as nearest during month of June. This is the basic reason for summer. Figure 4.6 (*INFORSE*) shows the solar path during a day. The position of sun over the zenith during mid-day is the reason for maximum solar radiation reaching earth's surface.

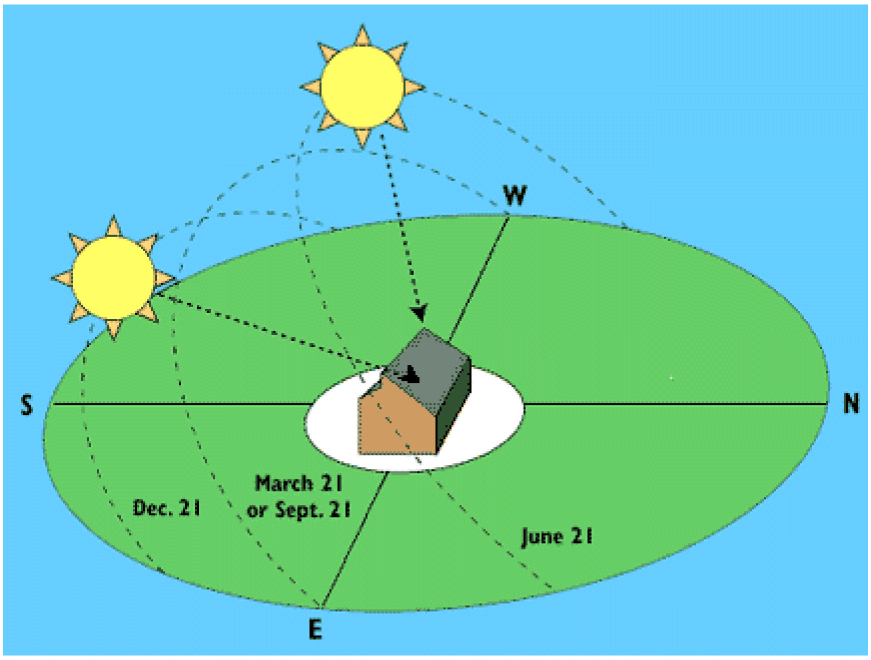

Figure 4.5 Seasonal Path of Sun

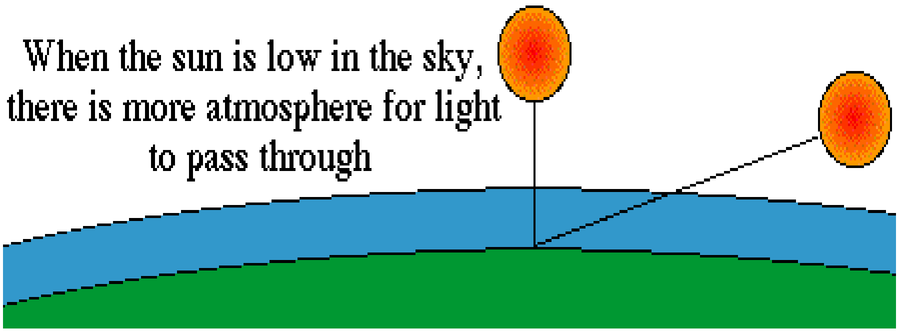

Figure 4.6 Hourly Path of Sun

Table 4-1 shows the hourly solar radiation values during a day at Louisville. Days selected are the starting days of seasons. The location of the weather measuring station is at Louisville airport whose latitude and longitude are 38.244 and -85.625. Whereas the latitude and longitude of the project site are 38.260 and -85.71. Figure 4.7 shows the chart developed showing the seasonal hourly variations of solar radiations in a day. This chart shows the maximum solar radiation between 1:00 pm an 4:00 pm and the zero value shows the solar radiation value before sunrise or after sunset. Whereas, there is a dissimilarity for fall season (2013-09-21) because of the high cloud cover recorded on that day. To demonstrate the relationship more clearly for fall season figure 4.8 is developed for the second day of fall season (2013-09-22) on which the cloud cover is minimal to zero. The effects of cloud cover on solar radiation is explained in *cloud cover* section.

Table 4-1 Seasonal Hourly Solar Radiation at Louisville

Hour	Solar Radiation (W/m^2)				
	Fall 2013		2013-12-21 (Winter)	2014-03-21 (Spring)	2014-06-21 (Summer)
	09-21	09-22			
0	0	0	0	0	0
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	10
7	0	0	0	0	118
8	24	122	0	79	292
9	89	323	8	281	460
10	276	516	27	436	582
11	417	671	13	612	715
12	468	776	8	714	806
13	503	815	13	738	831
14	517	797	24	672	790
15	696	698	41	390	639
16	523	527	39	301	491
17	330	325	18	198	355
18	129	128	0	94	224
19	0	0	0	0	110
20	0	0	0	0	10
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0

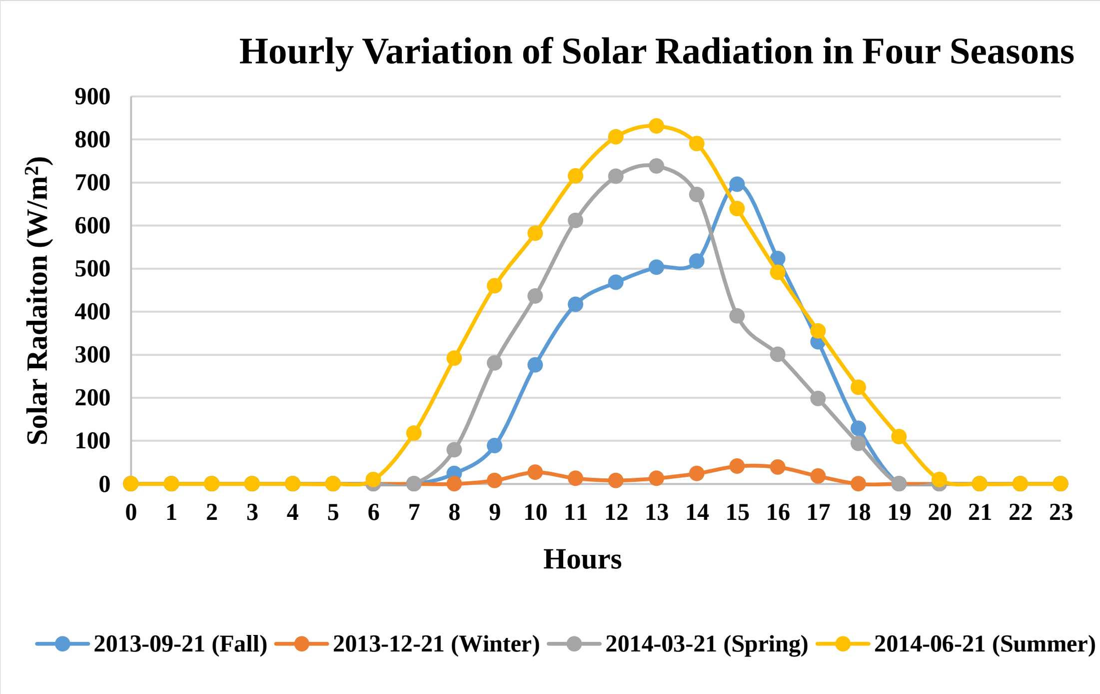

Figure 4.7 Hourly Variation of Solar Radiation on First Days of 4 Seasons

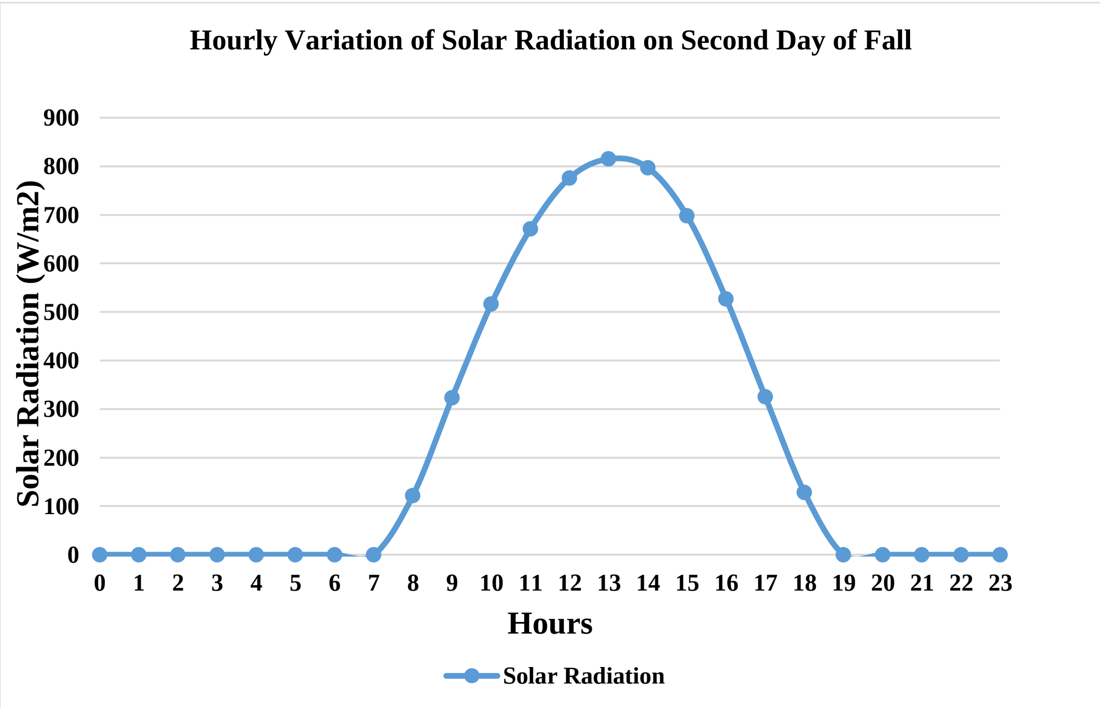

Figure 4.8 Hourly Variation of Solar Radiation on Second Day of Fall 2013

4.5 Cloud Cover

Cloud cover is the most important factor affecting the solar radiation reaching earth's surface. Amount of cloud cover is inversely proportional to the solar radiation reaching earth's surface. Cloud cover is measured in percentage and is measured by human observations. Table 4-3 shows the cloud cover (CC) and solar radiation (SIR) values for the start days of the seasons. Figures 4.9, 4.11, 4.12, and 4.13 are the charts showing the relationship between solar radiation and cloud cover during fall, winter, spring and summer. Figure 4.10 shows the chart developed for the second of fall 2013 to demonstrate the inverse relationship of solar radiation and cloud cover more clearly.

Table 4-2 Cloud Cover and Solar Radiation on First Days of Seasons

Hour	Fall				2013-12-21 (Winter)		2014-03-21 (Spring)		2014-06-21 (Summer)	
	2013-09-21		2013-09-22							
	SIR (W/m^2)	CC (%)	SIR (W/m^2)	CC (%)	SIR (W/m^2)	CC (%)	SIR (W/m^2)	CC (%)	SIR (W/m^2)	CC (%)
0	0	100	0	1	0	100	0	0	0	92
1	0	100	0	0	0	100	0	1	0	59
2	0	100	0	0	0	100	0	3	0	61
3	0	100	0	0	0	100	0	4	0	60
4	0	100	0	0	0	100	0	4	0	60
5	0	100	0	0	0	100	0	6	0	57
6	0	100	0	0	0	100	0	12	10	57
7	0	100	0	0	0	100	0	56	118	66
8	24	100	122	0	0	100	79	53	292	68
9	89	100	323	0	8	100	281	36	460	61
10	276	98	516	0	27	100	436	31	582	56
11	417	90	671	0	13	100	612	31	715	54
12	468	77	776	0	8	100	714	38	806	55
13	503	3	815	0	13	100	738	96	831	69
14	517	3	797	0	24	100	672	97	790	79
15	696	2	698	0	41	100	390	96	639	84
16	523	2	527	0	39	100	301	92	491	87
17	330	2	325	0	18	100	198	90	355	89
18	129	2	128	0	0	100	94	88	224	91
19	0	3	0	0	0	100	0	87	110	96
20	0	1	0	0	0	100	0	91	10	83
21	0	1	0	0	0	100	0	91	0	86
22	0	2	0	0	0	100	0	88	0	83
23	0	1	0	0	0	100	0	80	0	82

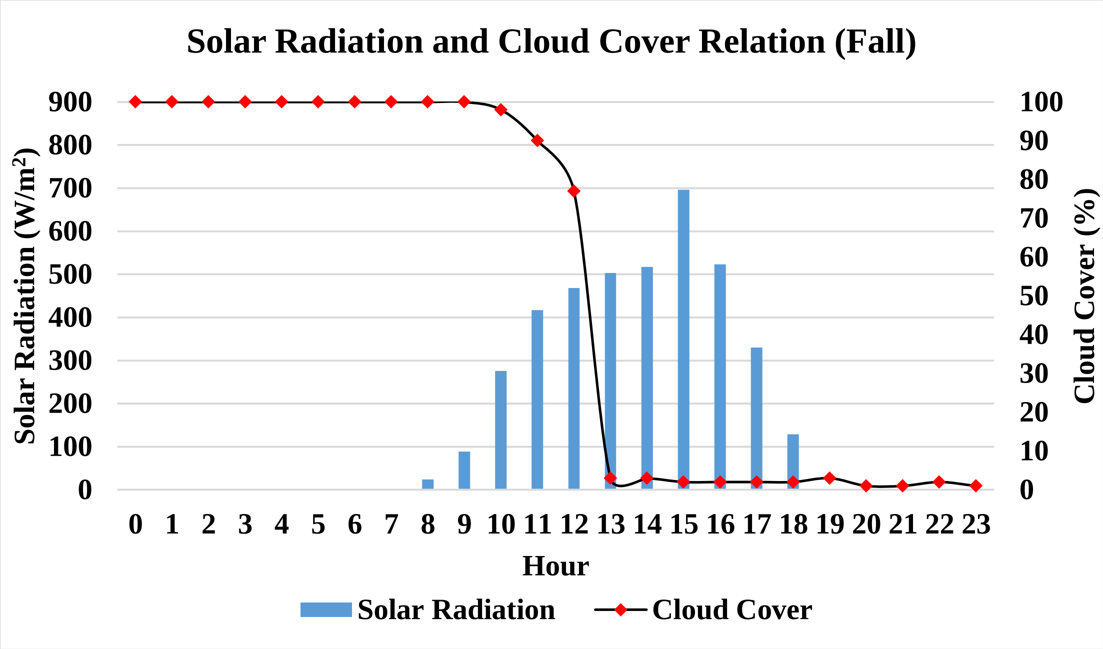

Figure 4.9 Hourly Relation of Solar Radiation and Cloud Cover in Fall (09-21-2013)

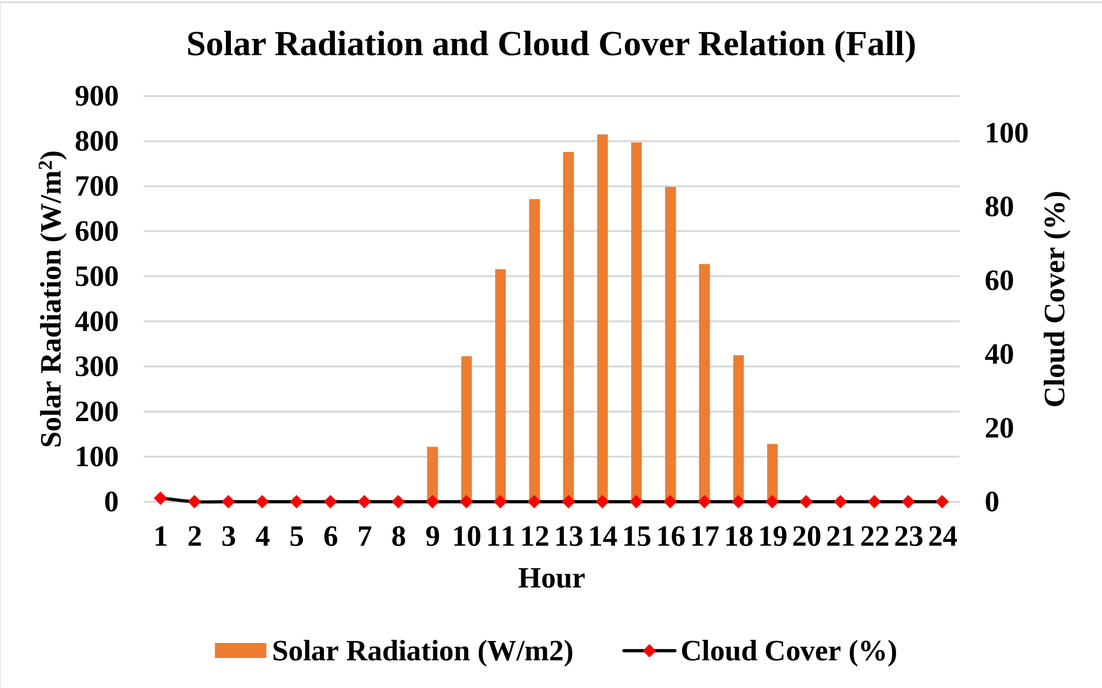

Figure 4.10 Hourly Relation of Solar Radiation and Cloud Cover in Fall (09-22-2013)

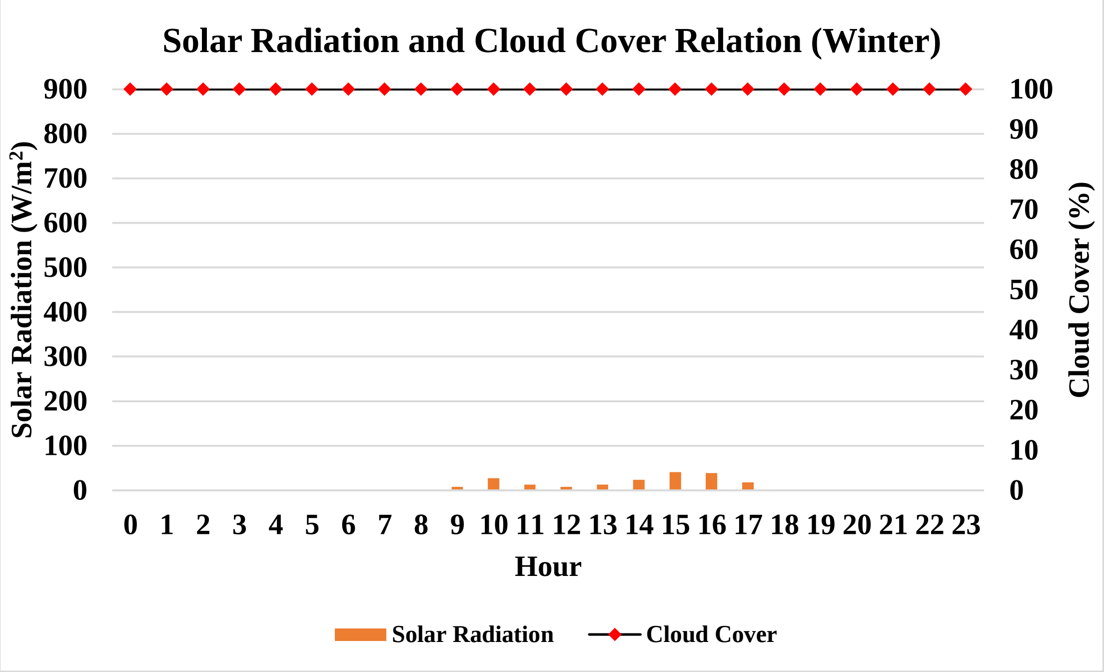

Figure 4.11 Hourly Relation of Solar Radiation and Cloud Cover in Winter (12-21-2013)

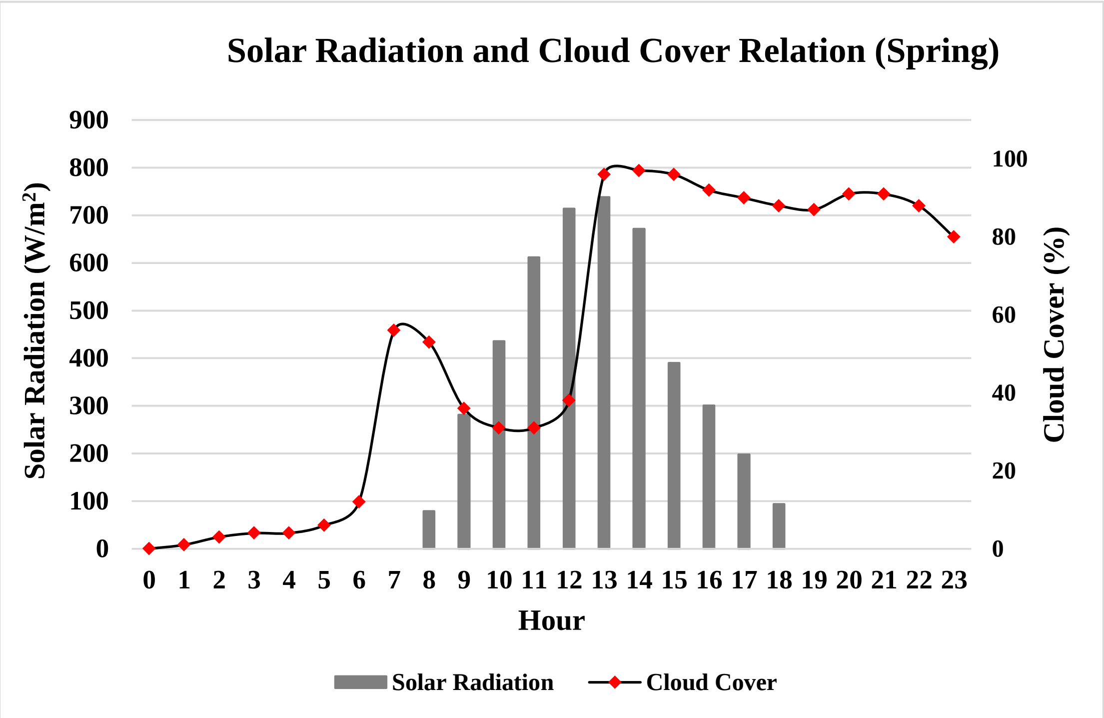

Figure 4.12 Hourly Relation of Solar Radiation and Cloud Cover in Spring (03-21-2014)

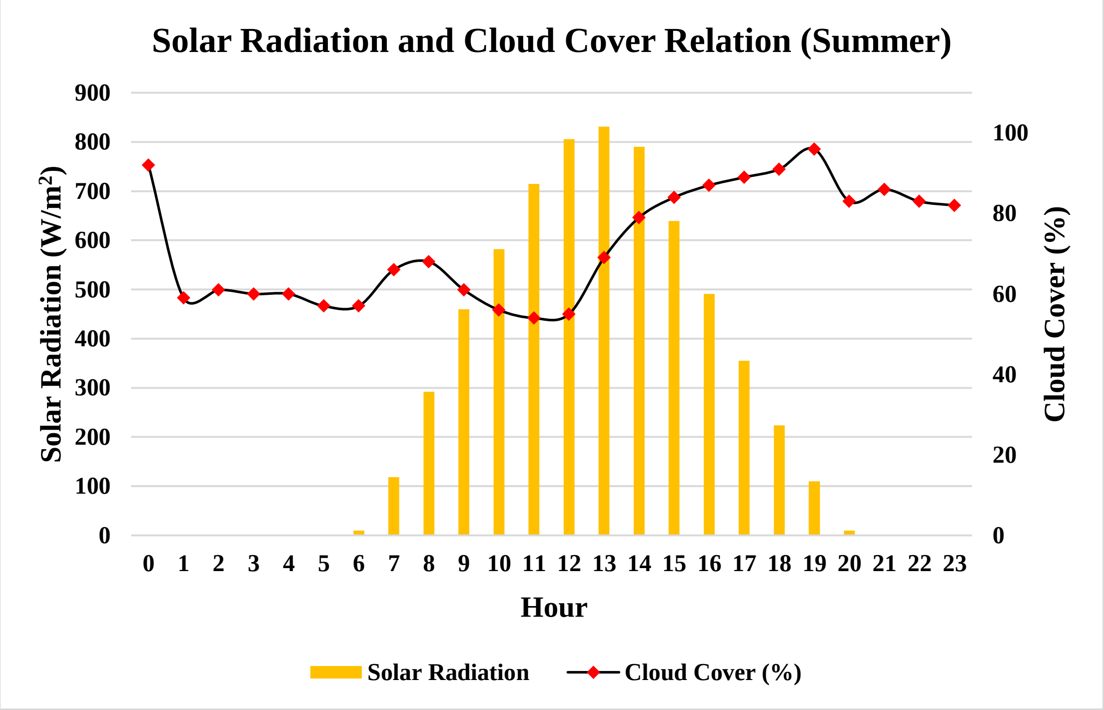

Figure 4.13 Hourly Relation of Solar Radiation and Cloud Cover in Summer (06-21-2014)

Temperature and Solar Radiation

Temperature is directly proportional to solar radiation. Temperature decreases with decrease in the solar radiation. Table 4-3 shows the hourly temperature and solar radiation values on the starting days of fall, winter, spring, and summer. Figures 4.14, 4.15, 4.16, and 4.17 shows the relation between hourly solar radiation and temperature.

Table 4-3 Hourly Variations of Temperature and Solar Radiation

Hours	2013-09-21 (Fall)		2013-12-21 (Winter)		2014-03-21 (Spring)		2014-06-21 (Summer)	
	Temp (F)	SIR (W/m^2)	Temp (F)	SIR (W/m^2)	Temp (F)	SIR (W/m^2)	Temp (F)	SIR (W/m^2)
0	68	0	60.2	0	41.9	0	68.2	0
1	65.9	0	61.5	0	43.5	0	70.3	0
2	65	0	61.1	0	42.5	0	69.3	0
3	63.7	0	60.4	0	41.7	0	67.7	0
4	62.4	0	60.5	0	40.7	0	67.6	0
5	61	0	61	0	40	0	69.1	0
6	59.3	0	61.7	0	39.9	0	72	10
7	59.7	0	60.2	0	44.5	0	75.2	118
8	59.3	24	61	0	49.9	79	79.4	292
9	61.1	89	61.5	8	54.3	281	83.2	460
10	66.1	276	61.8	27	58.6	436	85.5	582
11	70.1	417	62.4	13	61.4	612	87.2	715
12	72.4	468	63	8	63.2	714	88.6	806
13	72.2	503	62.7	13	66.5	738	89.9	831
14	72.6	517	64.2	24	66	672	89.7	790
15	72.1	696	65.2	41	65.1	390	88.7	639
16	70.5	523	65	39	62.9	301	87.3	491
17	66.2	330	65	18	58.7	198	85.2	355
18	59.6	129	65.4	0	54.3	94	80.5	224
19	58.8	0	65.8	0	54.5	0	71.1	110
20	56.7	0	66.6	0	53.4	0	66.1	10
21	54.7	0	67.7	0	52.1	0	65.8	0
22	54.3	0	67.4	0	51.7	0	65.3	0
23	53.8	0	66.6	0	51.3	0	66.5	0

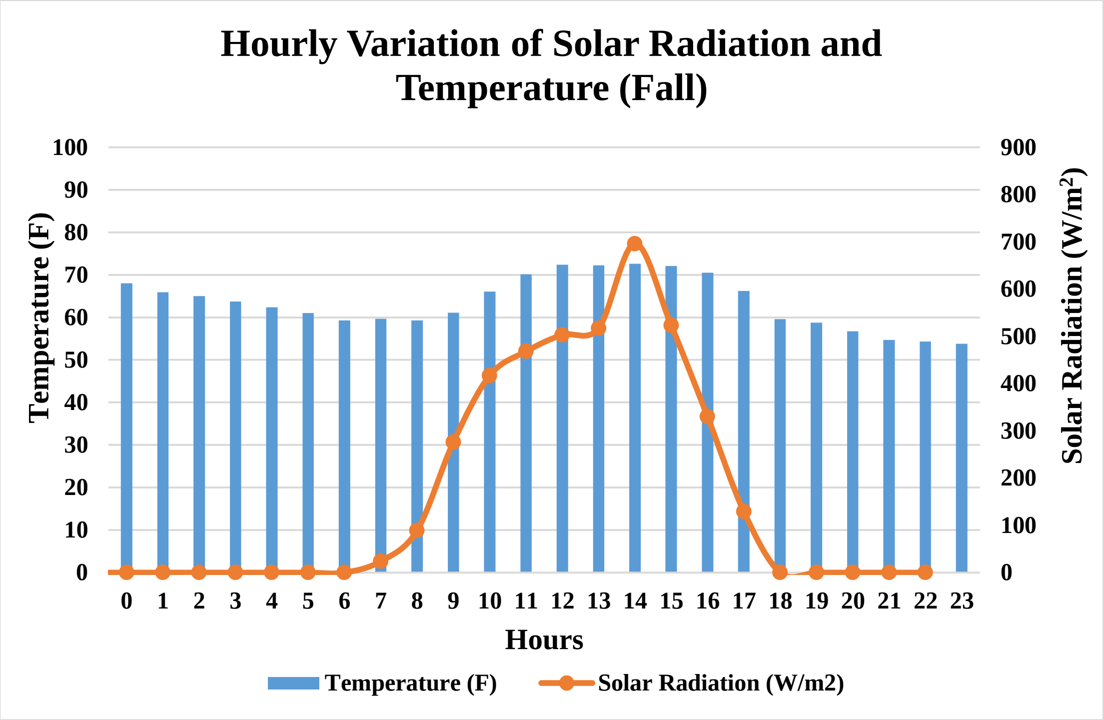

Figure 4.14 Hourly Variations of Temperature and Solar Radiation in Fall

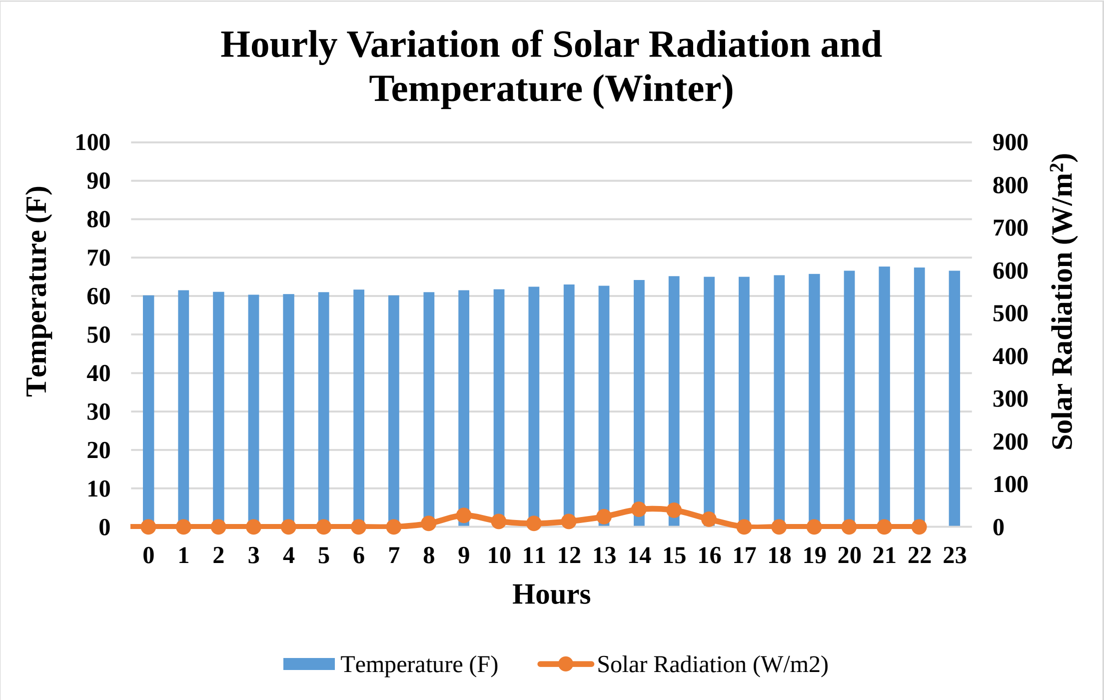

Figure 4.15 Hourly Variations of Temperature and Solar Radiation in Winter

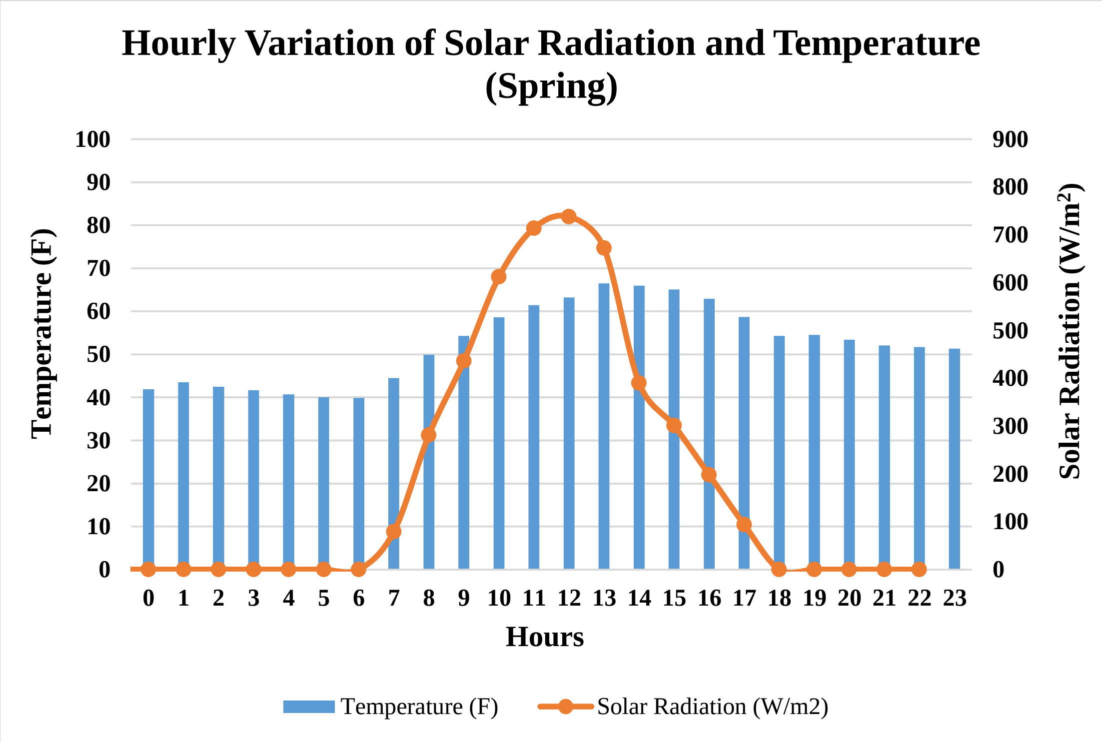

Figure 4.16 Hourly Variations of Temperature and Solar Radiation in Spring

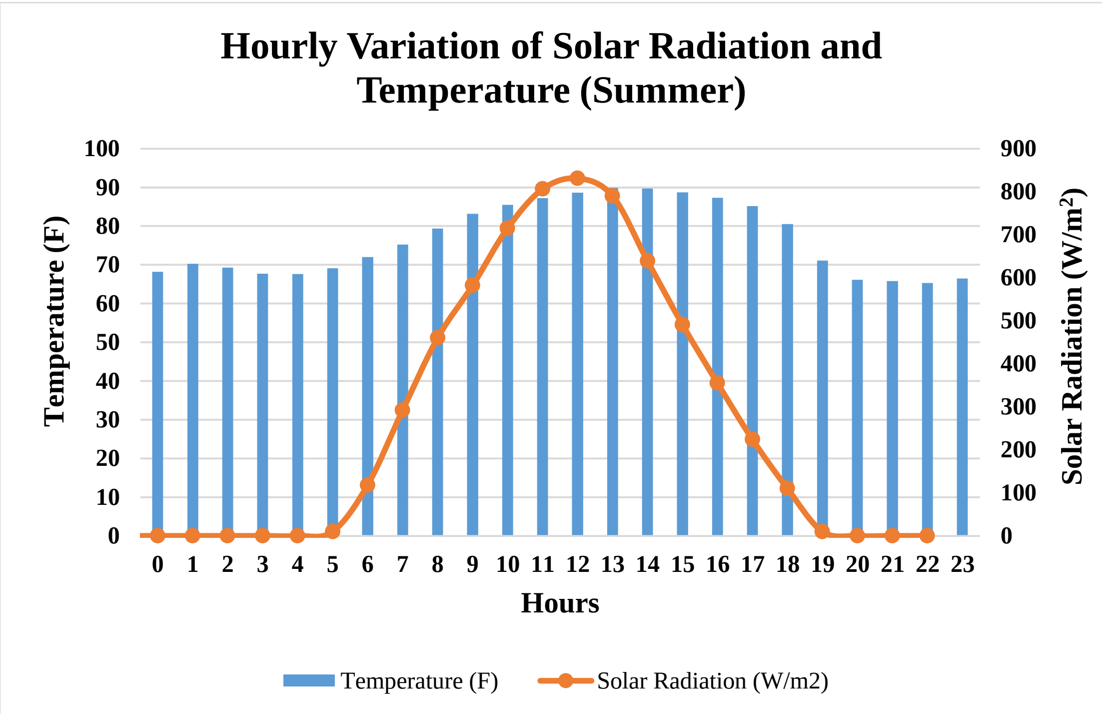

Figure 4.17 Hourly Variations of Temperature and Solar Radiation in Summer

Conclusion

From the above data and results it is learnt that the solar radiation reaching earth surface at a given time is dependent on the season, time of the day, and cloud cover at that time. Temperature increases with increase in solar radiation. For SODIS solar radiation and temperature are important factors. In addition, temperature is dependent on solar radiation. Therefore, a condition of no cloud cover and maximum solar radiation and temperature is ideal condition for carrying out SODIS experiments. However, this may not be achievable throughout the year and better conditions are possible during summer days. Chapter 5 discusses the solar radiation effects on disinfection of water.

5 RESULTS AND DISCUSSION

5.1 Introduction

This chapter discusses the *E. coli* concentration changes before and after filtration system and disinfection system separately. A discussion on individual performance of four filters, individual performance of four solar troughs in reducing *E.* coli concentration at different water flow rates at different solar irradiance values are done in this chapter.

Water samples are collected at the filters' inlets, outlets that are troughs' inlets, and troughs' outlets. Twelve samples were collected and tested per sampling event. Four samples are at inlets of filters that is one at each filter inlet; four samples at filter outlet or trough inlet that is one sample at each filter outlet and trough inlet; and four samples at the end of the period or water reaching the desired flow depth.

5.2 Filtration Performance

Four different filters comprising of three different filter materials in different configurations are tested. Table 5-1 gives the filter specifications and the title given to them. Filters' results and performance are discussed individually and the better-performing filter is discussed.

Table 5-1 Filter Specifications and Titles

Filter	Filter Media (cm)	Title
1	Gravel – 27.94; Oyster Shells – 17.78; Sand – 8.89	F1
2	Gravel – 27.94; Oyster Shells – 15.24; Activated Charcoal – 8.89	F2
3	Gravel – 27.94; Activated Charcoal – 17.78	F3
4	Gravel – 27.94; Oyster Shells – 17.78	F4

5.2.1 Filter 1

Filter 1 is comprised of gravel in the bottom, oyster shells over it and sand on the top. A maximum of 2.43-log (99.63%) reduction of *E. coli* concentration is achieved. Table 5-2 gives the *E.coli* concentration in water flowing in and flowing out of F1 along with the percent and log reduction of the *E. coli* concentration in 2014. Figure 5.1 is the chart developed from the Table 5-2 data.

Table 5-2 Filter 1 Performance in E. coli Concentration Reduction in 2014

Sampled Days	*E. coli* Concentration (CFU/100ml)		*E. coli* Reduction	
	Into Filter	Out of Filter	Percent	Log
30-May	8300	3120	62.41	0.42
04-Jun	910	160	82.42	0.75
06-Jun	820	500	39.02	0.21
10-Jun	1100	870	20.91	0.10
12-Jun	7900	1200	84.81	0.82
16-Jun	660	240	63.64	0.44
17-Jun	290	40	86.21	0.86
01-Jul	490	60	87.76	0.91
03-Jul	8040	30	99.63	2.43
03-Jul	6080	30	99.51	2.31
06-Jul	620	20	96.77	1.49
09-Jul	2930	180	93.86	1.21
16-Jul	1330	290	78.20	0.66
26-Jul	620	40	93.55	1.19
01-Aug	920	110	88.04	0.92
02-Aug	150	10	93.33	1.18
13-Aug	3700	428	88.43	0.94
15-Aug	330	60	81.82	0.74

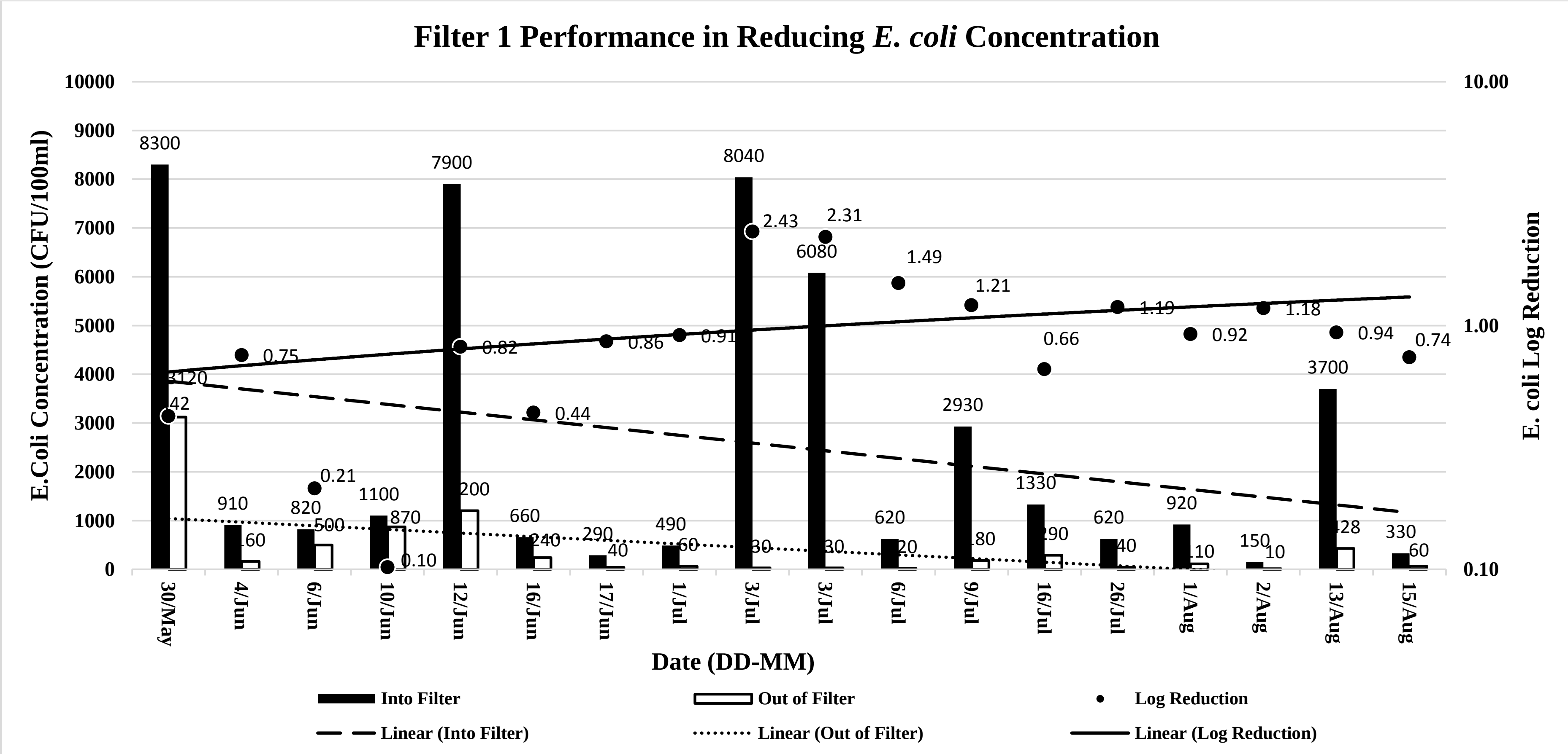

Figure 5.1 Filter 1 Performance in Reducing *E. coli* Concentration

Discussion

Filter 1 performance in reducing *E. coli* concentration improved over time this may be because of the development of the bio film *Schmutzdecke* and low pore size. Usage of fine grain sand sometimes resulted in blockage of the filter. Sedimentation was not done prior to filters. This allowed suspended particles to enter into filters and was observed that the sediment is a reason for blocking the pores that are already small because of the fine sand. At its peak performance (3^{rd} July – 9^{th} July), filter 1 is effective in reducing *E. coli* concentration. This helped in reducing the *E. coli* loading on solar disinfection system.

5.2.2 Filter 2

Filter 2 is comprised of gravel in the bottom, oyster shells over it and activated charcoal on the top. A maximum of 1.27-log (94.65%) reduction in *E. coli* concentration was achieved. Table 5-3 gives the E.coli concentration in water flowing in and flowing out of filter 2 along with the percent and log reduction of the *E. coli* concentration. Figure 5.2 is the chart developed from the Table 5-3 data.

Table 5-3 Filter 2 Performance in E. coli Concentration Reduction in 2014

Sampled Days	*E. coli* Concentration (CFU/100ml)		*E. coli* Reduction	
	Into Filter	Out of Filter	Percent	Log
30-May	7800	6470	17.05	0.08
4-Jun	600	260	56.67	0.36
6-Jun	720	150	79.17	0.68
6-Jun	760	500	34.21	0.18
10-Jun	1260	370	70.63	0.53
12-Jun	7900	7100	10.13	0.05
16-Jun	520	490	5.77	0.03
17-Jun	360	230	36.11	0.19
25-Jun	4800	2900	39.58	0.22
1-Jul	390	200	48.72	0.29
3-Jul	7600	440	94.21	1.24
3-Jul	5700	2040	64.21	0.45
6-Jul	580	220	62.07	0.42
9-Jul	2110	710	66.35	0.47
16-Jul	1260	1030	18.25	0.09
26-Jul	490	220	55.10	0.35
1-Aug	940	80	91.49	1.07
2-Aug	140	10	92.86	1.15
13-Aug	1780	640	64.04	0.44
15-Aug	350	80	77.14	0.64
19-Aug	1800	184	89.78	0.99
22-Aug	670	68	89.85	0.99
23-Aug	7300	564	92.27	1.11
25-Aug	1670	172	89.70	0.99
26-Aug	1870	100	94.65	1.27

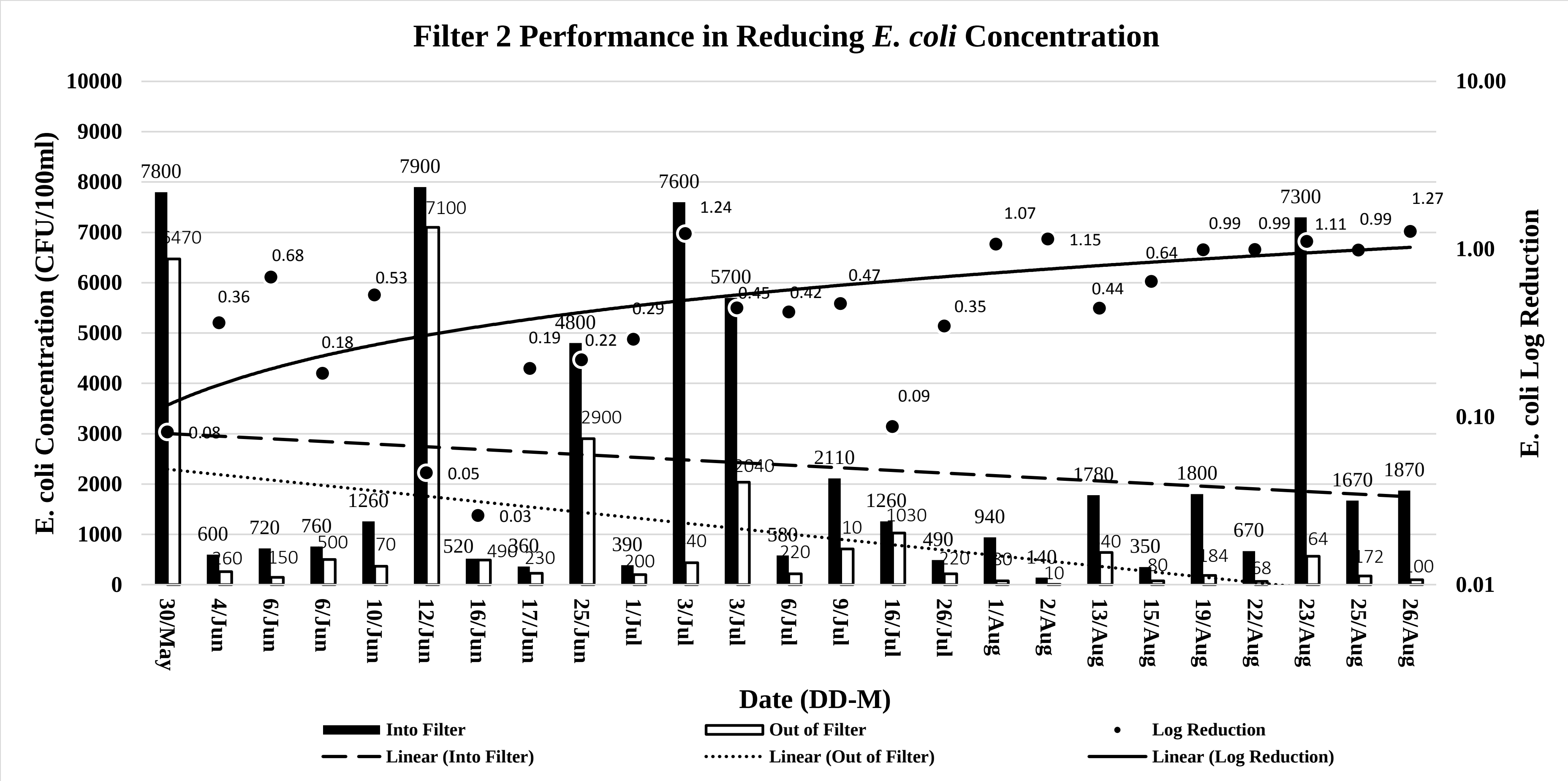

Figure 5.2 Filter 2 Performance in Reducing *E. coli* Concentration

Discussion

A maximum of the 1.27-log reduction is achieved in filter 2. But, there are no events of blockage of the filter. This is due to the usage of activated charcoal, which is an adsorbing agent. Usage of activated charcoal also helped in reducing the E. coli concentration because of adsorption. Using of crushed oyster shells as a filter material also created more pore size and helped in avoiding blockage.

5.2.3 Filter 3

Filter 3 is comprised of gravel in the bottom, and activated charcoal on the top. A maximum of 1.08-log (91.67%) reduction in *E. coli* concentration is achieved. Table 5-4 gives the *E. coli* concentration in water flowing in and flowing out of filter 3 along with the percent and log reduction of the *E. coli* concentration. Figure 5.3 is the chart developed from the Table 5-4 data.

Table 5-4 Filter 3 Performance in E. coli Concentration Reduction in 2014

Sampling Day	E. coli Concentration (CFU/100ml)		E. coli Reduction	
	Into Filter	Out of Filter	Percent	Log
30-May	9530	6340	33.47	0.18
4-Jun	540	410	24.07	0.12
6-Jun	550	510	7.27	0.03
10-Jun	1420	310	78.17	0.66
12-Jun	8280	5720	30.92	0.16
16-Jun	540	470	12.96	0.06
17-Jun	360	220	38.89	0.21
1-Jul	350	90	74.29	0.59
3-Jul	7500	1000	86.67	0.88
3-Jul	5200	1170	77.50	0.65
6-Jul	520	290	44.23	0.25
9-Jul	2860	1210	57.69	0.37
16-Jul	1340	1070	20.15	0.10
26-Jul	420	280	33.33	0.18
1-Aug	1010	240	76.24	0.62
2-Aug	120	10	91.67	1.08
13-Aug	1810	800	55.80	0.35
15-Aug	360	120	66.67	0.48
19-Aug	1900	580	69.47	0.52
22-Aug	750	168	77.60	0.65
23-Aug	8600	2054	76.12	0.62
25-Aug	1580	632	60.00	0.40
26-Aug	1900	345	81.84	0.74

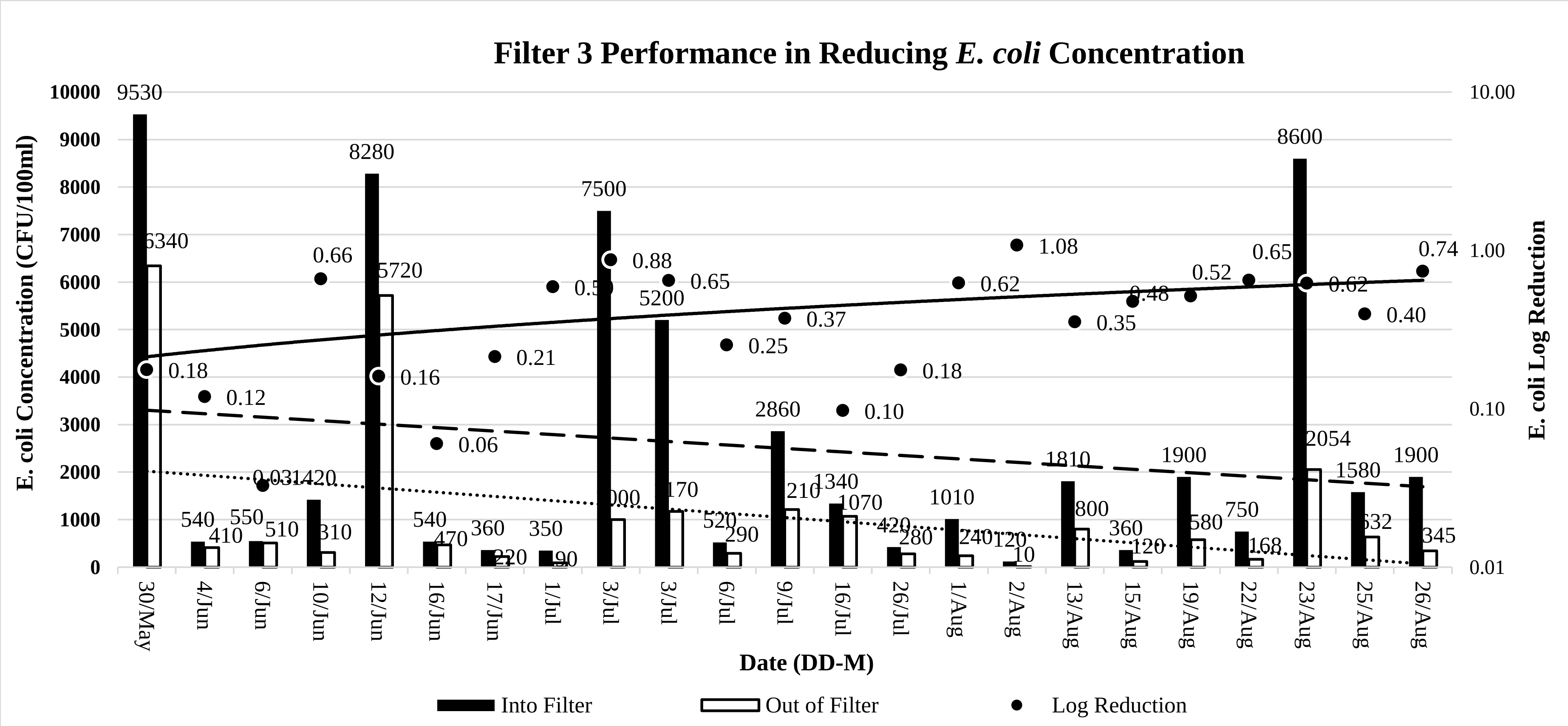

Figure 5.3 Filter 3 Performance in Reducing *E. coli* Concentration

Discussion

A maximum of the 1.08-log (91.67) reduction is achieved in filter 3. However, there are no events of blockage of the filter. Usage of activated charcoal helped in reducing the E. coli concentration because of adsorption.

5.2.4 Filter 4

Filter 4 is comprised of gravel in the bottom, and crushed oyster shells on the top. A maximum of 0.78-log (83.22%) reduction in *E. coli* concentration is achieved. Table 5-5 gives the *E. coli* concentration in water flowing in and flowing out of filter 4 along with the percent and log reduction of the *E. coli* concentration. Figure 5.4 is the chart developed from the Table 5-5 data.

Table 5-5 Filter 4 Performance in E. coli Concentration Reduction in 2014

Sampling Day	E. coli Concentration (CFU/100ml)		E. coli Reduction	
	Into Filter	Out of Filter	Percent	Log
30-May	9530	5150	45.96	0.27
4-Jun	530	250	52.83	0.33
6-Jun	530	90	83.02	0.77
6-Jun	840	510	39.29	0.22
10-Jun	1320	460	65.15	0.46
12-Jun	6580	5930	9.88	0.05
16-Jun	570	340	40.35	0.22
17-Jun	380	150	60.53	0.40
25-Jun	3570	3150	11.76	0.05
1-Jul	480	190	60.42	0.40
3-Jul	7330	1230	83.22	0.78
3-Jul	5140	1680	67.32	0.49
9-Jul	2290	890	61.14	0.41
16-Jul	1170	810	30.77	0.16
26-Jul	490	270	44.90	0.26
1-Aug	1040	480	53.85	0.34
2-Aug	210	70	66.67	0.48
13-Aug	1810	800	55.80	0.35
15-Aug	360	120	66.67	0.48
19-Aug	1900	580	69.47	0.52
22-Aug	750	168	77.60	0.65
23-Aug	8600	2054	76.12	0.62
25-Aug	1580	632	60.00	0.40
26-Aug	1900	345	81.84	0.74

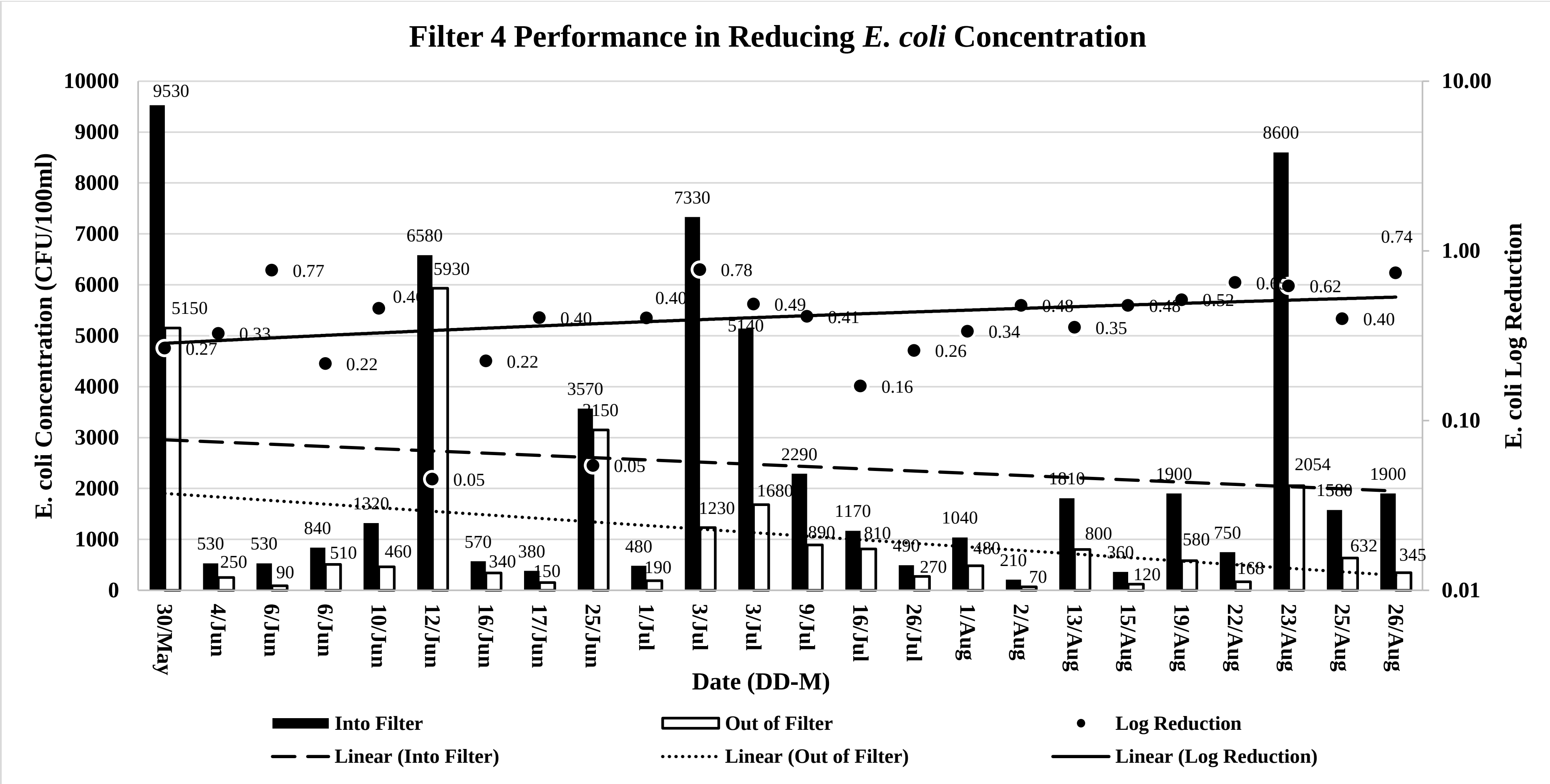

Figure 5.4 Filter 4 Performance in Reducing E. coli Concentration

Discussion

Filter 4 achieved a maximum of 0.78-log (83.22%) reduction in *E. coli* concentration. Filter 4's reduction of E. coli concentration never reached 1-log (90%). This is due to the high pore size than the other filters, because of the bigger particle size when compared to sand and activated charcoal.

5.2.5 Filtration discussion

Four filters comprised of three different filter materials in different proportions are tested in this project. All four filters are successful in reducing the *E.coli* concentration. However, filter 1 performed better than rest of three filters by achieving more than 2-log reduction in two events. Rest of the filters never achieved a 2-log reduction. Low pore size was created because of using fine sand in filter 1. This resulted in trapping more *E. coli* than the other three filters. In addition, the development of bio-layer on top of sand layer helped increase the reduction of *E. coli*. Development of bio-film is not observed in the other three filters. Based on the maximum percent reduction of *E. coli* during a single run filter 2 performed better than filters 3 and 4, and filter 3 performed better than filter 4. A statistical analysis was carried out on the *E.coli* reduction data to find out the better performing filter. The effect of the filters on the *E. coli* reduction is analysed at a significance level of 90%. A Box Cox transformation of the response variables was performed to make sure the residual's assumptions are maintained. With a p-value of 0.003, filter 1 is shown to be significant in reducing *E. coli*. A grouping value of A denotes most significant factor, grouping value B denotes less significant factor. Filter 1 managed a grouping value of A and the rest of the filters attained grouping value of B. This shows that filter 1 performed better than rest of the filters. However, filters 2 & 3 performed better than filter 4 in attaining greater percent reduction of *E. coli* in few runs. Considering all runs has shown that filters 2, 3, and 4 have same significant levels in reducing *E. coli.* Table 5-5A shows the grouping values.

Table 5-5A ANOVA Results on Filters' Performance

Filter	N	Mean	Grouping
1	18	81.26	A
2	25	64.56	B
3	24	58.42	B
4	23	57.98	B

5.3 Solar Disinfection (SODIS)

Solar disinfection is carried out by exposing water flowing in an open channel. Reason for adopting open channel is for utilizing all the solar radiation reaching the earth's surface at the project location. This section discusses the *E. coli* reduction due to the solar radiation in all the four troughs. Each trough is painted with different reflective materials and heat absorbing materials. Table 5-6 gives the paints in four troughs and the titles give to them for easy reference. Troughs' performance in four different testing conditions divided in two phases are discussed and the final discussion gives the trough that performed better than the other three troughs. Water flowing into troughs is water flowing out of filters. Therefore, the *E. coli* concentration in water flowing into troughs are the *E. coli* concentration in water flowing out of filters.

Table 5-6 Trough Specifications and Titles

Trough	Paint	Purpose	Title
1	White (Brush painted)	Best reflector, and cheap reflecting agent	T1
2	Aluminum (Spray painted)	Better reflector than White but expensive	T2
3	None	Left unpainted for control	T3
4	Black (Brush painted)	Absorbs more heat than other materials	T4

5.3.1 Phase I

In phase I the SODIS is tested as static batch system. This involved filling up the troughs up to 8 inches, which is equal to a volume of 113 gallons. Water is exposed to sunlight for 2 hours. Table 5-7 gives the *E. coli* concentration changes in troughs 1 and 2 during static system testing. Table 5-8 gives the *E. coli* concentration changes in troughs 3 and 4 during static system testing. Figures 5.5, 5.6, 5.7 and 5.8 are the charts developed by using the data from tables 5-7 and 5-8. This phase helped as pre-check for observing the effectiveness of SODIS in reducing the *E. coli* in water in an open channel trough, which is different from conventional closed transparent pipes SODIS concepts.

Table 5-7 E. coli Concentration Changes in Troughs 1 and 2 during Static Operation

		Trough 1				Trough 2			
		E. coli Concentration							
Date	Average Solar Radiation	Into the Trough	After 2 hours	Reduction		Into the Trough	After 2 hours	Reduction	
				Percent	Log			Percent	Log
13- May	549.50	670	10	98.51	1.83	1070	115	89.25	0.97
06 - May	776.50	30	1	96.67	1.48	1600	10	99.38	2.20
08 - May	819.00	460	15	96.74	1.49	1100	15	98.64	1.87

Table 5-8 E. coli Concentration Changes in Troughs 3 and 4 during Static Operation

		Trough 3				Trough 4			
		E. coli Concentration							
Date	Average Solar Radiation	Into the Trough	After 2 hours	Reduction		Into the Trough	After 2 hours	Reduction	
				Percent	Log			Percent	Log
13- May	549.50	900	160	82.22	0.75	930	192	79.35	0.69
06 - May	776.50	1630	10	99.39	2.21	1650	20	98.79	1.92
08 - May	819.00	1630	5	99.69	2.51	1370	25	98.18	1.74

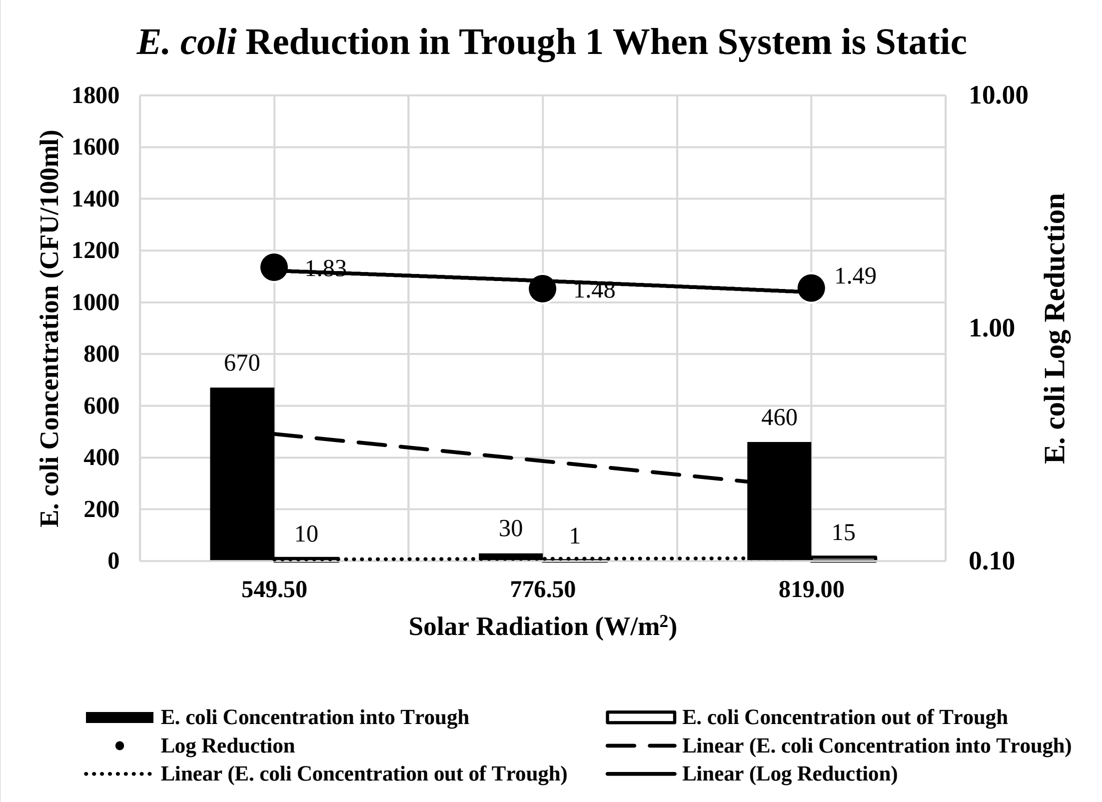

Figure 5.5 E. coli Concentration Changes in Trough 1 when System is Static

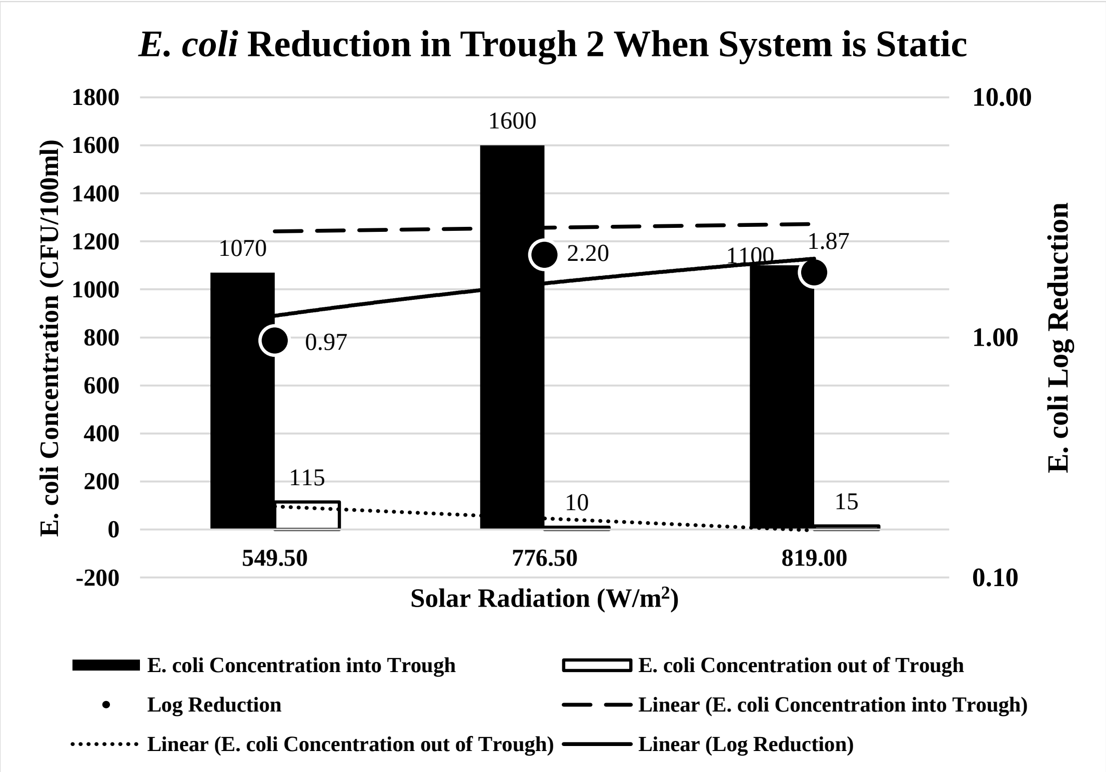

Figure 5.6 E. coli Concentration Changes in Trough 2 when System is Static

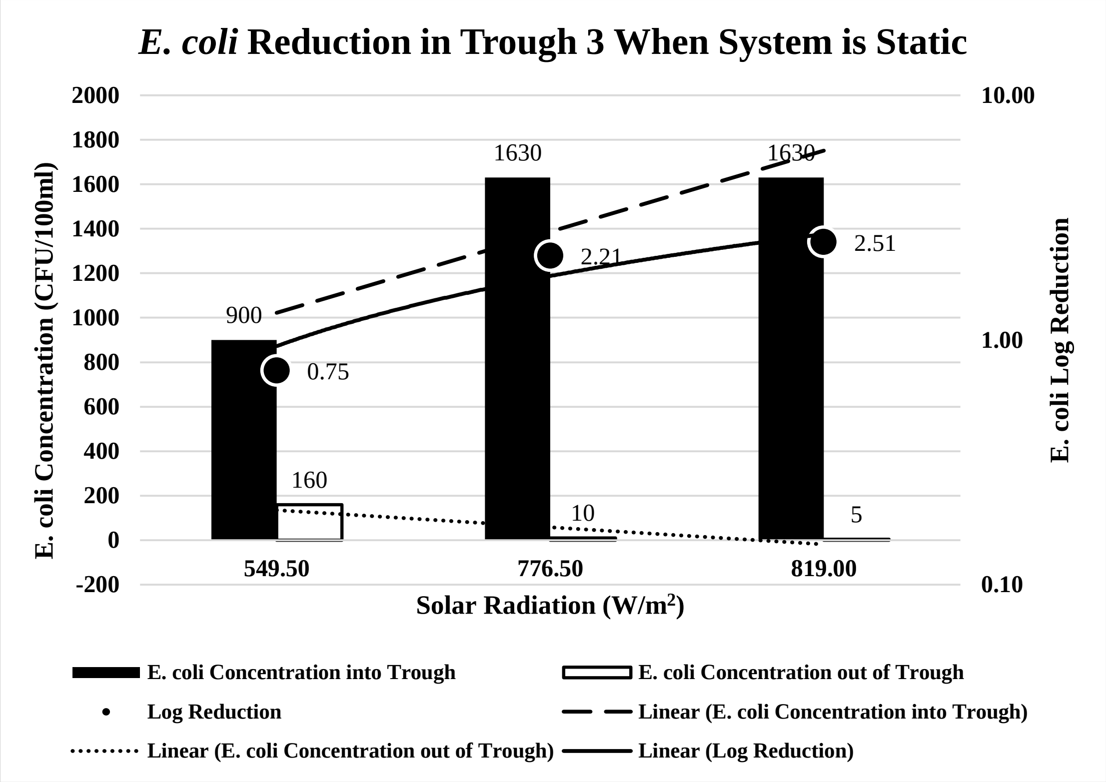

Figure 5.7 E. coli Concentration Changes in Trough 3 when System is Static

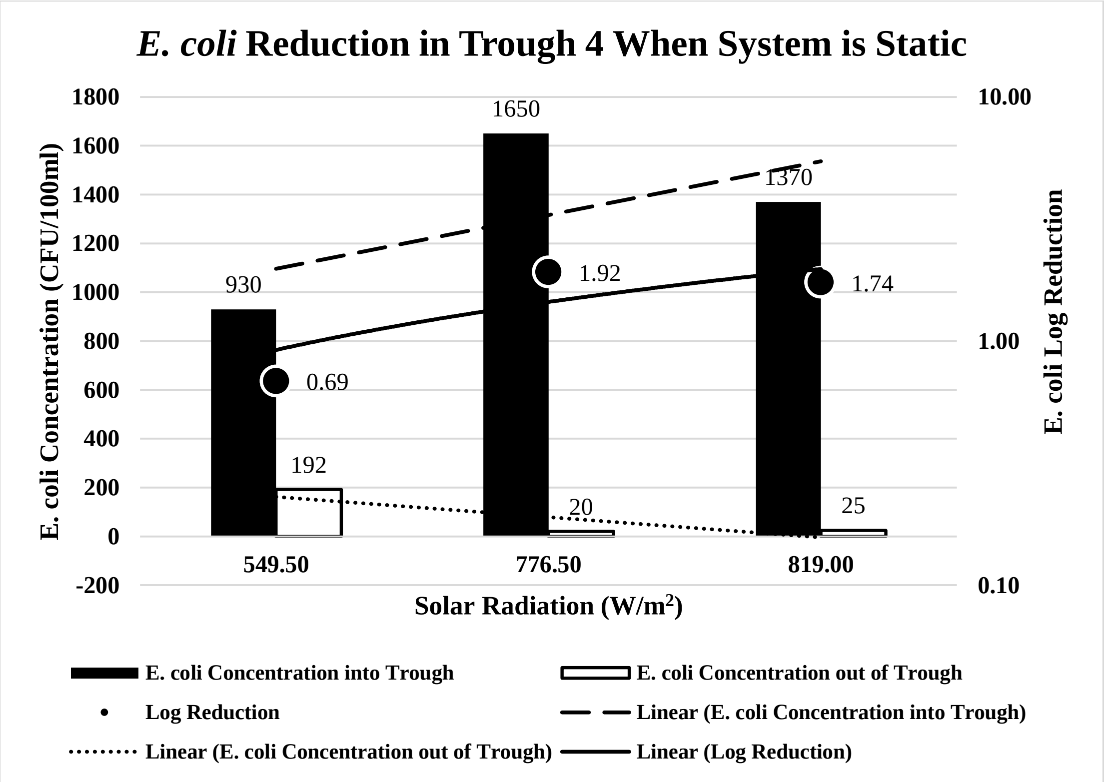

Figure 5.8 E. coli Concentration Changes in Trough 4 when System is Static

Discussion

All the troughs performed well in this phase. Whereas Trough 3 performed better in reducing the *E. coli* concentration in water with log reduction values higher than 2.0 in couple of events. This phase helped in finding out that *E. coli* concentration can be reduced in water when exposed to sunlight in open channel. Though it takes more time but financially viable. Results from this phase are not considered in the analysis for finding out the better performing trough in *E. coli* concentration reduction. Because, in phase II water was flowing at different flow rates.

5.3.2 Phase II

In phase II the SODIS is tested as dynamic system. This involved filling the troughs up to desired depth in different time intervals. Water depths of 8 inches (113 gallons of water), and 3.5 inches (36.15 gallons of water) are achieved in troughs in different intervals. Phase has three different scenarios. Results for each scenario is presented for all the four troughs in following section

5.3.2.1 Scenario I

Flow rate of 32.43 gal/hr is maintained into the troughs for 3.5 hrs to achieve a water depth of 8.0 inches. The system was started at 9:00 am on the day of testing and samples were collected at 12:30 pm. But the trough painted white that is attached to the filter 1 never achieved the desired flow depth because the fine grained sand used in the filter created low pore size and not allowed water pass through like the other filters. Tables 5-9, and 5-10 gives the *E. coli* concentration changes in trough 1 with respect to solar radiation, and pH, temperature respectively. Figures 5.9, 5.10 and 5.11 shows the graphical representation of the relation between *E.coli* concentration changes between water at input and output, with respect to average solar radiation, pH and temperature. Solid diamonds shows the *E. coli* concentration in water flowing out of the filter and flowing into the troughs. The solid circles show the reduction in *E. coli* concentration in troughs. Solid cross points represent the log reduction of the *E. coli* concentration. Negative log reduction is not shown in the charts because negative or zero values cannot be plotted correctly on log charts.

Table 5-9 E. coli Concentration Changes in Trough 1 in Scenario I

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
10 - June	381.6	870	650	220	25.29	0.13
30 – May	595.8	3120	1590	1530	49.04	0.29
12 – June	634	1200	166	1034	86.17	0.86
06 – June	666.8	1550	4	1546	99.74	2.59
07 – June	714.2	500	62	438	87.6	0.91
16 - June	727.8	240	36	204	85.0	0.82

Table 5-10 Water pH and Temperature Changes in Trough 1 in Scenario I

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Into Trough	Out of Trough	Into Trough	Out of Trough
10 - June	381.6	7.85	8.01	23.6	25.9
30 – May	595.8	7.77	7.98	23.9	26.6
12 – June	634	7.72	8.12	22.9	31.4
06 – June	666.8	7.74	8.39	22.3	32.1
07 – June	714.2	7.83	7.98	26.4	23.2
16 - June	727.8	7.72	7.89	21.9	24.8

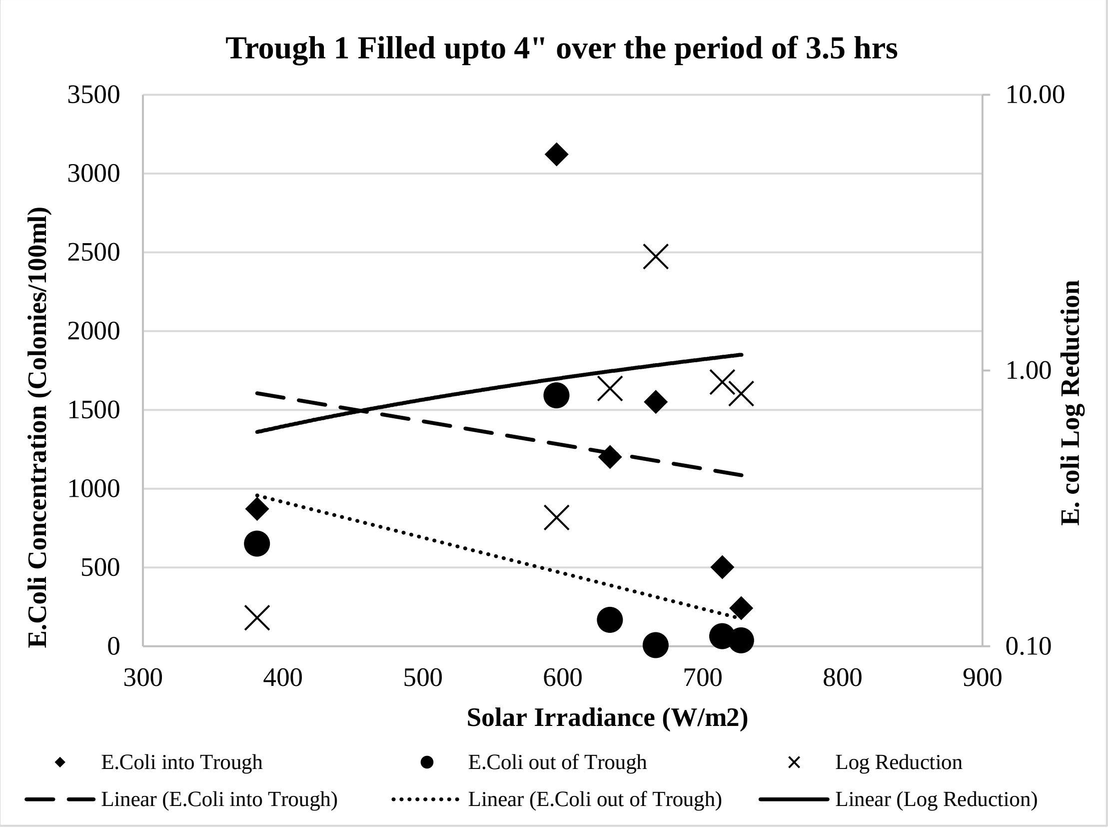

Figure 5.9 Change in E. coli Concentration in Trough 1 in Scenario I

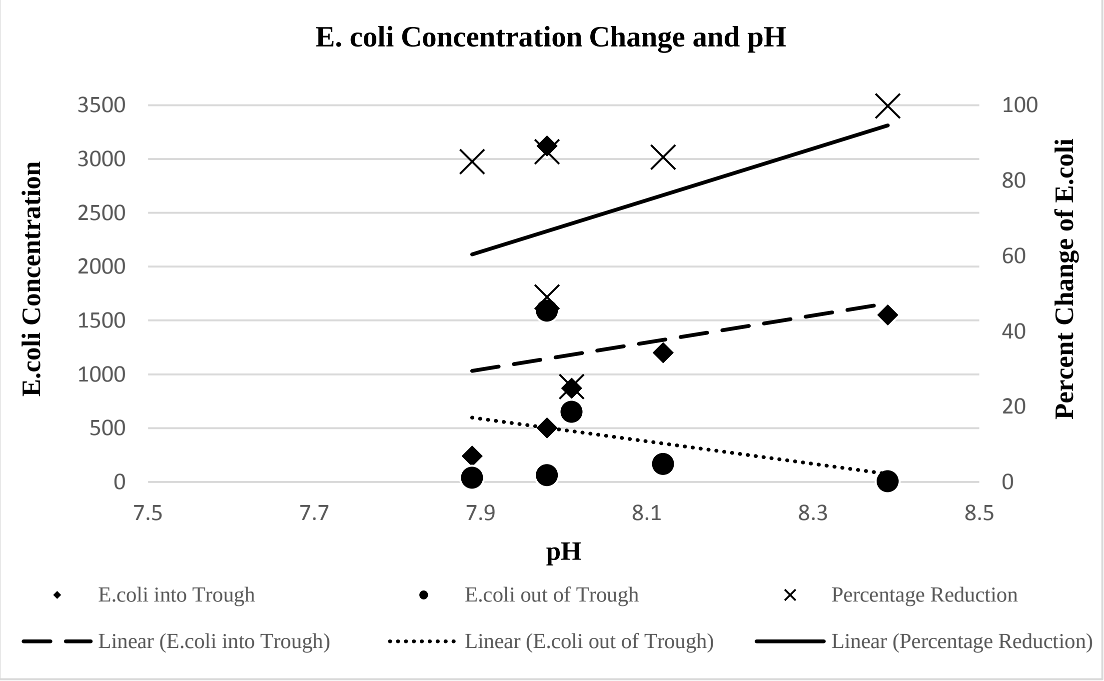

Figure 5.10 Relation between Water pH and E. coli Concentration Change in Trough 1

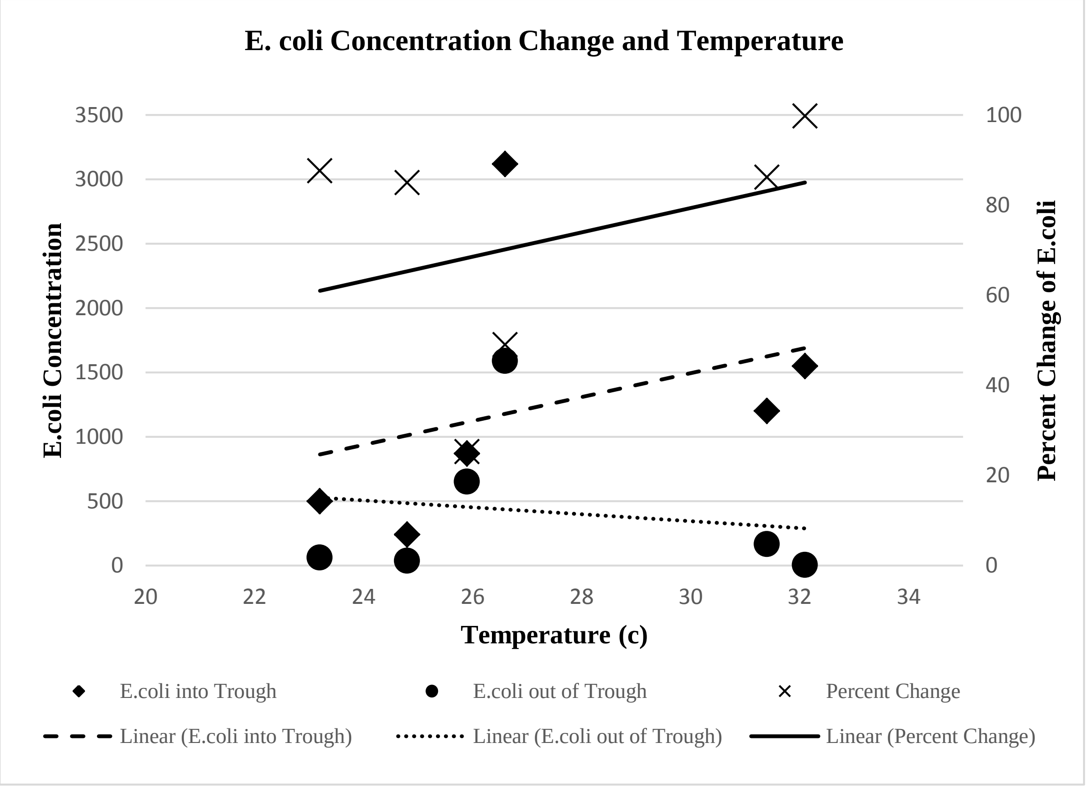

Figure 5.11 Relation between water Temperature and E. coli Concentration Change in Trough 1

Tables 5-11, and 5-12 gives the *E. coli* concentration changes in trough 2 with respect to solar radiation, and pH, temperature respectively. Figures 5.12, 5.13 and 5.14 shows the graphical representation of the relation between *E.coli* concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-11 E. coli Concentration Changes in Trough 2 when Flow is 32.3gal/hr for 3.5 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
10 - June	381.60	370	202	168	45.41	0.26
04 – June	536.40	260	210	50	19.23	0.09
30 – May	595.80	6470	2208	4262	65.87	0.47
12 – June	634.00	7100	2900	4200	59.15	0.39
07 – June	714.20	500	210	290	58.00	0.38
25 – June	721.00	2900	900	2000	68.97	0.51
16 - June	727.80	490	258	232	47.35	0.28
17 - June	871.20	230	176	54	23.48	0.12

Table 5-12 Water pH and Temperature Changes in Trough 2 in Scenario I

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-06-10	381.60	7.84	7.97	22.1	25.1
2014-06-04	536.40	7.88	7.95	24	26.8
2014-05-30	595.80	7.73	7.91	23.7	26.6
2014-06-12	634.00	7.8	7.84	22.7	28.6
2014-06-06	714.20	7.86	7.97	23.7	23.1
2014-06-25	721.00	7.65	7.89	24.9	26.5
2014-06-16	727.80	7.72	7.89	21.8	23.4
2014-06-17	871.20	7.84	8.12	23.7	25.1

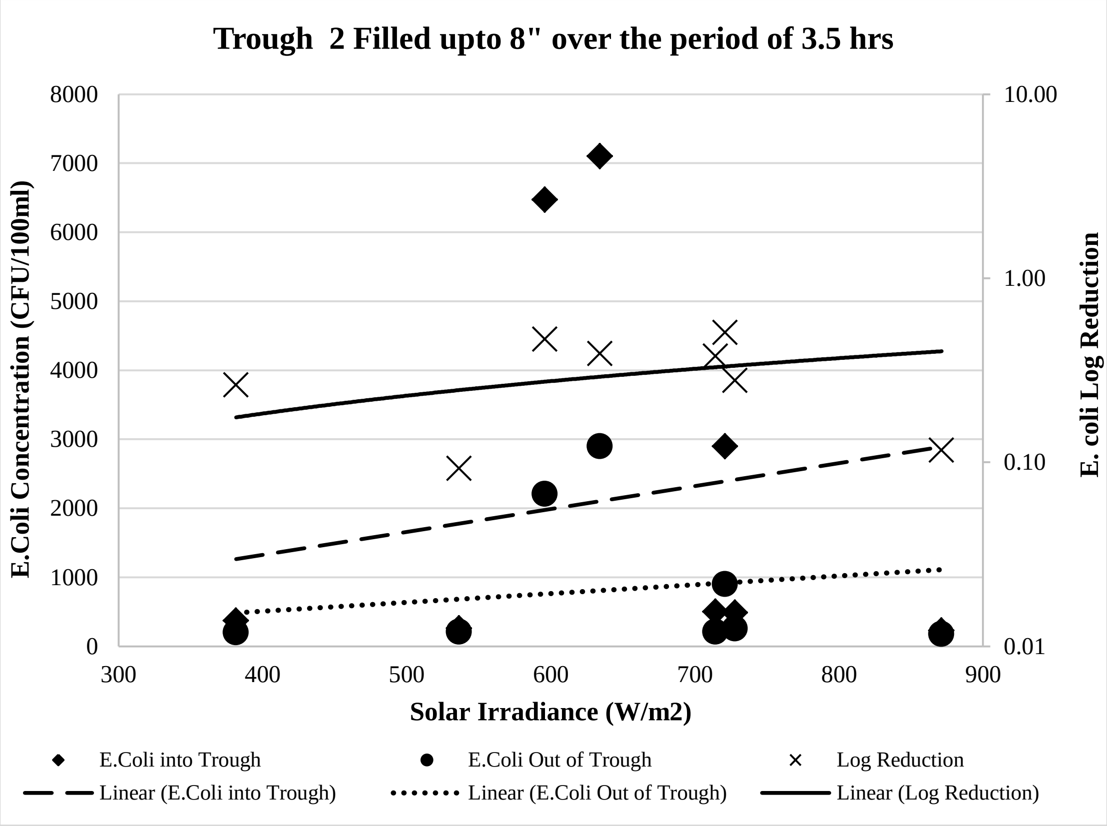

Figure 5.12 E. coli Concentration Changes in Trough 2 when Flow is 32.3gal/hr for 3.5 hrs

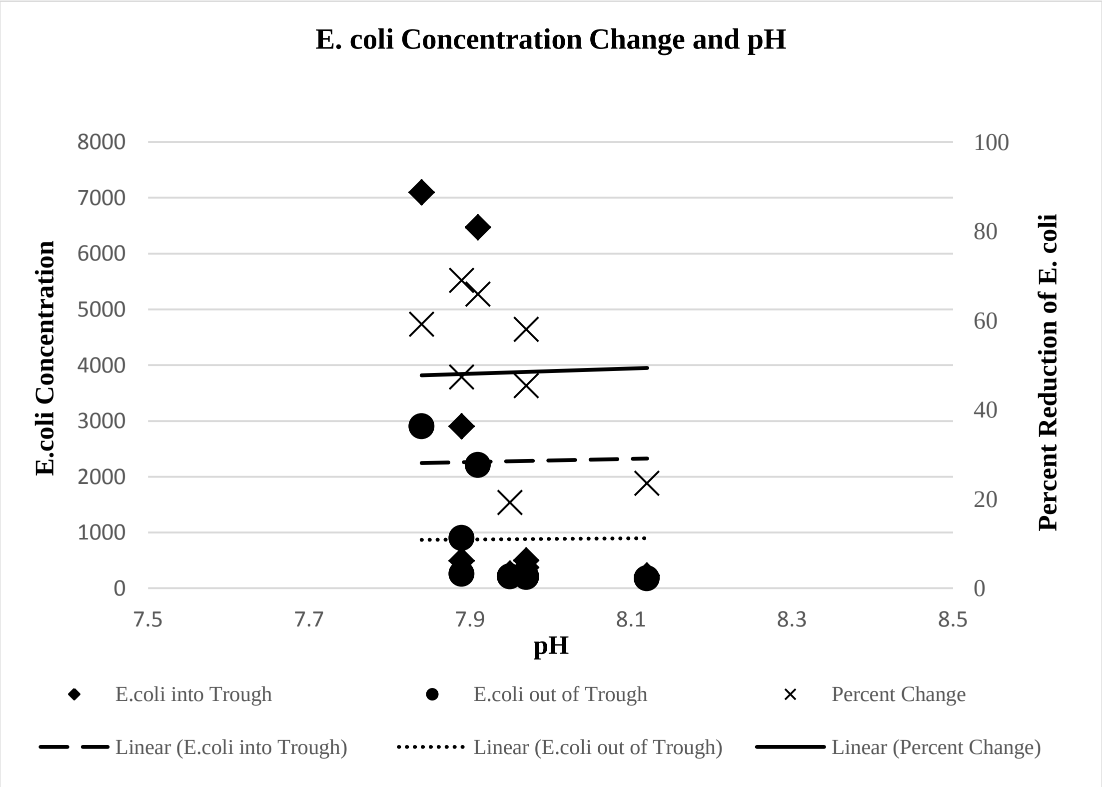

Figure 5.13 Relation between Water pH and E. coli Concentration Change in Trough 2

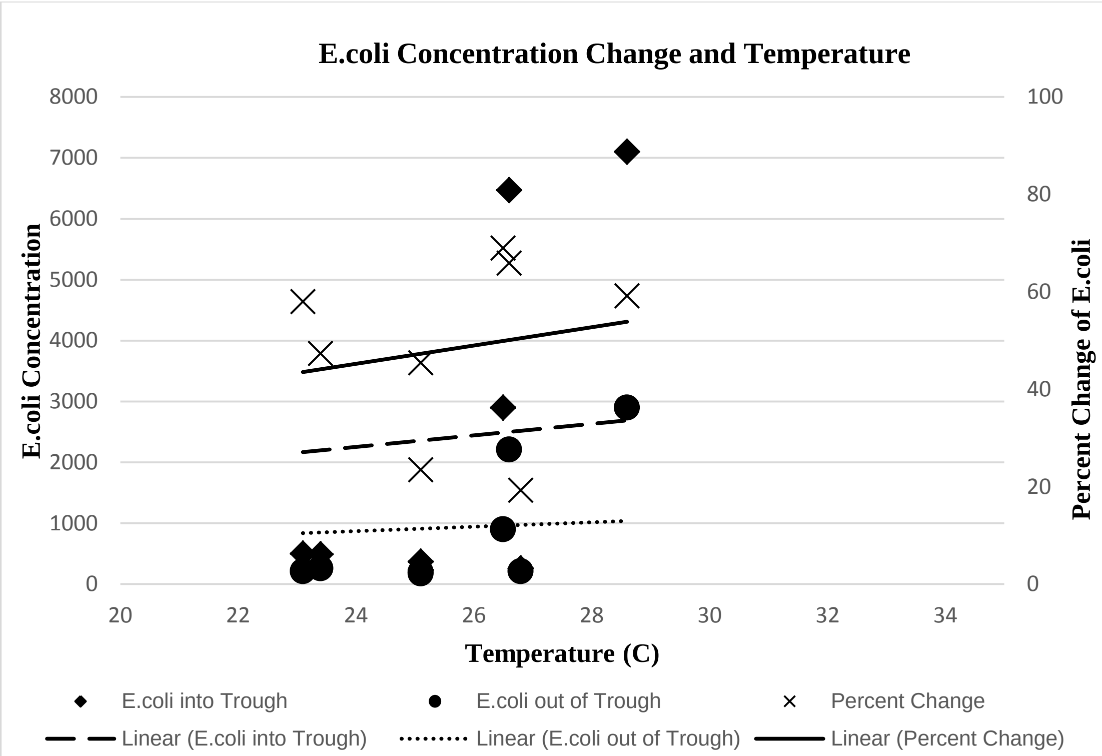

Figure 5.14 Relation between Water Temperature and E. coli Concentration Change in Trough 2

Tables 5-13, and 5-14 gives the *E. coli* concentration changes in trough 3 with respect to solar radiation, and pH, temperature respectively. Figures 5.15, 5.16 and 5.17 shows the graphical representation of the relation between *E.coli* concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-13 E. coli Concentration Changes in Trough 3 when Flow is 32.3gal/hr for 3.5 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
10 - June	381.60	310	206	104	33.55	0.18
04 – June	536.40	410	310	100	24.39	0.12
30 – May	595.80	6340	1970	4370	68.93	0.51
12 – June	634.00	5720	2020	3700	64.69	0.45
06 – June	666.80	510	354	156	30.59	0.16
07 – June	714.20	630	384	246	39.05	0.22
25 – June	721.00	4450	1600	2850	64.04	0.44
16 - June	727.80	470	172	298	63.40	0.44
17 - June	871.20	220	152	68	30.91	0.16

Table 5-14 Water pH and Temperature Changes in Trough 3 in Scenario I

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-06-10	381.60	7.82	7.97	21.9	24.6
2014-06-04	536.40	7.86	7.93	23.8	25.6
2014-05-30	595.80	7.71	7.84	24.1	26.3
2014-06-12	634.00	7.68	7.88	22.5	28.4
2014-06-06	666.80	7.81	7.96	22	27.8
2014-06-06	714.20	7.87	8.01	23.4	23
2014-06-25	721.00	7.65	7.89	25.1	29.2
2014-06-16	727.80	7.72	7.89	21.9	26.1
2014-06-17	871.20	7.84	8.12	24.2	28.9

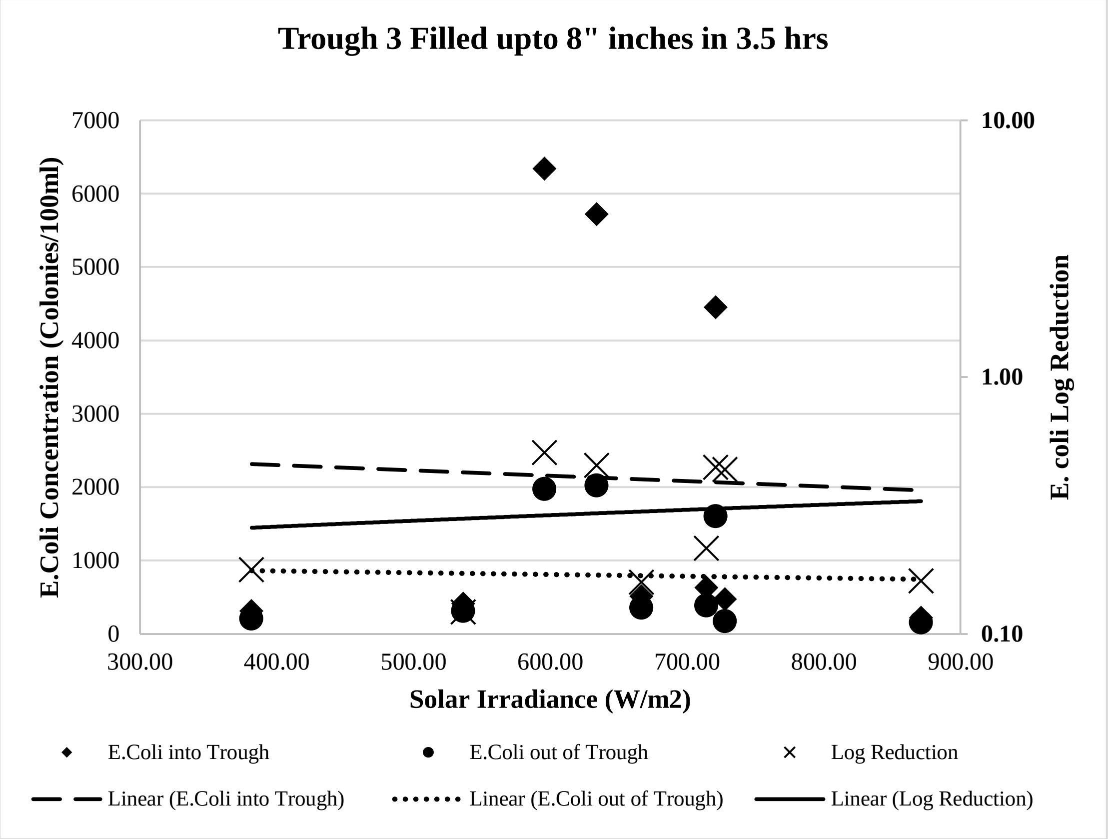

Figure 5.15 E. coli Concentration Changes in Trough 3 when Flow is 32.3gal/hr for 3.5 hrs

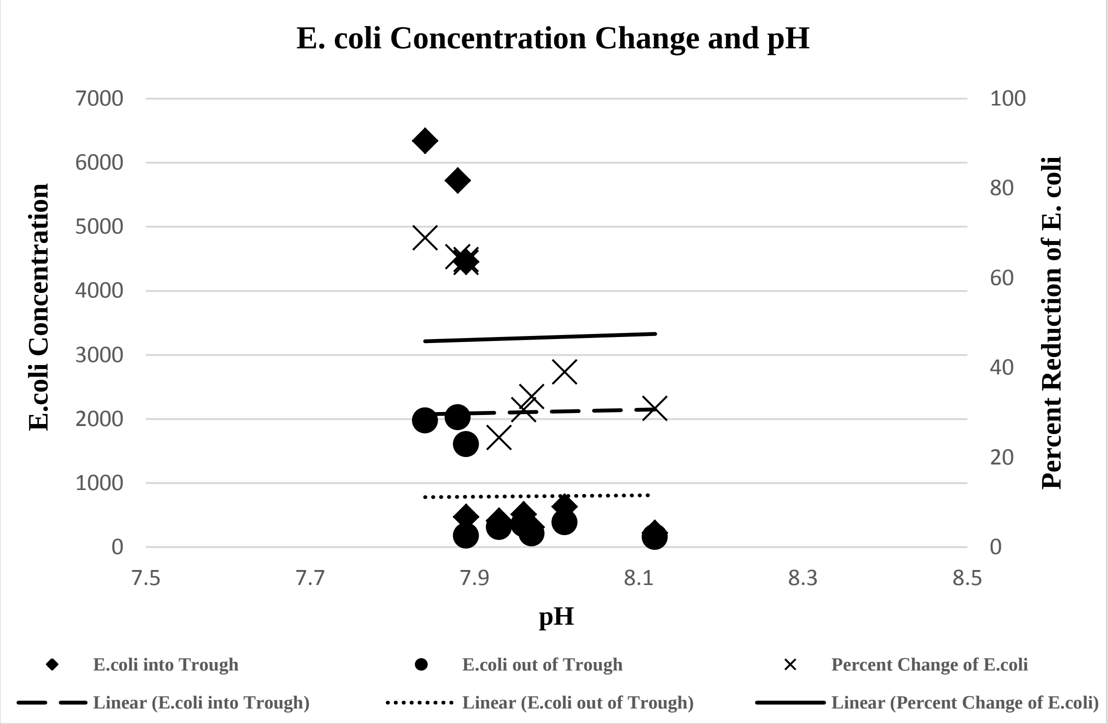

Figure 5.16 Relation between Water pH and E. coli Concentration Change in Trough 3

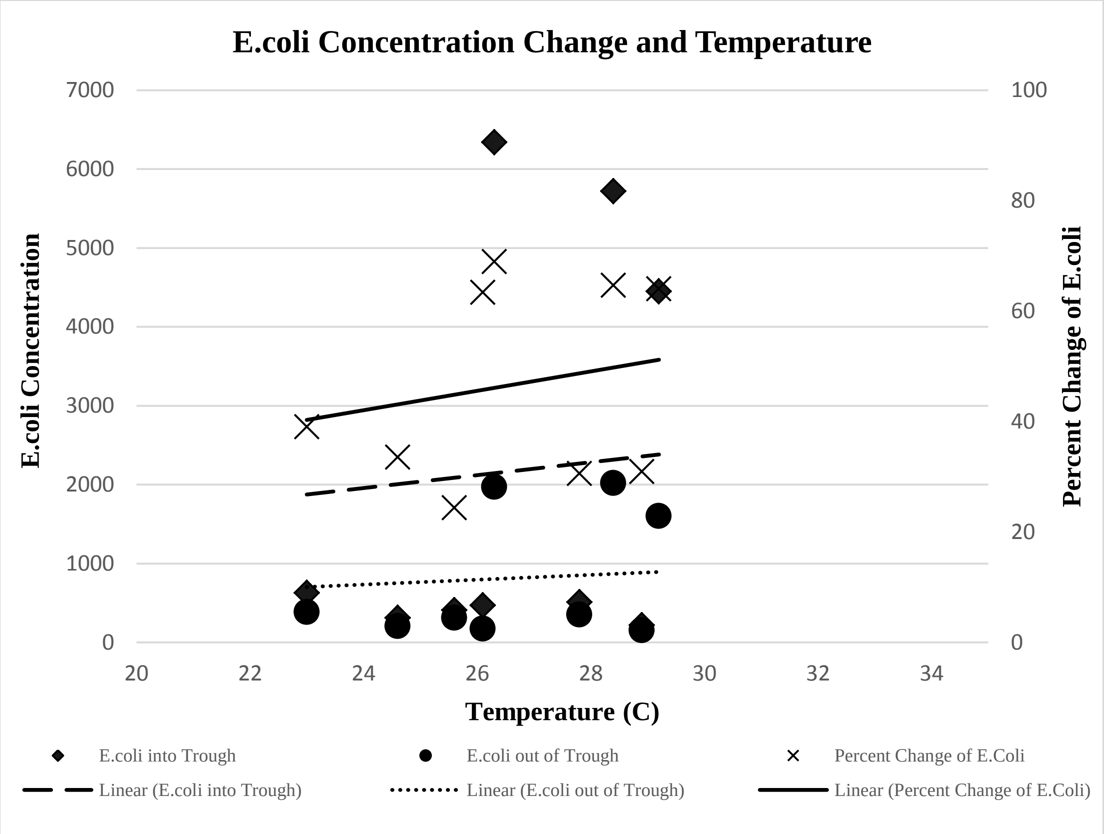

Figure 5.17 Relation between Water Temperature and E. coli Concentration Change in Trough 3

Tables 5-15, and 5-16 gives the *E. coli* concentration changes in trough 4 with respect to solar radiation, and pH, temperature respectively. Figures 5.18, 5.19 and 5.20 shows the graphical representation of the relation between *E.coli* concentration changes in water at input and output, with respect to average solar radiation, pH and temperature. And figures 5.21 and 5.22 shows the graphical representation of relation between *E. coli* concentration change and pH and temperature in all troughs.

Table 5-15 E. coli Concentration Changes in Trough 4 when Flow is 32.3gal/hr for 3.5 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
10 - June	381.60	460	1116	-656	-142.61	-0.38
04 – June	536.40	250	200	50	20.00	0.10
30 – May	595.80	5150	1950	3200	62.14	0.42
12 – June	634.00	5930	1640	4290	72.34	0.56
06 – June	666.80	90	196	-106	-117.78	-0.34
07 – June	714.20	510	260	250	49.02	0.29
25 – June	721.00	3150	1060	2090	66.35	0.47
16 - June	727.80	340	418	-78	-22.94	-0.09
17 - June	871.20	150	272	-122	-81.33	-0.26

Table 5-16 Water pH and Temperature Changes in Trough 4 in Scenario I

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-06-10	381.6	7.87	8.05	22.2	25.9
2014-06-04	536.4	7.82	7.98	24.2	26.9
2014-05-30	595.8	7.75	7.85	24.2	26.8
2014-06-12	634	7.69	7.98	23.2	30.3
2014-06-06	666.8	7.86	8.05	22.7	30.6
2014-06-06	714.2	7.91	8.25	23.3	23.9
2014-06-25	721	7.54	7.87	24.5	26.7
2014-06-16	727.8	7.77	7.99	21.9	25.5
2014-06-17	871.2	7.94	8.12	24.2	27.8

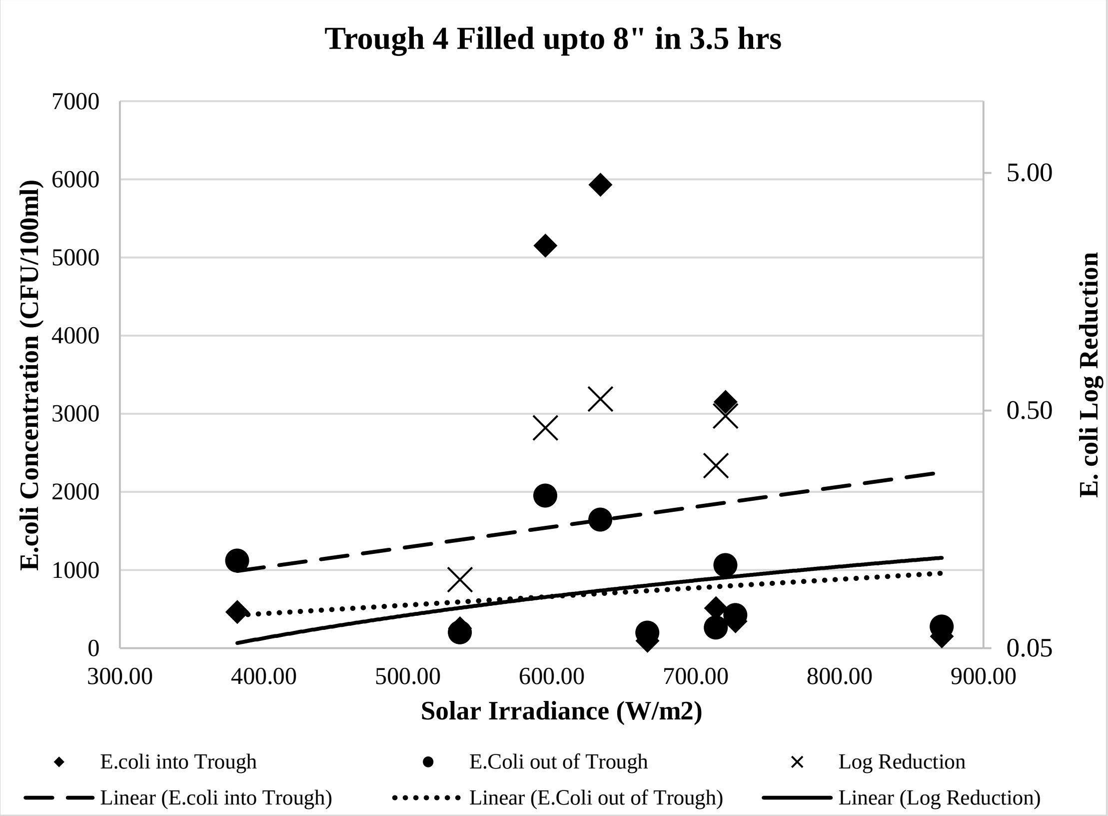

Figure 5.18 E. coli Concentration Changes in Trough 4 when Flow is 32.3gal/hr for 3.5 hrs

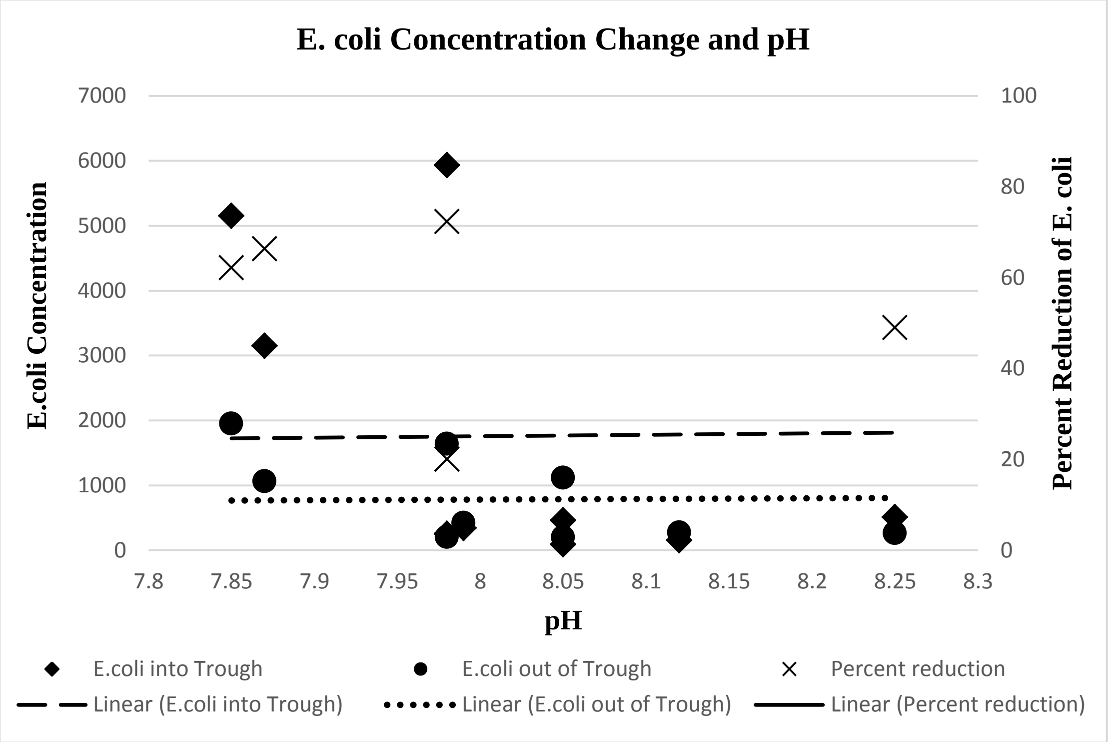

Figure 5.19 Relation between Water pH and E. coli Concentration Change in Trough 4

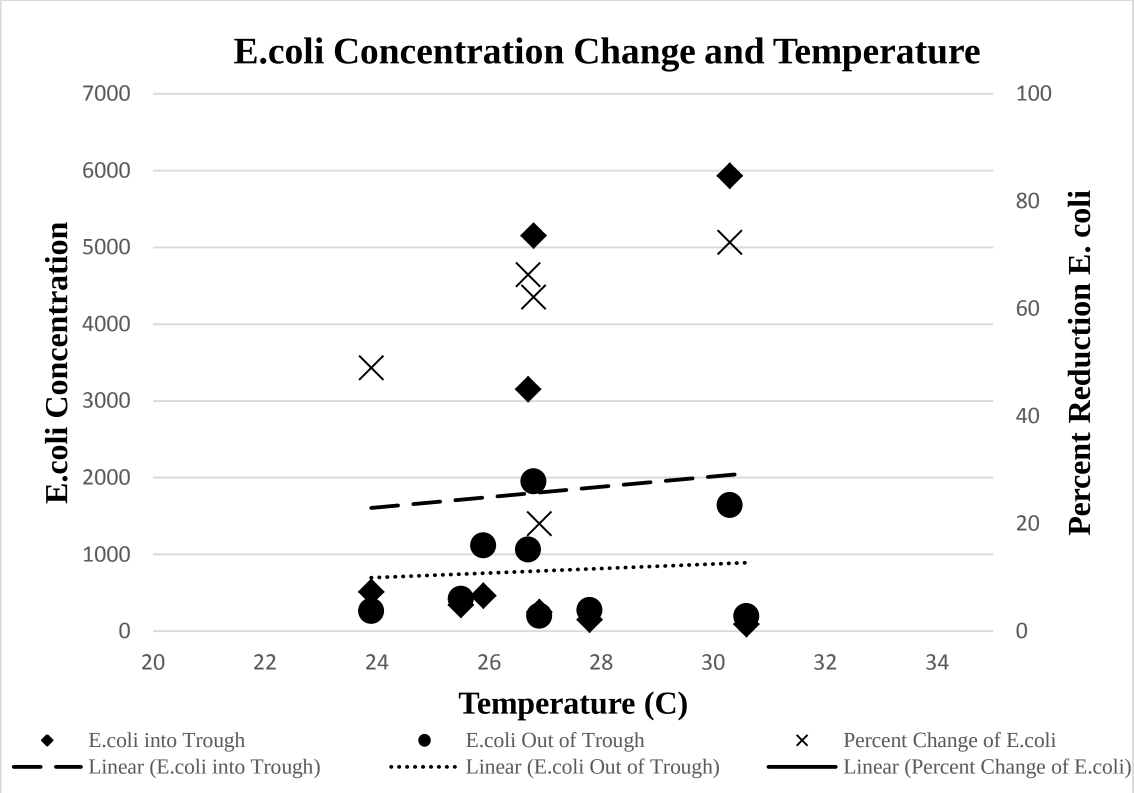

Figure 5.20 Relation between Water Temperature and E. coli Concentration Change in Trough 4

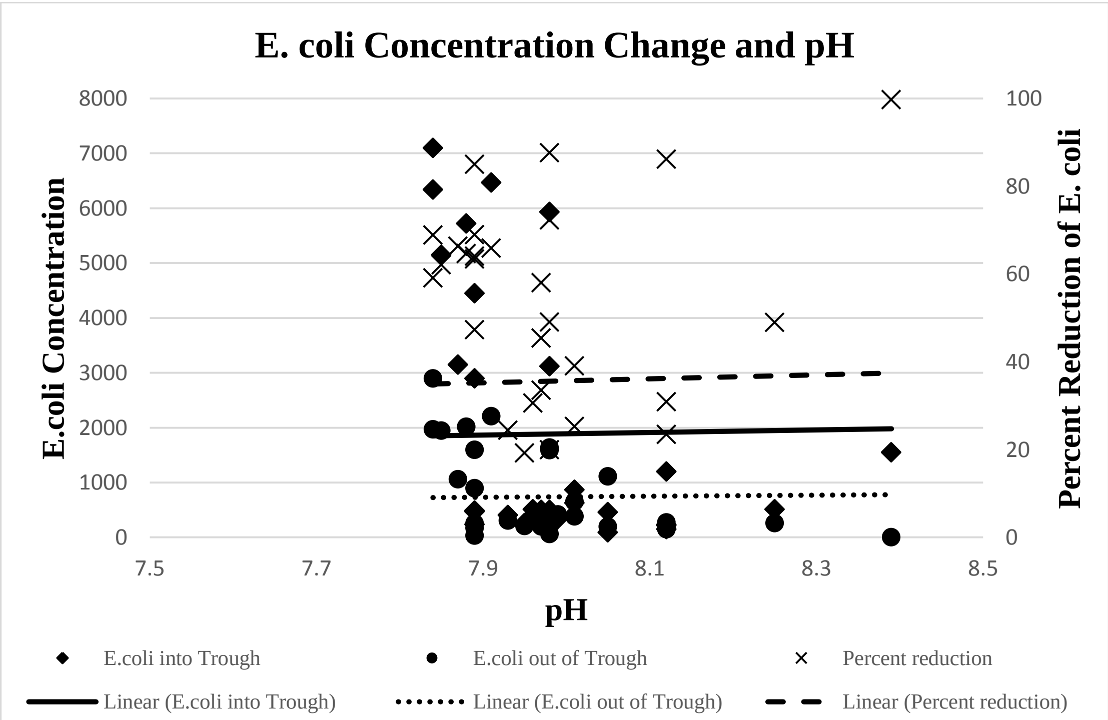

Figure 5.21 Relation between Water pH and E. coli Concentration Change in all Troughs in Scenario I

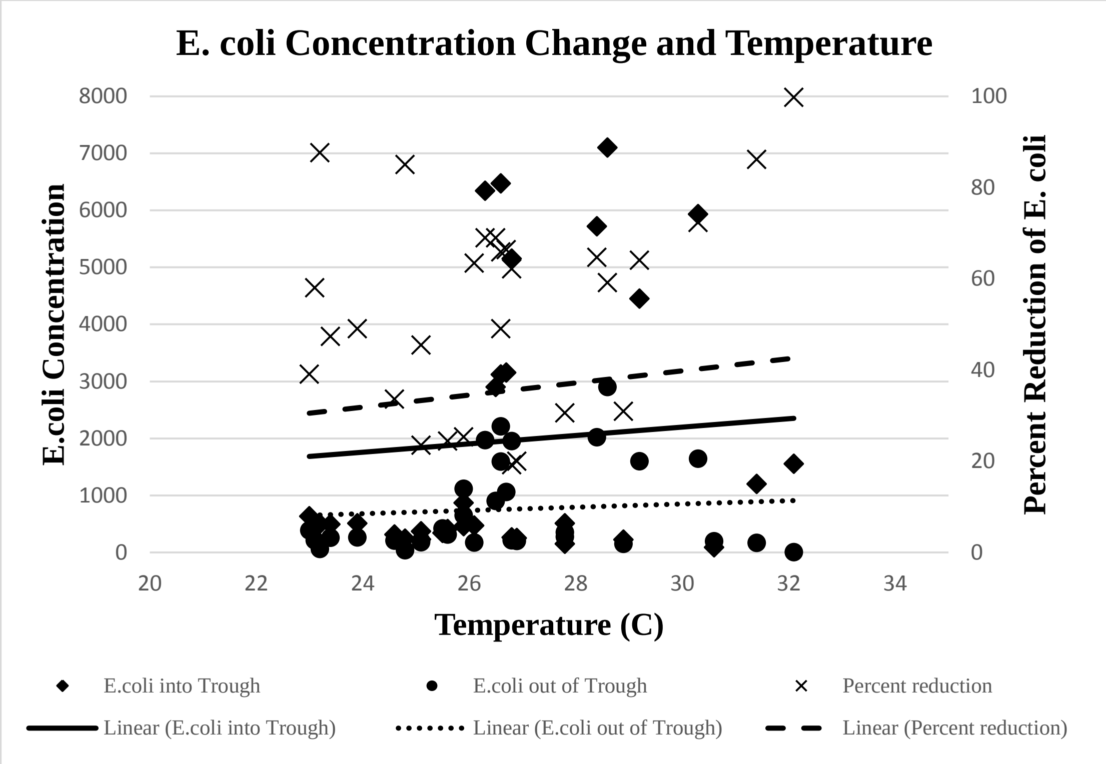

Figure 5.22 Relation between Water Temperature and E. coli Concentration Change in all Troughs in Scenario I

Discussion

In this scenario, none of the troughs' has achieved at least 1 log-reduction (90%) of *E. coli* concentration. This might be because of the less exposure time to sunlight with high flow rate. Trough 4 has some negative reduction values that shows an increase in *E. coli* concentration in the trough at the end of the testing time. This might be because of the sediments in water reducing the solar radiation penetration to deeper levels of water in the trough.

Water temperatures in troughs never achieved 38° C, which is the starting point of the disinfection. SODIS disinfection is independent of water pH between 4.0 and 9.0 (*Rincón A-G, Pulgarin, C 2004*). Though water pH increased, it was never observed that the final water pH values never reached 9.0 and water never recorded acidic values.

5.3.2.2 Scenario II

In scenario II a flow rate of 18.8 gal/hr is maintained into the troughs for 6.0 hrs to achieve a water depth of 8.0 inches. Trough painted white that is attached to the filter 1 have achieved the desired flow depth in this scenario. Table 5-17 gives the E. coli concentration changes in troughs when water depth is 0 inches (time = 0 hrs, 10 am) and 8.0 inches (time = 6.0 hrs, 4 pm). In this scenario, system is tested during nights that is when solar radiation is 0 W/m^2. This showed that *E. coli* concentration increases without sunlight and decreases with sunlight. Solid diamonds shows the *E. coli* concentration in water flowing out of the filter and flowing into the troughs. The solid circles show the reduction in *E. coli* concentration in troughs. Solid cross points represent the log reduction of the *E. coli* concentration. Negative log reduction is not shown in the charts because negative or zero values cannot be plotted correctly on log charts. Tables 5-17, and 5-18 gives the E. coli concentration changes in trough 1 with respect to solar radiation, and pH, temperature respectively. Figures 5.23, 5.24 and 5.25 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-17 E. coli Concentration Changes in Trough 1 when Flow is 18.8 gal/hr for 6.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
03 – July	0.00	30	400	-370	-1233.33	-1.12
06 - July	0.00	20	1420	-1400	-7000.00	-1.85
02 – Aug	0.00	10	200	-190	-1900.00	-1.30
26 – July	545.86	40	6	34	85.00	0.82
03 – July	670.71	30	1	29	96.67	1.48
01 – July	830.00	60	38	22	36.67	0.20
01 – Aug	839.57	110	30	80	72.73	0.56
09 – July	850.71	180	30	150	83.33	0.78
16 - July	851.71	290	70	220	75.86	0.62

Table 5-18 Water pH and Temperature Changes in Trough 1 in Scenario II

Date	Average Solar Radiation (W/m^2)	pH		Temperature	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-07-03	0.00	7.95	8.15	20.3	16.3
2014-07-06	0.00	7.79	8.01	20.8	17.4
2014-08-02	0.00	7.8	8.13	21.8	20.9
2014-07-26	545.86	7.55	7.63	29.7	32.6
2014-07-03	670.71	7.35	7.67	23.4	29.5
2014-07-01	830.00	7.55	7.79	26.1	31.2
2014-08-01	839.57	7.73	7.99	24.2	33.3
2014-07-09	850.71	8.11	8.31	28	32.4
2014-07-16	851.71	7.63	7.79	22.2	26.8

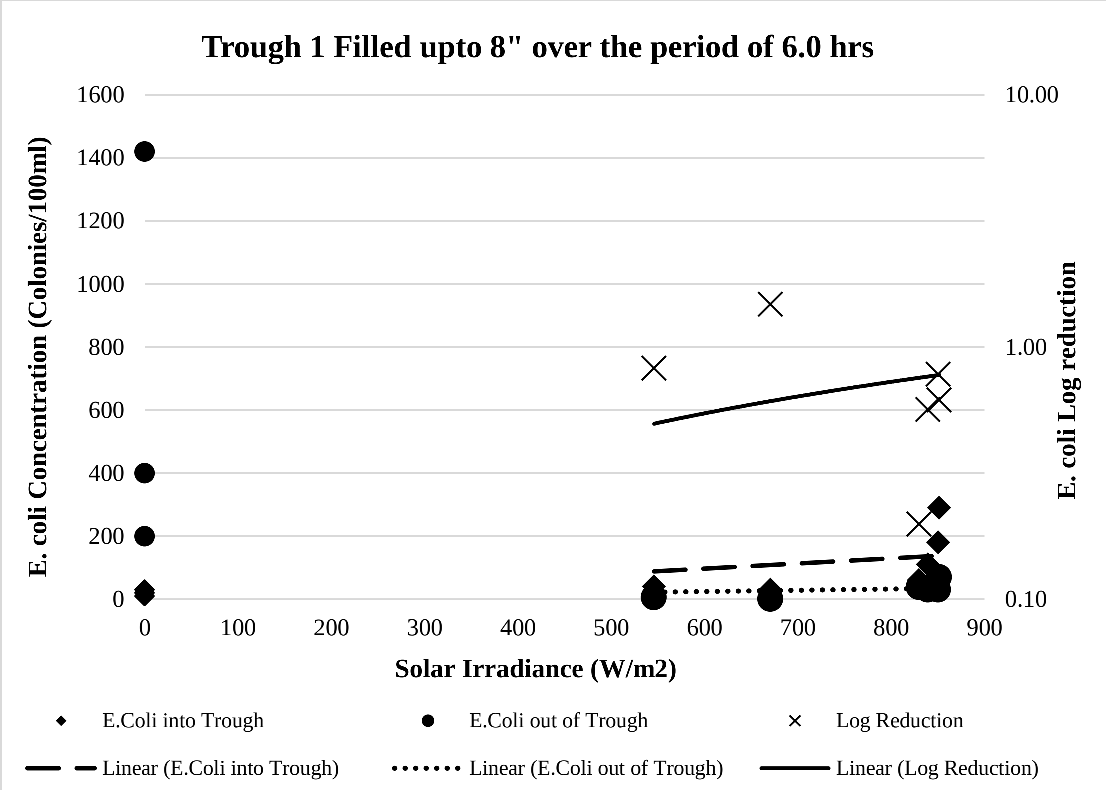

Figure 5.23 E. coli Concentration Changes in Trough 1 when Flow is 18.8 gal/hr for 6.0 hrs

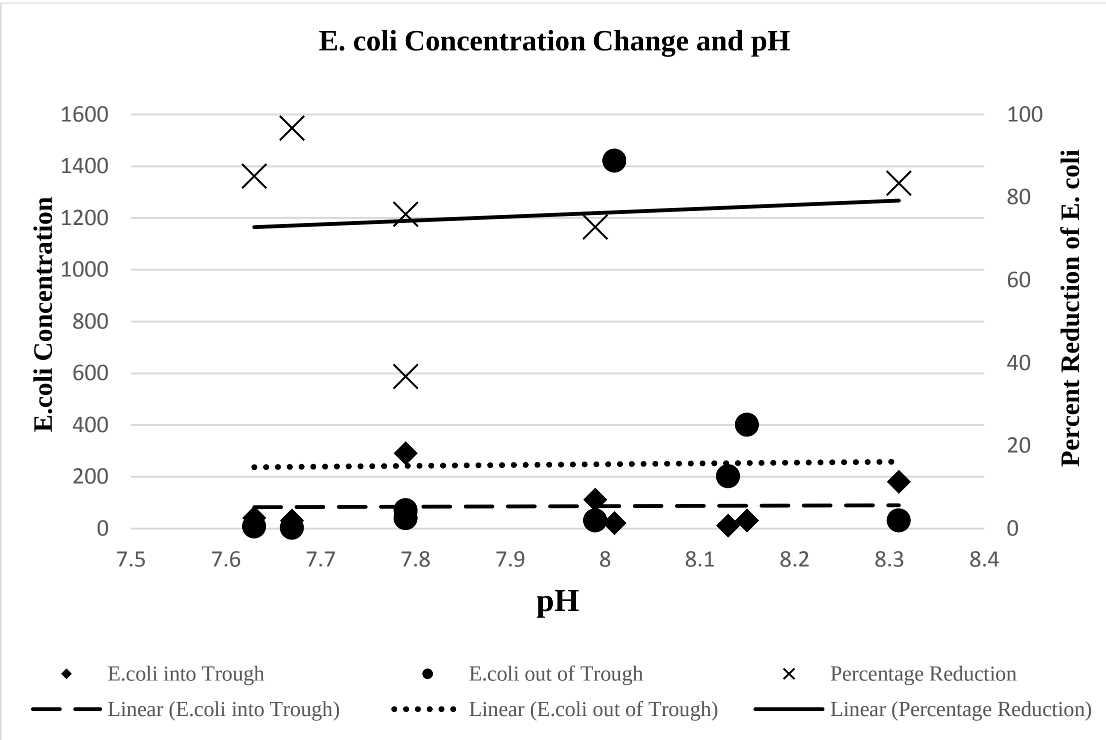

Figure 5.24 Relation between Water pH and E. coli Concentration Change in Trough 1

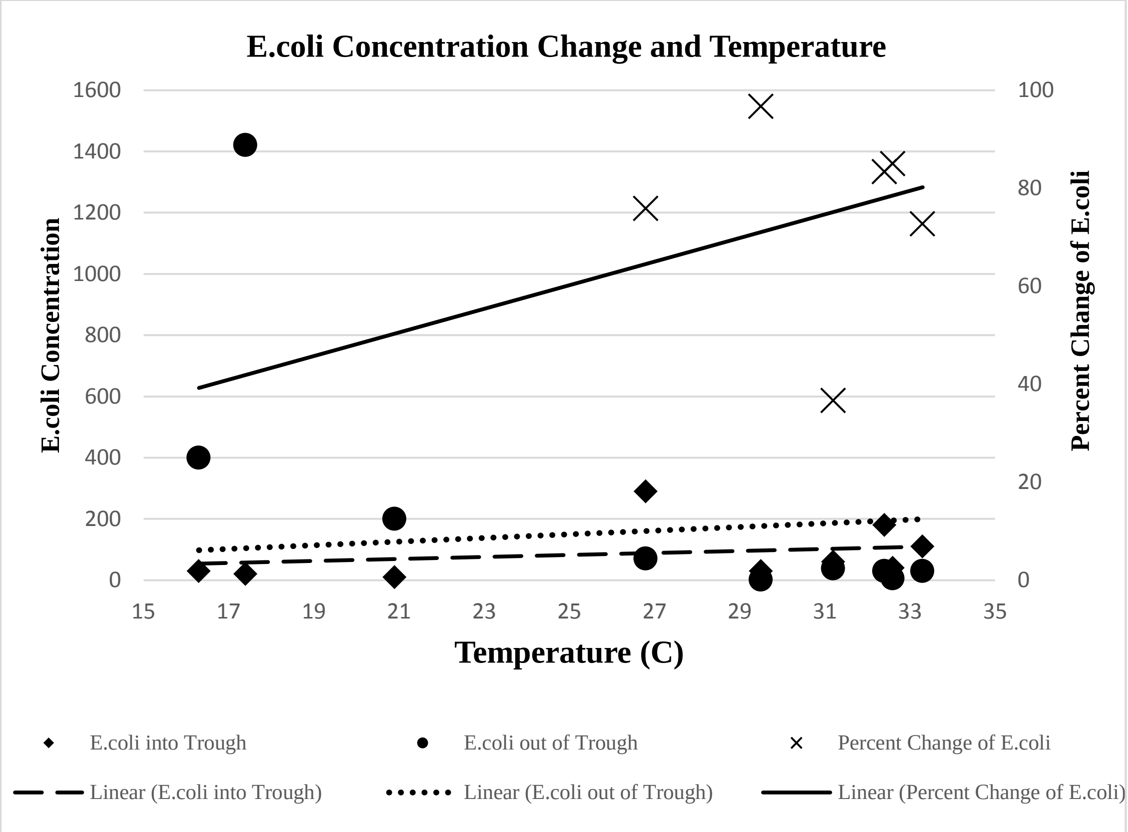

Figure 5.25 Relation between Water Temperature and E. coli Concentration Change in Trough 1

Tables 5-19, and 5-20 gives the E. coli concentration changes in trough 2 with respect to solar radiation, and pH, temperature respectively. Figures 5.26, 5.27 and 5.28 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-19 E. coli Concentration Changes in Trough 2 when Flow is 18.8 gal/hr for 6.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
03 – July	0.00	440	860	-420	-95.45	-0.29
06 - July	0.00	220	350	-130	-59.09	-0.20
02 – Aug	0.00	10	30	-20	-200.00	-0.48
26 – July	545.86	220	36	184	83.64	0.79
03 – July	670.71	2040	804	1236	60.59	0.40
01 – July	830.00	200	16	184	92.00	1.10
01 – Aug	839.57	80	28	52	65.00	0.46
09 – July	850.71	710	148	562	79.15	0.68
16 - July	851.71	1030	220	810	78.64	0.67

Table 5-20 Water pH and Temperature Changes in Trough 2 in Scenario II

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-07-03	0.00	7.95	8.15	21.5	17.2
2014-07-06	0.00	7.79	8.01	22.9	18.3
2014-08-02	0.00	7.8	8.13	21.3	20.9
2014-07-26	545.86	7.55	7.63	27.7	32.8
2014-07-03	670.71	7.35	7.67	23.9	31.7
2014-07-01	830.00	7.55	7.79	25.8	32.9
2014-08-01	839.57	7.73	7.99	24.3	33.8
2014-07-09	850.71	8.11	8.31	27.1	32.5
2014-07-16	851.71	7.63	7.79	21.9	26.4

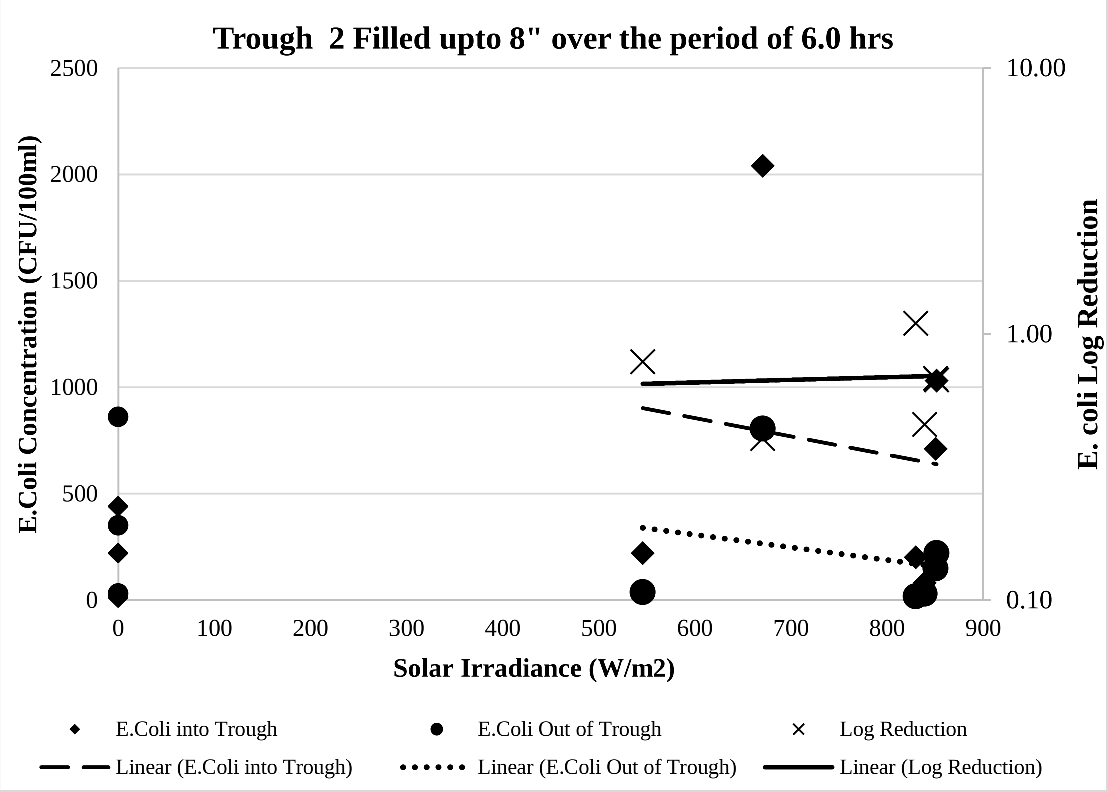

Figure 5.26 E. coli Concentration Changes in Trough 2 when Flow is 18.8 gal/hr for 6.0 hrs

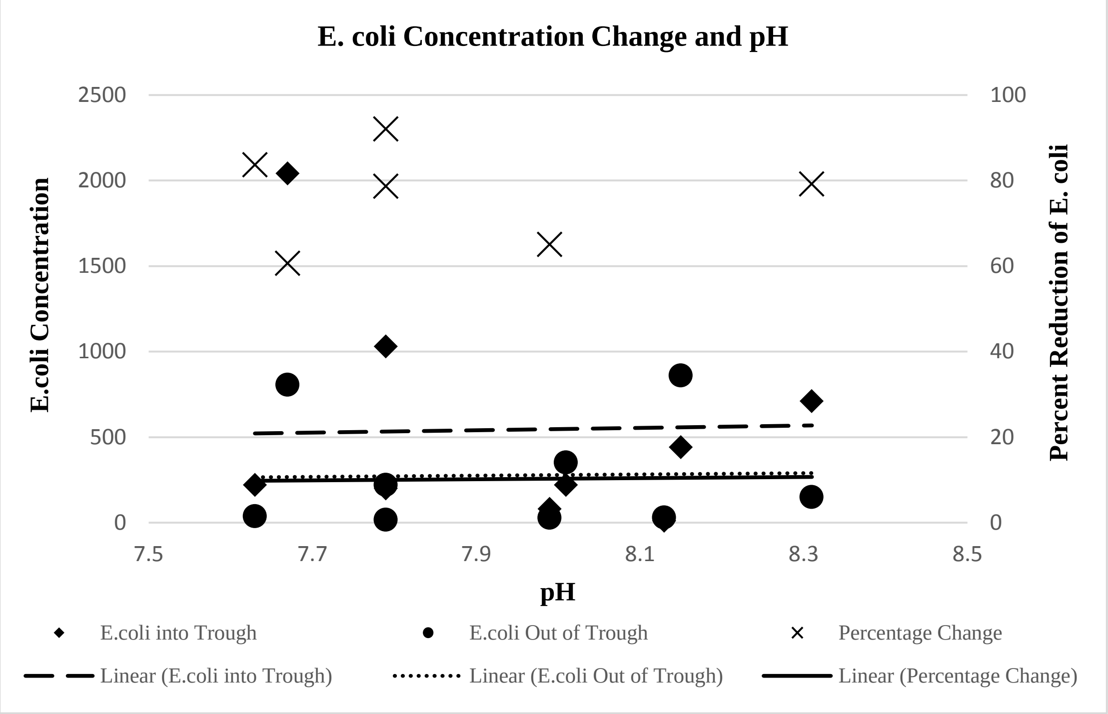

Figure 5.27 Relation between Water pH and E. coli Concentration Change in Trough 2

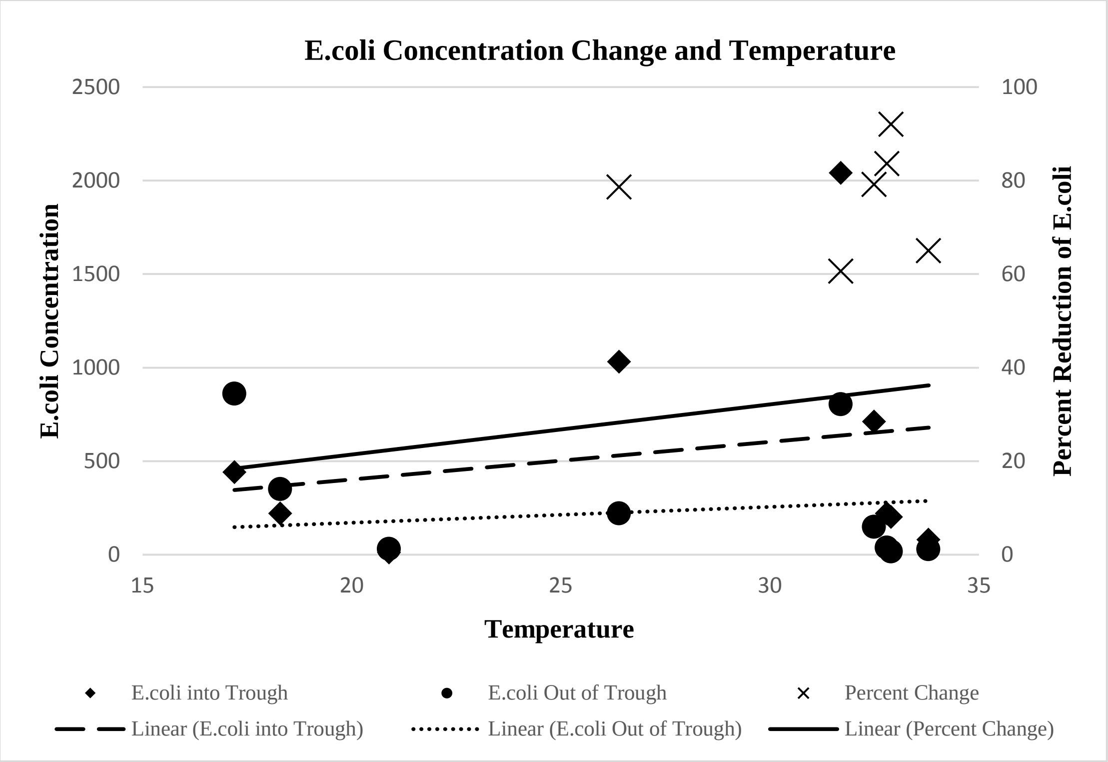

Figure 5.28 Relation between Water Temperature and E. coli Concentration Change in Trough 2

Tables 5-21, and 5-22 gives the E. coli concentration changes in trough 3 with respect to solar radiation, and pH, temperature respectively. Figures 5.29, 5.30 and 5.31 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-21 E. coli Concentration Changes in Trough 3 when Flow is 18.8 gal/hr for 6.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
03 – July	0.00	1000	1820	-820	-82.00	-0.26
06 - July	0.00	220	290	-70	-31.82	-0.12
02 – Aug	0.00	10	80	-70	-700.00	-0.90
26 – July	545.86	280	92	188	67.14	0.48
03 – July	670.71	1170	684	486	41.54	0.23
01 – July	830.00	90	720	-630	-700.00	-0.90
01 – Aug	839.57	240	180	60	25.00	0.12
09 – July	850.71	1210	1632	-422	-34.88	-0.13
16 - July	851.71	1070	292	778	72.71	0.56

Table 5-22 Water pH and Temperature Changes in Trough 3 in Scenario II

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-07-03	0.00	7.95	8.15	21.7	18.7
2014-07-06	0.00	7.79	8.01	22.7	18.4
2014-08-02	0.00	7.8	8.13	21.2	21.1
2014-07-26	545.86	7.55	7.63	26.4	32.1
2014-07-03	670.71	7.35	7.67	24.1	30.2
2014-07-01	830.00	7.55	7.79	25.7	31.9
2014-08-01	839.57	7.73	7.99	24.8	32.8
2014-07-09	850.71	8.11	8.31	26.5	32.5
2014-07-16	851.71	7.63	7.79	21.8	26.1

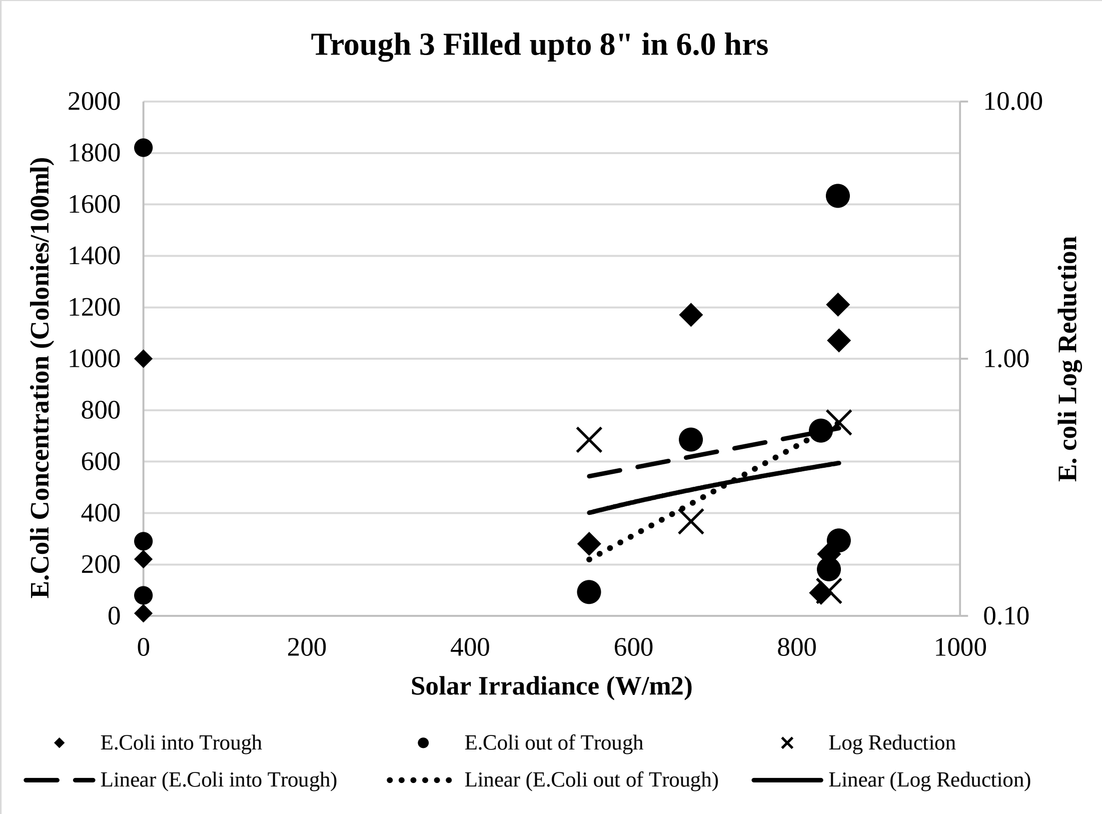

Figure 5.29 E. coli Concentration Changes in Trough 3 when Flow is 18.8 gal/hr for 6.0 hrs

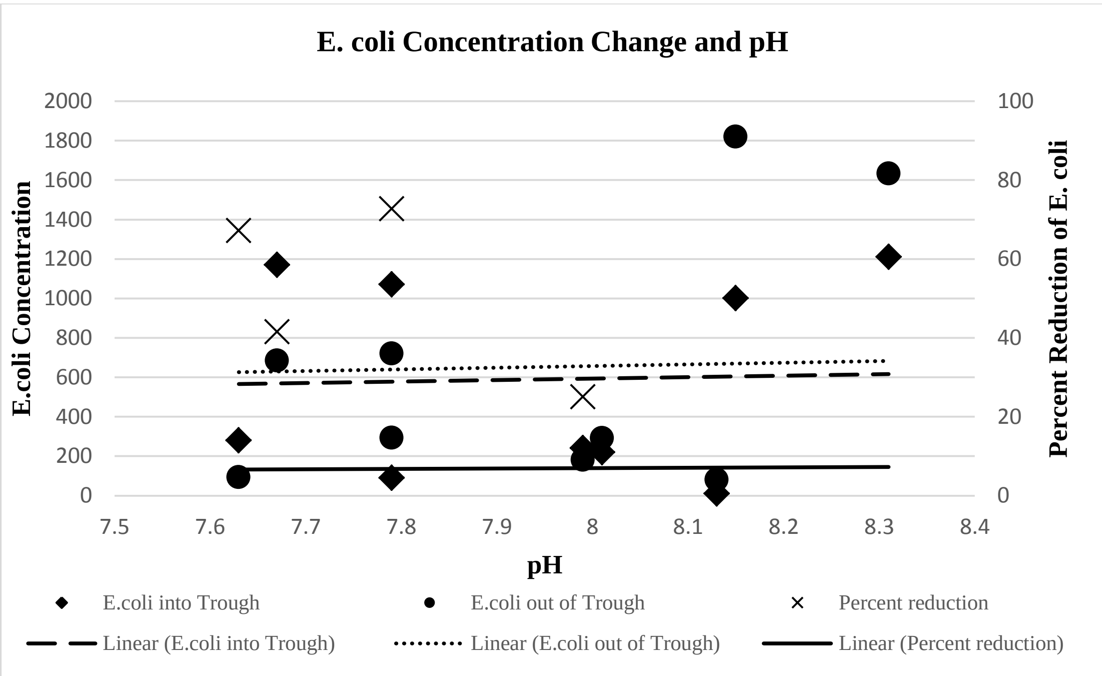

Figure 5.30 Relation between Water pH and E. coli Concentration Change in Trough 3

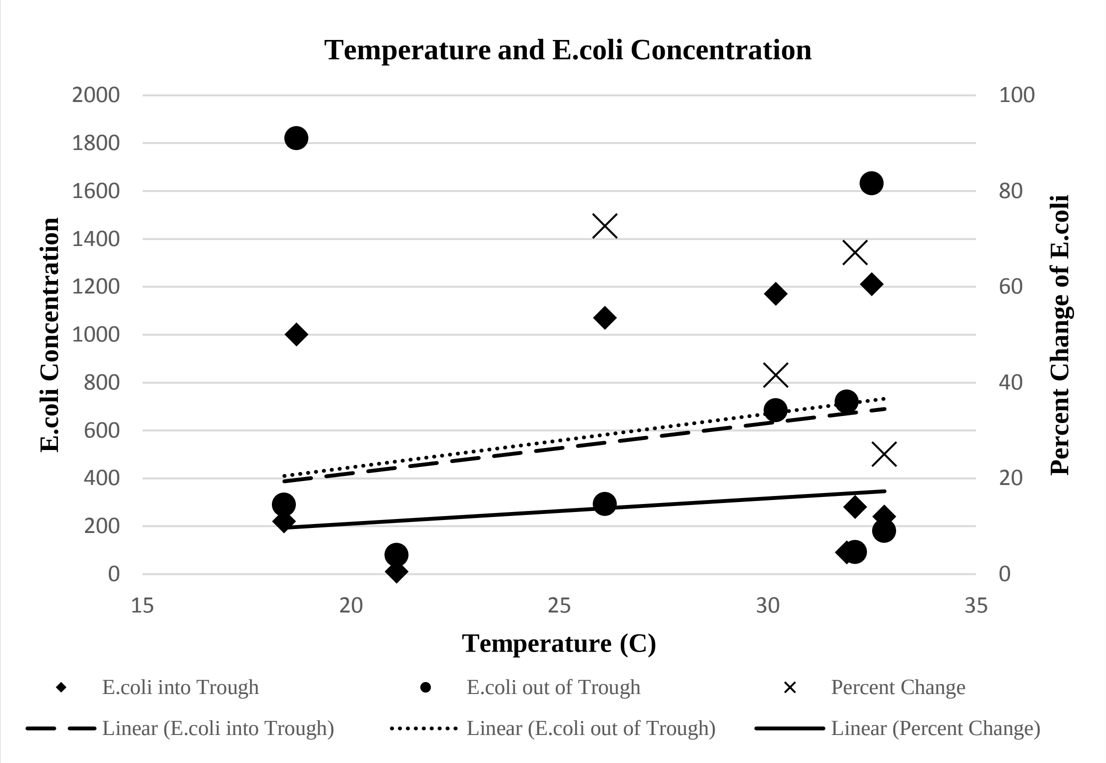

Figure 5.31 Relation between Water Temperature and E. coli Concentration Change in Trough 3

Tables 5-23, and 5-24 gives the E. coli concentration changes in trough 4 with respect to solar radiation, and pH, temperature respectively. Figures 5.32, 5.33 and 5.34 shows the graphical representation of the relation between *E.coli* concentration changes between water at input and output, with respect to average solar radiation, pH and temperature. Figures 5.35 and 5.36 shows the graphical representation of relation between *E. coli* concentration change and final pH and final temperature in all troughs during scenario II.

Table 5-23 E. coli Concentration Changes in Trough 4 when Flow is 18.8 gal/hr for 6.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
03 – July	0.00	1230	3550	-2320	-188.62	-0.46
06 - July	0.00	70	80	-10	-14.29	-0.06
26 – July	545.86	270	52	218	80.74	0.72
03 – July	670.71	1680	884	796	47.38	0.28
01 – July	830.00	190	1200	-1010	-531.58	-0.80
01 – Aug	839.57	480	244	236	49.17	0.29
09 – July	850.71	890	684	206	23.15	0.11
16 - July	851.71	810	328	482	59.51	0.39

Table 5-24 Water pH and Temperature Changes in Trough 4 in Scenario II

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-07-03	0.00	7.93	8.1	23.2	18.9
2014-08-02	0.00	7.97	8.14	21.7	21
2014-07-26	545.86	7.68	7.82	27.5	33.5
2014-07-03	670.71	7.35	7.5	23.9	32.3
2014-07-01	830.00	7.99	8.23	25.8	33.5
2014-08-01	839.57	7.89	8.03	24.4	32.8
2014-07-09	850.71	8.35	8.49	26.2	34.1
2014-07-16	851.71	7.75	7.87	21.9	26.8

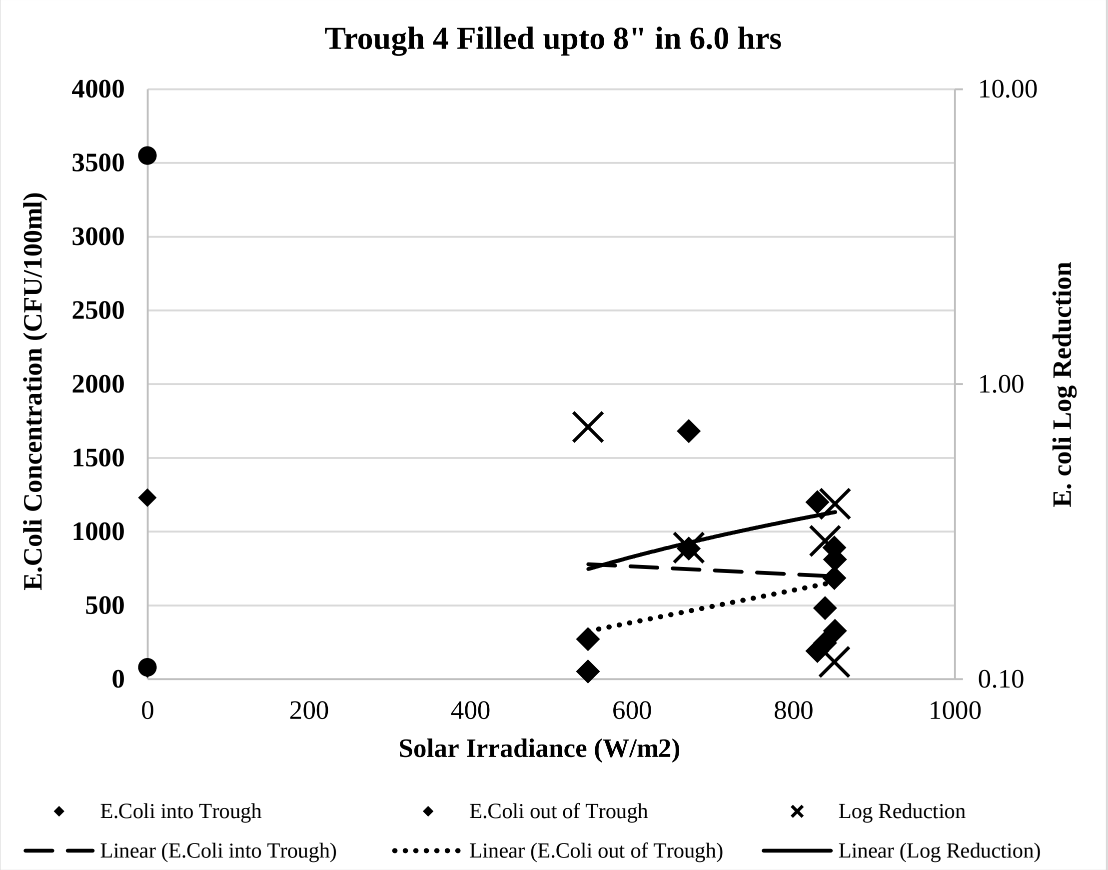

Figure 5.32 E. coli Concentration Changes in Trough 4 when Flow is 18.8 gal/hr for 6.0 hrs

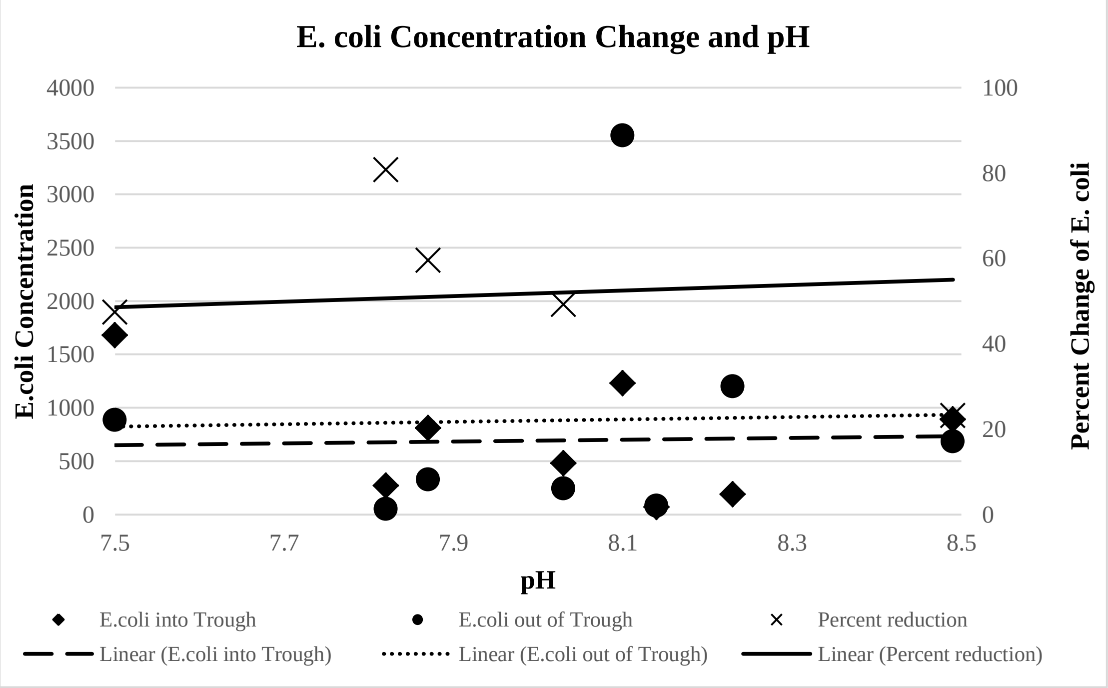

Figure 5.33 Relation between Water pH and E. coli Concentration Change in Trough 4

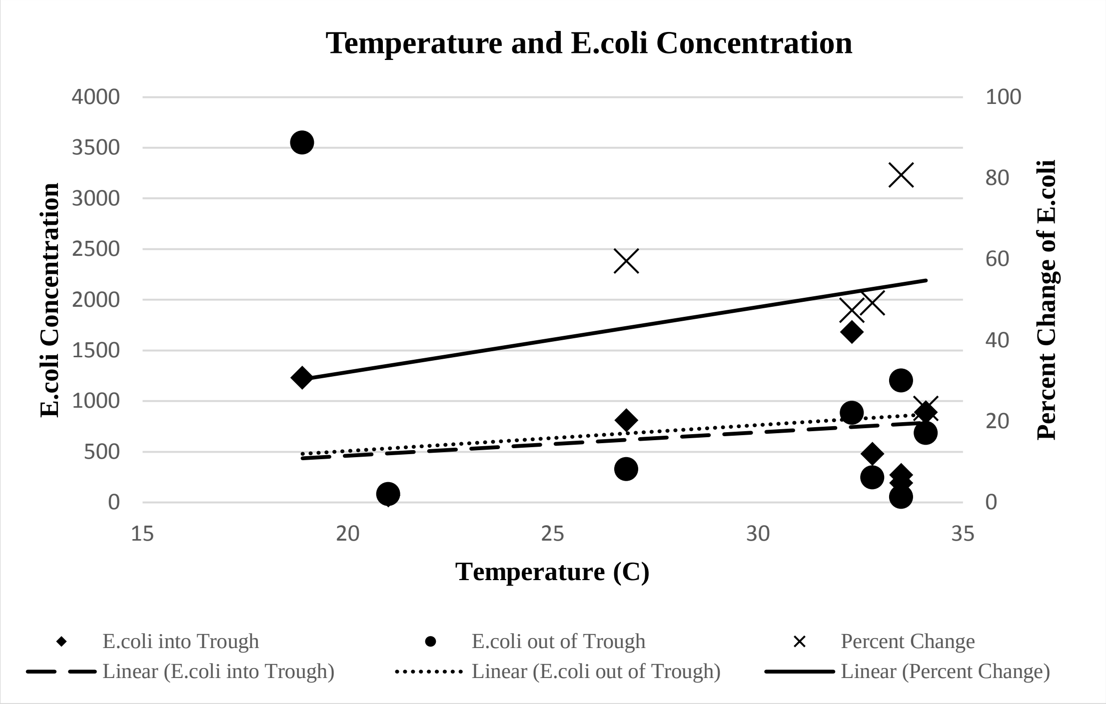

Figure 5.34 Relation between Water Temperature and E. coli Concentration Change in Trough 4

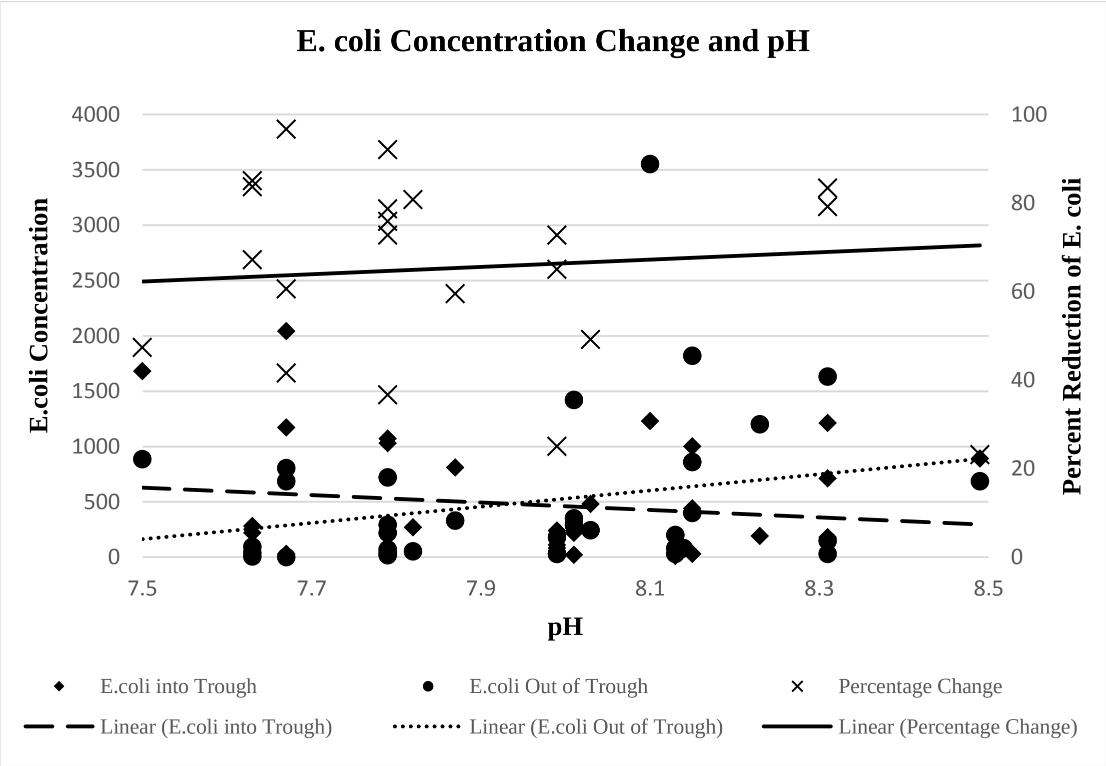

Figure 5.35 Relation between Water pH and E. coli Concentration Change in all Troughs in Scenario II

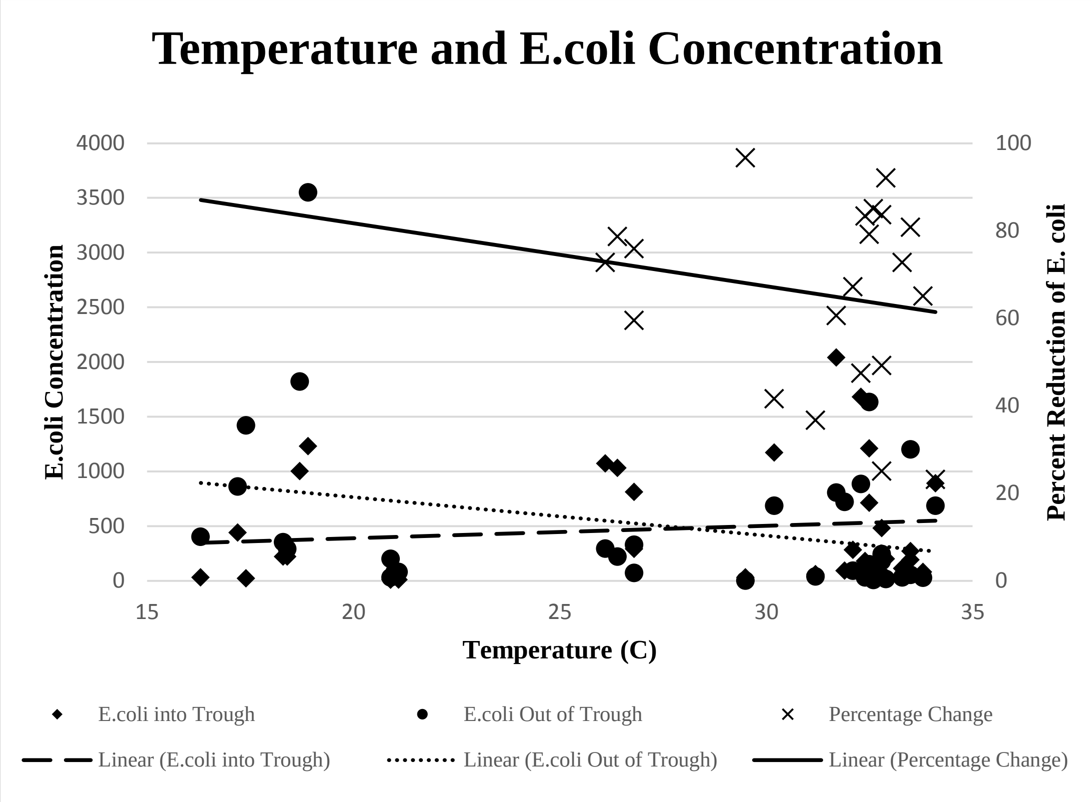

Figure 5.36 Relation between Water Temperature and E. coli Concentration Change in all Troughs in Scenario II

Discussion

In this scenario, Trough 1 performed better than other with a maximum of 1.48 log reduction and no increase in *E. coli* reduction. In this scenario, SODIS is tested in the night-time where solar radiation of is 0 W/m^2. *E. coli* concentration has increased when tested the system in morning. Troughs 3 and 4 have some negative reduction values shows an increase in *E. coli* concentration in the trough at the end of the testing time during the sunny time. One reason behind this might be the sediments in water reducing the solar radiation penetration to deeper levels of water in the trough. In addition, the other reason can be the result of ideal conditions for incubation of *E. coli*, which is temperature of 35° C, availability of nutrients, as the water used for testing the system is from an urban stream, and availability of nutrients in urban streams is proven high. Water temperatures in troughs never achieved the disinfection beginning temperature, which is 38° C. Water pH never recorded values below 4.0 or above 9.0.

5.3.2.3 Scenario III

Flow rate of 7.3 gal/hr is maintained into the troughs for 5.0 hrs to achieve a water depth of 3.5 inches. Trough painted white is connected to the filter 1 have achieved the desired flow depth in this scenario. Table 5-25 gives the E. coli concentration changes in troughs when water depth is 0 inches (time = 0 hrs) and 3.5 inches (time = 5.0 hrs. Tables 5-25, and 5-26 gives the E. coli concentration changes in trough 1 with respect to solar radiation, and pH, temperature respectively. Figures 5.37, 5.38 and 5.39 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-25 E. coli Concentration Changes in Trough 1 when Flow is 7.3 gal/hr for 5.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
23 – Aug	556.17	6120	1550	4570	74.67	0.60
22 – Aug	582.17	460	32	428	93.04	1.16
25 – Aug	632.17	11200	142	11058	98.73	1.90
26 – Aug	699.83	1760	308	1452	82.50	0.76
15 – Aug	796.67	60	1	59	98.33	1.78
19 – Aug	799.50	112	1	111	99.11	2.05
13 - Aug	821.83	428	1	427	99.77	2.63

Table 5-26 Water pH and Temperature Changes in Trough 1 in Scenario III

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-08-13	821.83	7.64	7.81	23.8	31
2014-08-15	556.17	7.85	7.99	28.5	32.9
2014-08-19	796.67	7.78	7.88	23.2	27.9
2014-08-22	799.5	8.21	8.32	29.6	36.6
2014-08-23	632.17	8.25	8.32	30.3	35.7
2014-08-25	699.83	8.16	8.28	25.8	36.2
2014-08-26	582.17	7.98	8.15	28.8	35.6

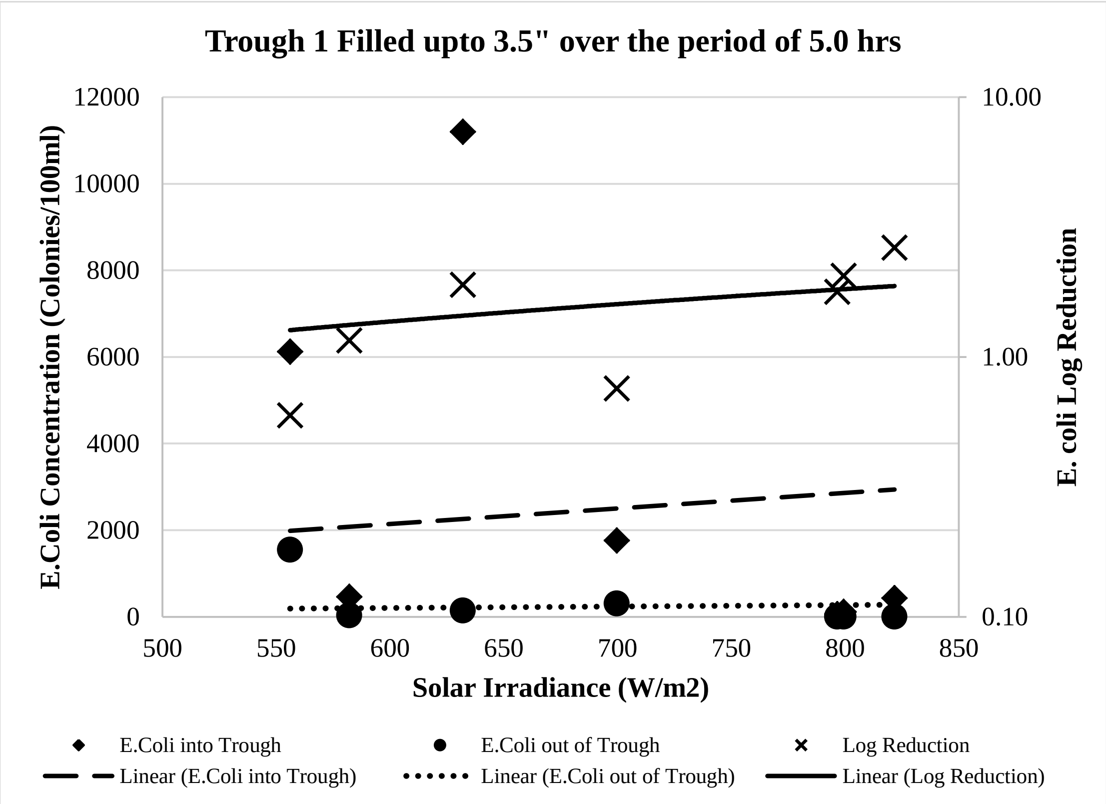

Figure 5.37 E. coli Concentration Changes in Trough 1 when Flow is 7.3 gal/hr for 5.0 hrs

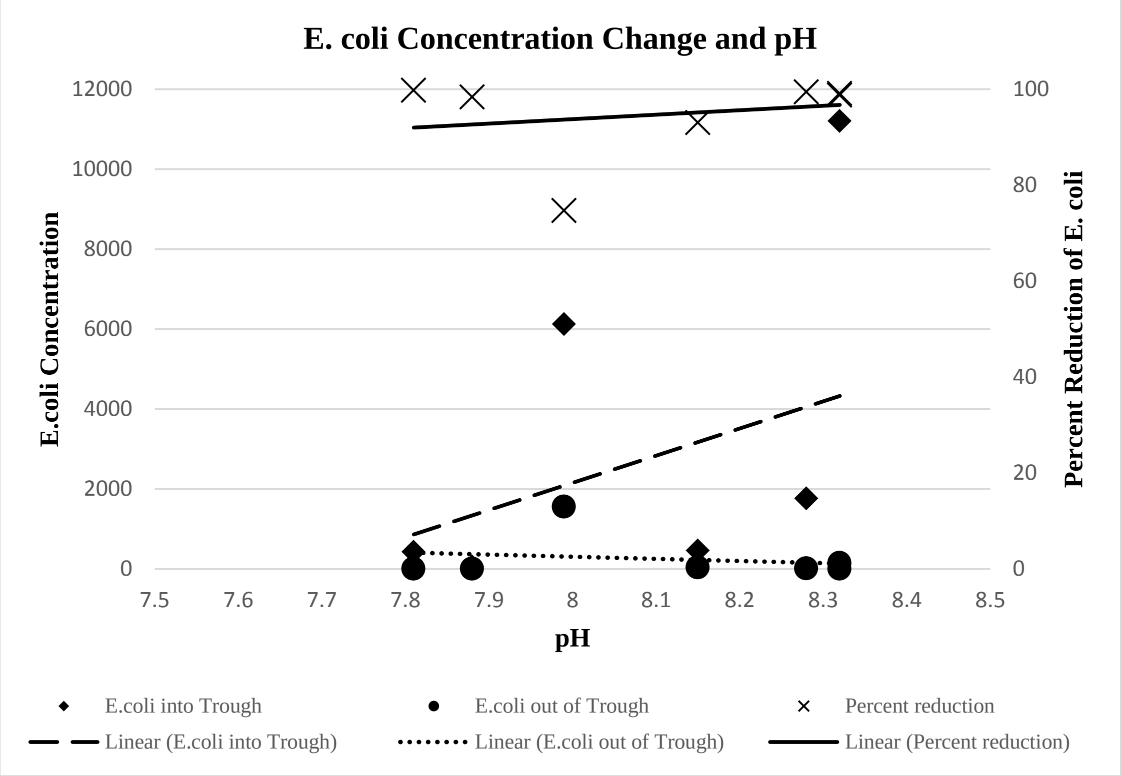

Figure 5.38 Relation between Water pH and E. coli Concentration Change in Trough 1

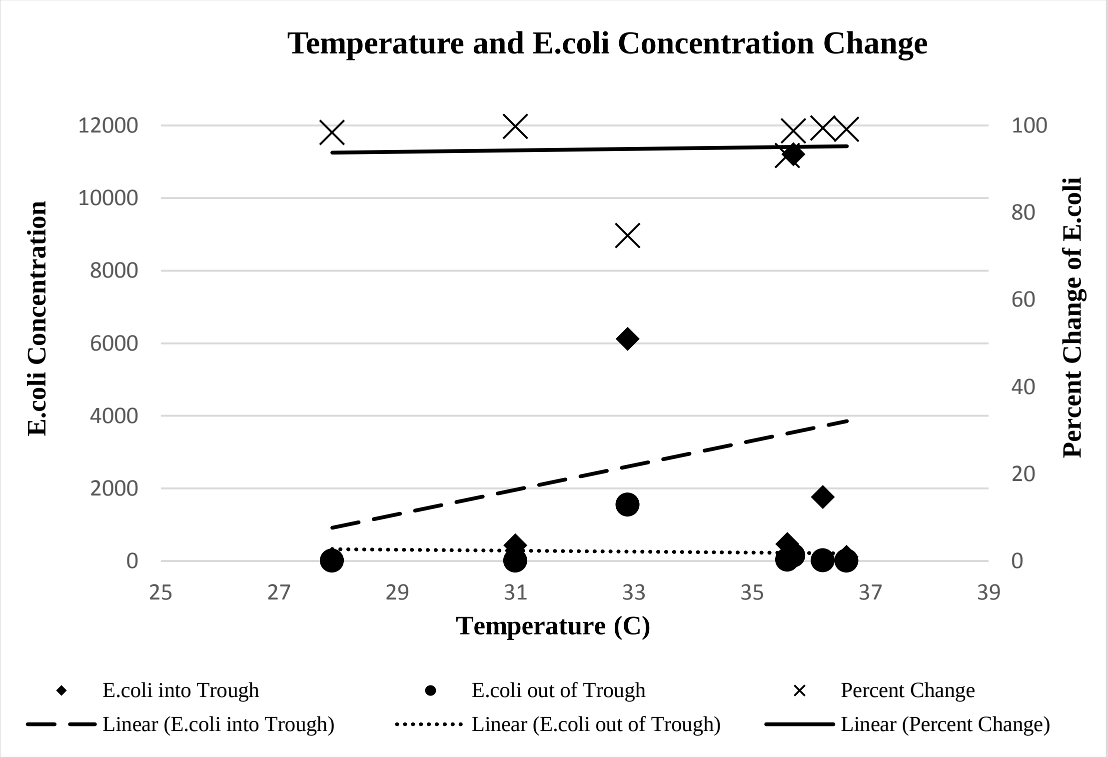

Figure 5.39 Relation between Water Temperature and E. coli Concentration Change in Trough 1

Tables 5-27, and 5-28 gives the E. coli concentration changes in trough 2 with respect to solar radiation, and pH, temperature respectively. Figures 5.40, 5.41 and 5.42 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-27 E. coli Concentration Changes in Trough 2 when Flow is 7.3 gal/hr for 5.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
23 – Aug	556.17	564	120	444	78.72	0.67
22 – Aug	582.17	68	1	67	98.53	1.83
25 – Aug	632.17	172	44	128	74.42	0.59
26 – Aug	699.83	100	10	90	90.00	1.00
15 – Aug	796.67	80	8	72	90.00	1.00
19 – Aug	799.50	184	4	180	97.83	1.66
13 - Aug	821.83	640	70	570	89.06	0.96

Table 5-28 Water pH and Temperature Changes in Trough 1 in Scenario III

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-08-13	821.83	7.57	7.65	23.1	31.2
2014-08-15	556.17	8.15	8.30	28.2	33.8
2014-08-19	796.67	7.74	7.82	22.8	29.8
2014-08-22	799.50	8.00	8.24	27.2	36.4
2014-08-23	632.17	8.07	8.35	29.1	35.6
2014-08-25	699.83	8.24	8.36	27.2	37.5
2014-08-26	582.17	8.07	8.19	28.6	36.3

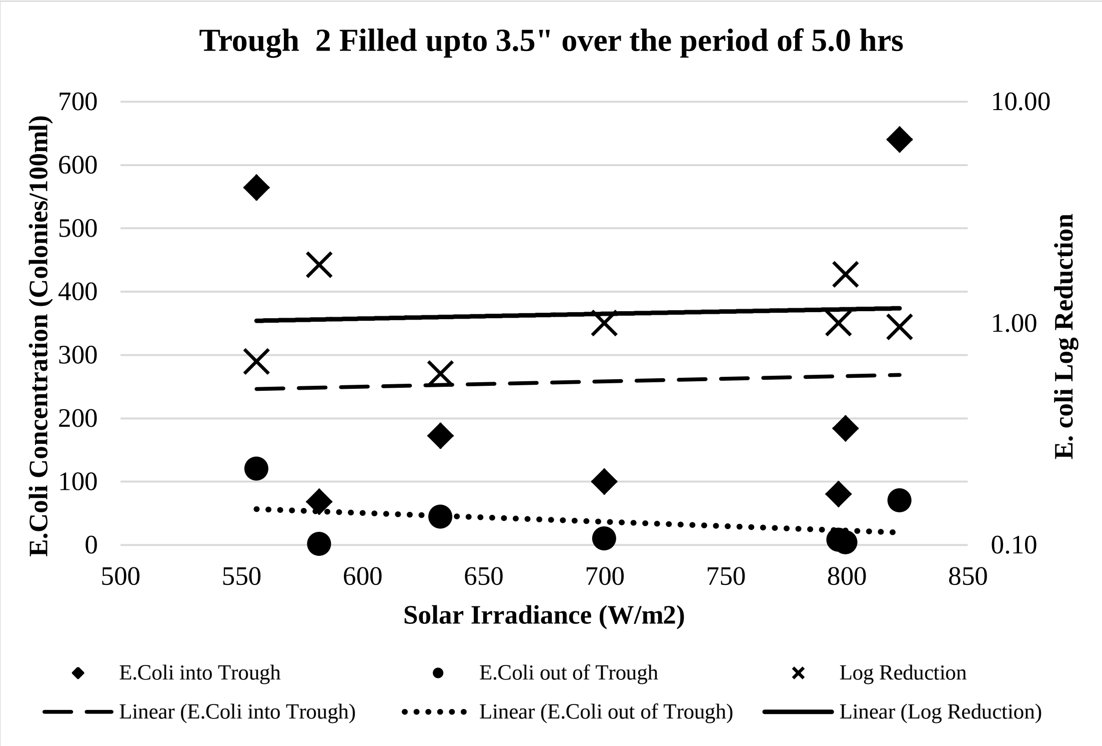

Figure 5.40 E. coli Concentration Changes in Trough 2 when Flow is 7.3 gal/hr for 5.0 hrs

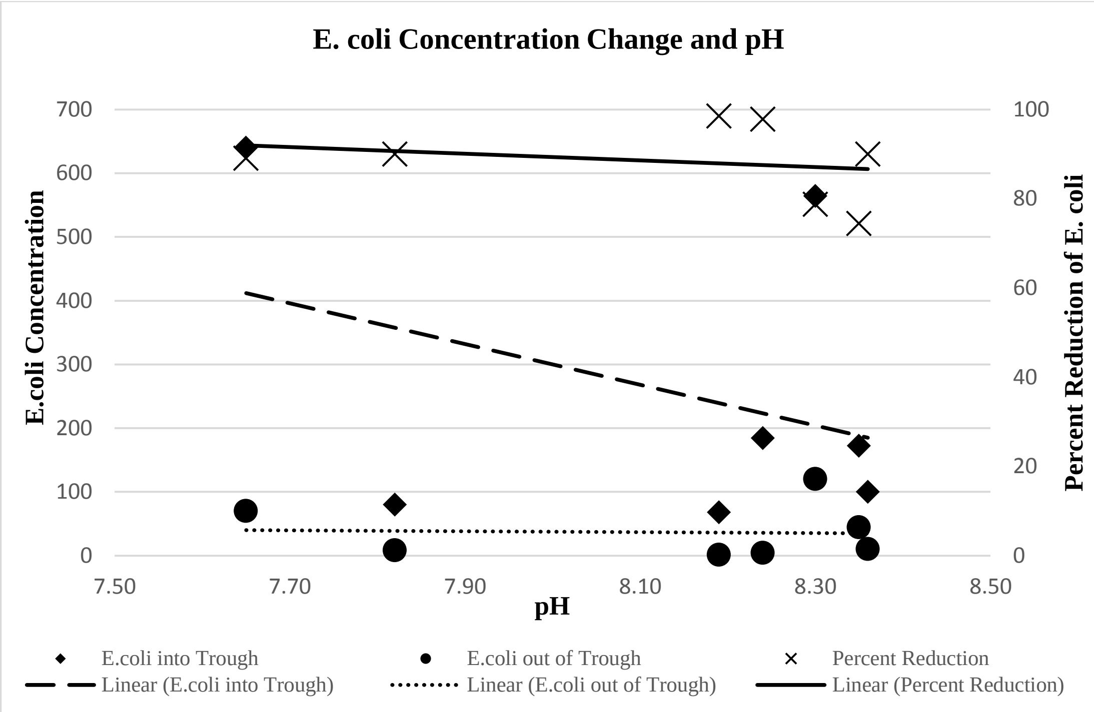

Figure 5.41 Relation between Water pH and E. coli Concentration Change in Trough 2

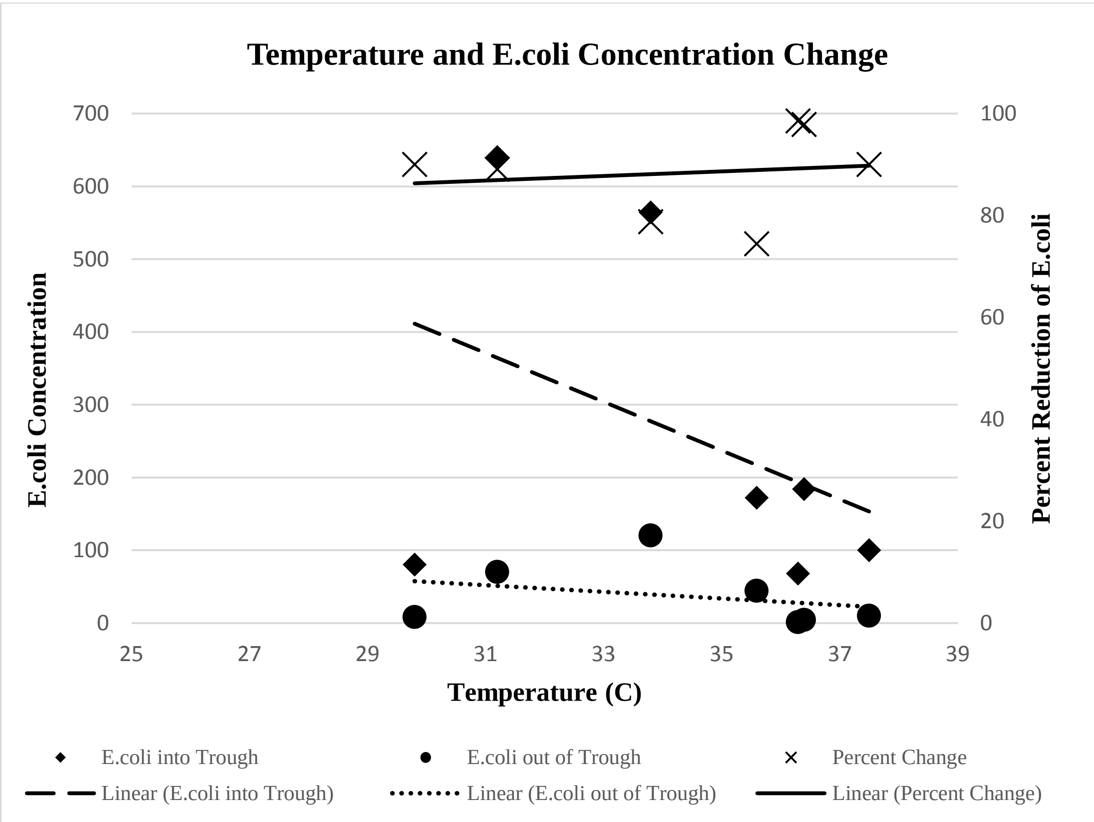

Figure 5.42 Relation between Water Temperature and E. coli Concentration Change in Trough 2

Tables 5-29, and 5-30 gives the E. coli concentration changes in trough 3 with respect to solar radiation, and pH, temperature respectively. Figures 5.43, 5.44 and 5.45 shows the graphical representation of the relation between E.coli concentration changes between water at input and output, with respect to average solar radiation, pH and temperature.

Table 5-29 E. coli Concentration Changes in Trough 3 when Flow is 7.3 gal/hr for 5.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
23 – Aug	556.17	2054	740	1314	63.97	0.44
22 – Aug	582.17	168	1	167	99.40	2.23
25 – Aug	632.17	632	104	528	83.54	0.78
26 – Aug	699.83	345	10	335	97.10	1.54
15 – Aug	796.67	120	14	106	88.33	0.93
19 – Aug	799.50	580	50	530	91.38	1.06
13 - Aug	821.83	800	70	730	91.25	1.06

Table 5-30 Water pH and Temperature Changes in Trough 3 in Scenario III

Date	Average Solar Radiation (W/m^2)	pH		Temperature (C)	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-08-13	796.67	7.80	7.94	23.1	29.7
2014-08-15	799.50	7.93	8.09	26.7	35.9
2014-08-19	582.17	8.02	8.17	28.7	36.5
2014-08-22	556.17	8.19	8.32	28.8	33.3
2014-08-23	821.83	7.57	7.65	23.3	31.3
2014-08-25	699.83	8.15	8.46	27.3	37.4
2014-08-26	632.17	8.04	8.20	28.4	35

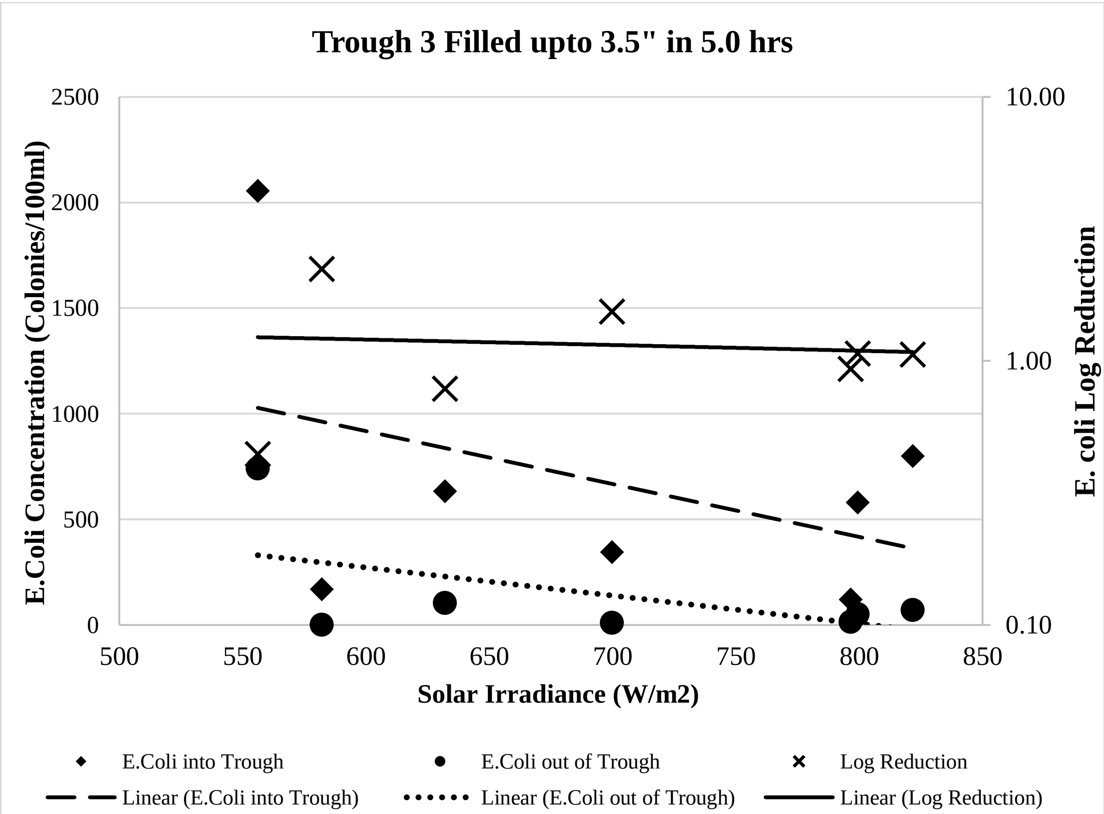

Figure 5.43 E. coli Concentration Changes in Trough 3 when Flow is 7.3 gal/hr for 5.0 hrs

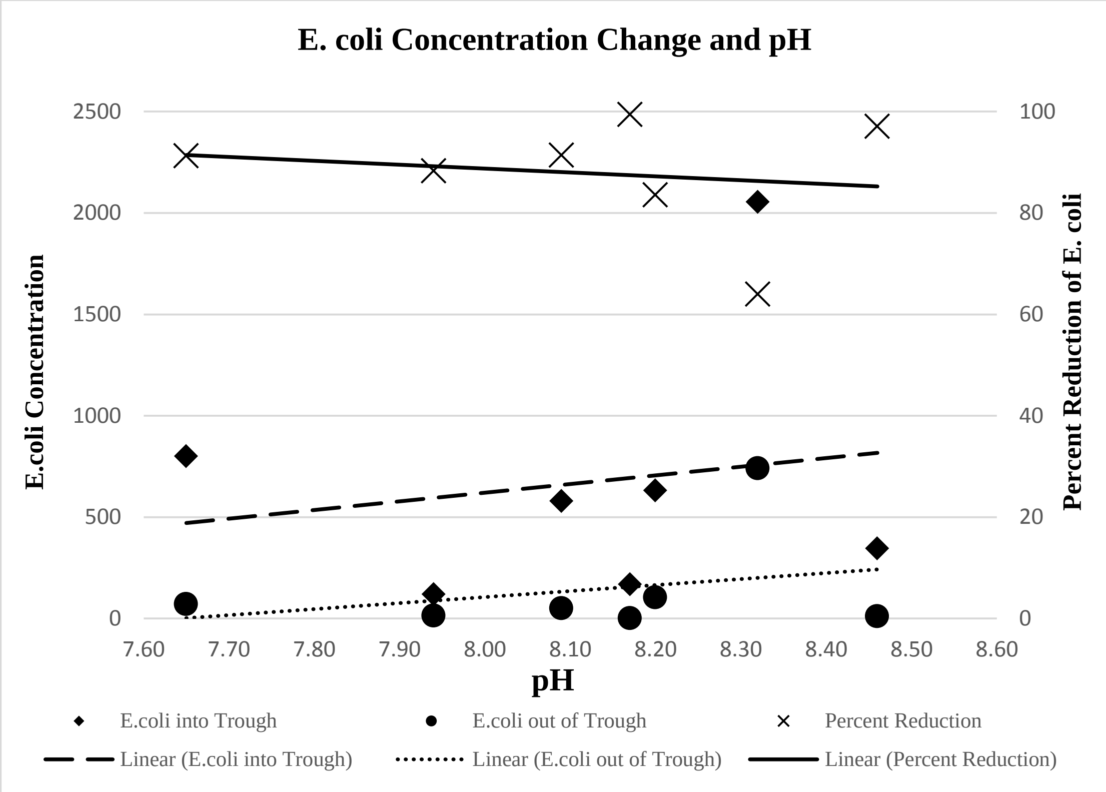

Figure 5.44 Relation between Water pH and E. coli Concentration Change in Trough 3

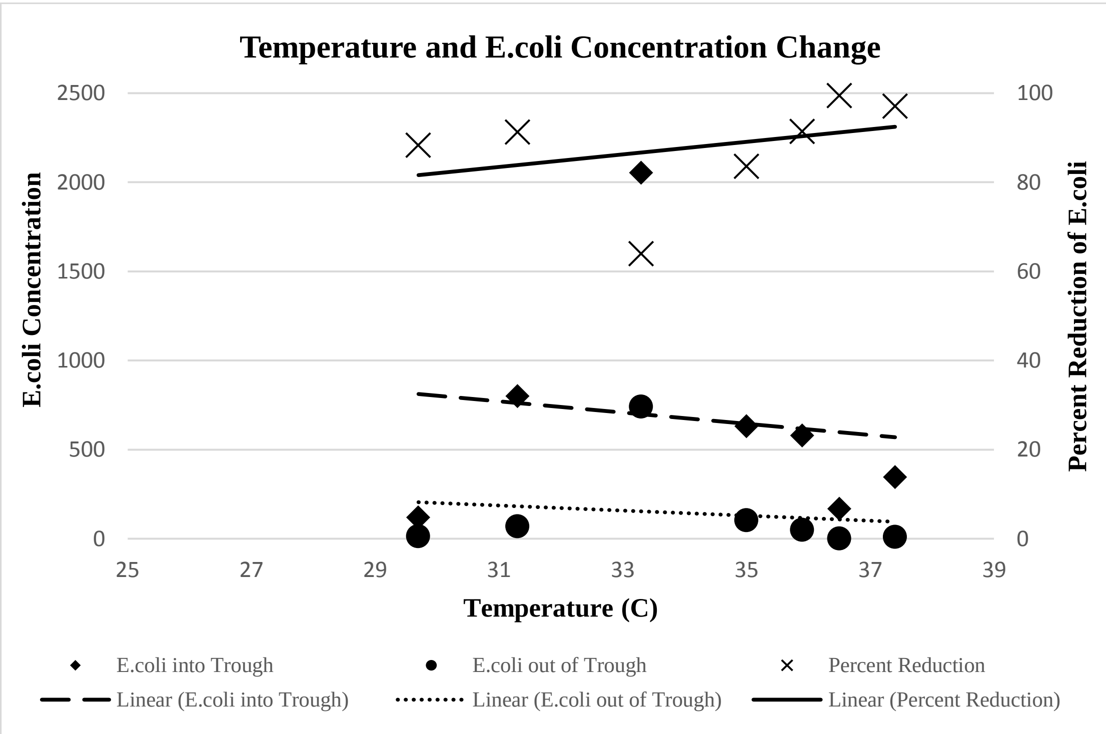

Figure 5.45 Relation between Water Temperature and E. coli Concentration Change in Trough 3

Tables 5-31, and 5-32 gives the E. coli concentration changes in trough 4 with respect to solar radiation, and pH, temperature respectively. Figures 5.46, 5.47 and 5.48 shows the graphical representation of the relation between *E.coli* concentration changes between water at input and output, with respect to average solar radiation, pH and temperature. Figures 5.49 and 5.50 shows the graphical representation of relation between *E. coli* concentration change and final pH and final temperature in all troughs during scenario II.

Table 5-31 E. coli Concentration Changes in Trough 4 when Flow is 7.3 gal/hr for 5.0 hrs

Date	Average Solar Radiation (W/m^2)	E.coli Concentration (Colonies/100ml)			Change	
		Into Trough	Out of Trough	Difference	Percent	Log
23 – Aug	821.83	925	50	875	94.59	1.27
22 – Aug	799.50	240	4	236	98.33	1.78
25 – Aug	796.67	76	16	60	78.95	0.68
26 – Aug	699.83	452	10	442	97.79	1.66
15 – Aug	632.17	864	440	424	49.07	0.29
19 – Aug	582.17	200	8	192	96.00	1.40
13 - Aug	556.17	420	34	386	91.90	1.09

Table 5-32 Water pH and Temperature Changes in Trough 4 in Scenario III

Date	Average Solar Radiation (W/m^2)	pH		Temperature	
		Out of Filter	In Trough	Out of Filter	In Trough
2014-08-13	821.83	7.66	7.87	23.3	33
2014-08-15	632.17	8.05	8.13	27.7	34.1
2014-08-19	796.67	7.84	7.98	24.1	31.4
2014-08-22	699.83	8.15	8.26	27.3	38
2014-08-23	556.17	8.16	8.30	28.8	35
2014-08-25	582.17	8.04	8.26	28.7	36.9
2014-08-26	799.50	8.02	8.24	27.5	37.1

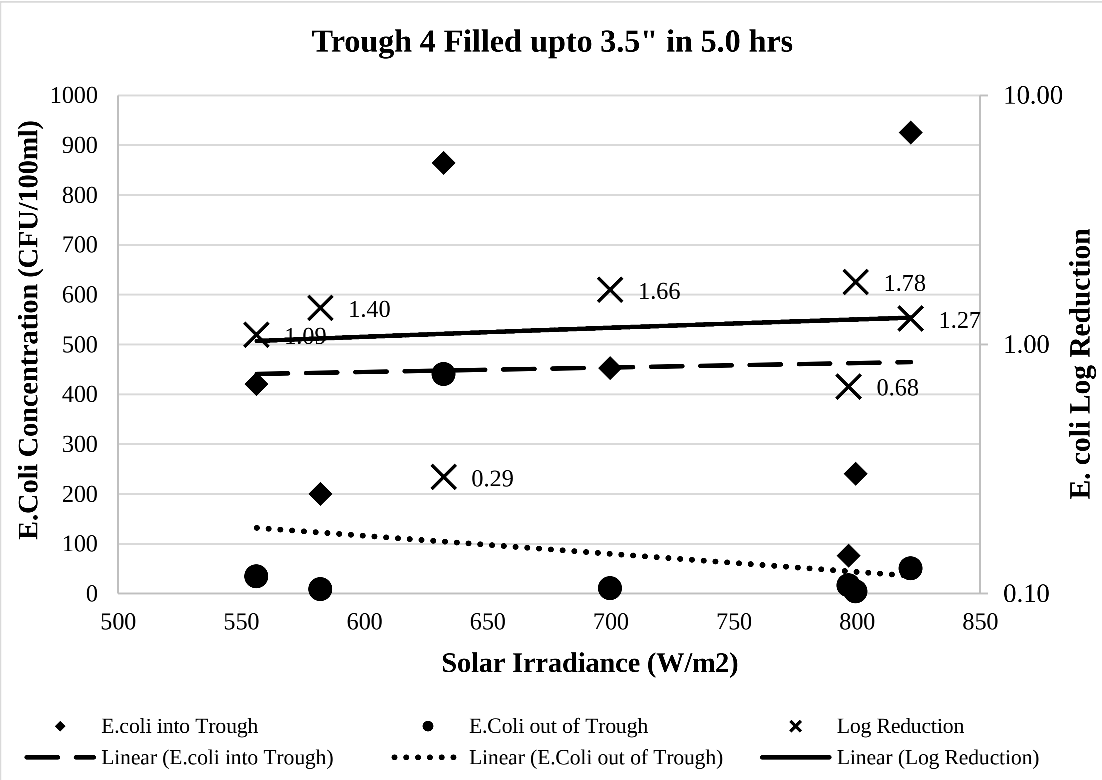

Figure 5.46 E. coli Concentration Changes in Trough 4 when Flow is 7.3 gal/hr for 5.0 hrs

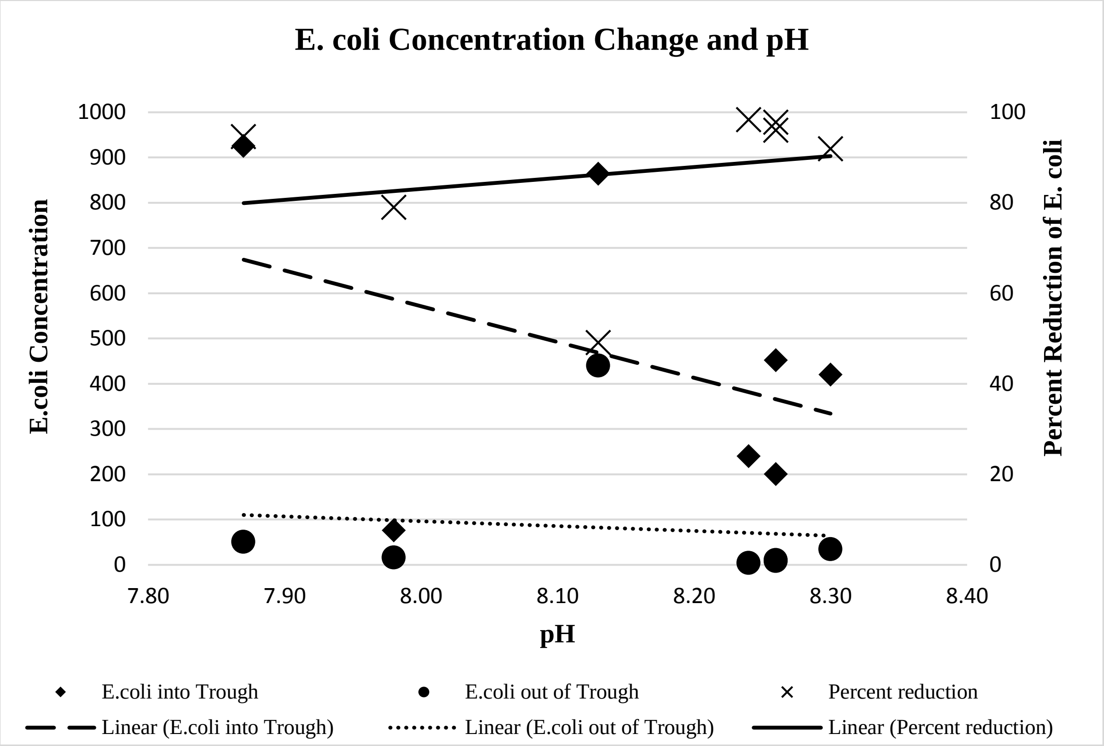

Figure 5.47 Relation between Water pH and E. coli Concentration Change in Trough 4

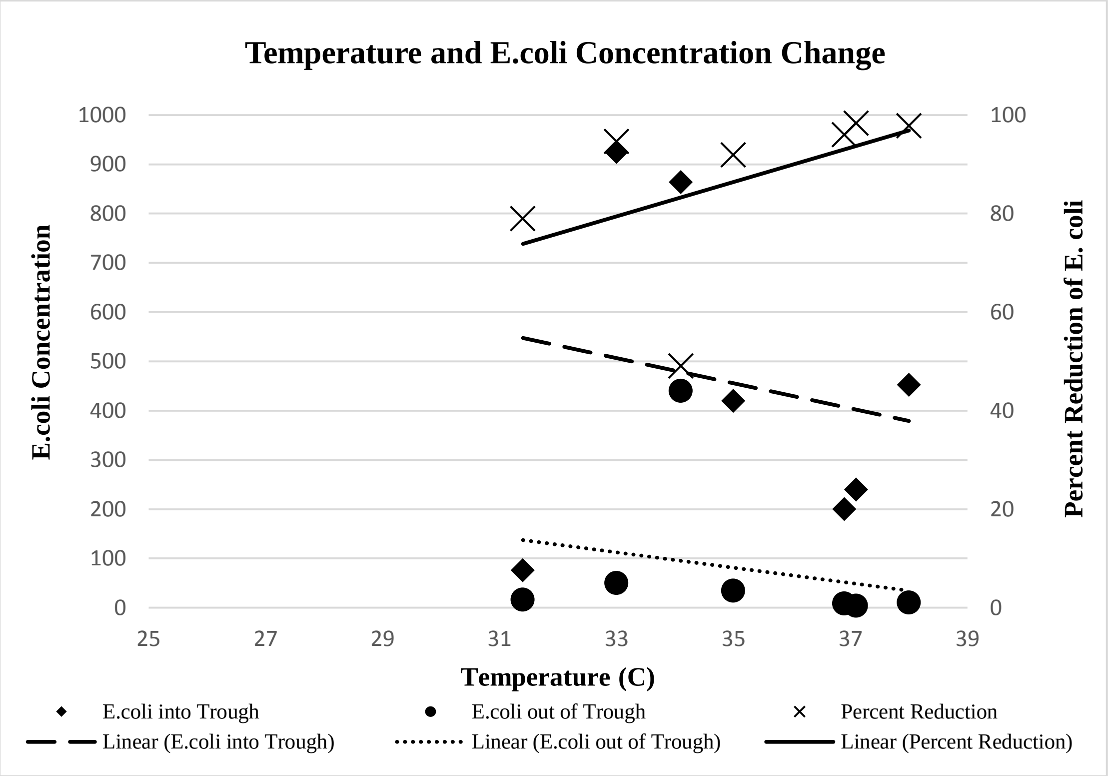

Figure 5.48 Relation between Water Temperature and E. coli Concentration Change in Trough 4

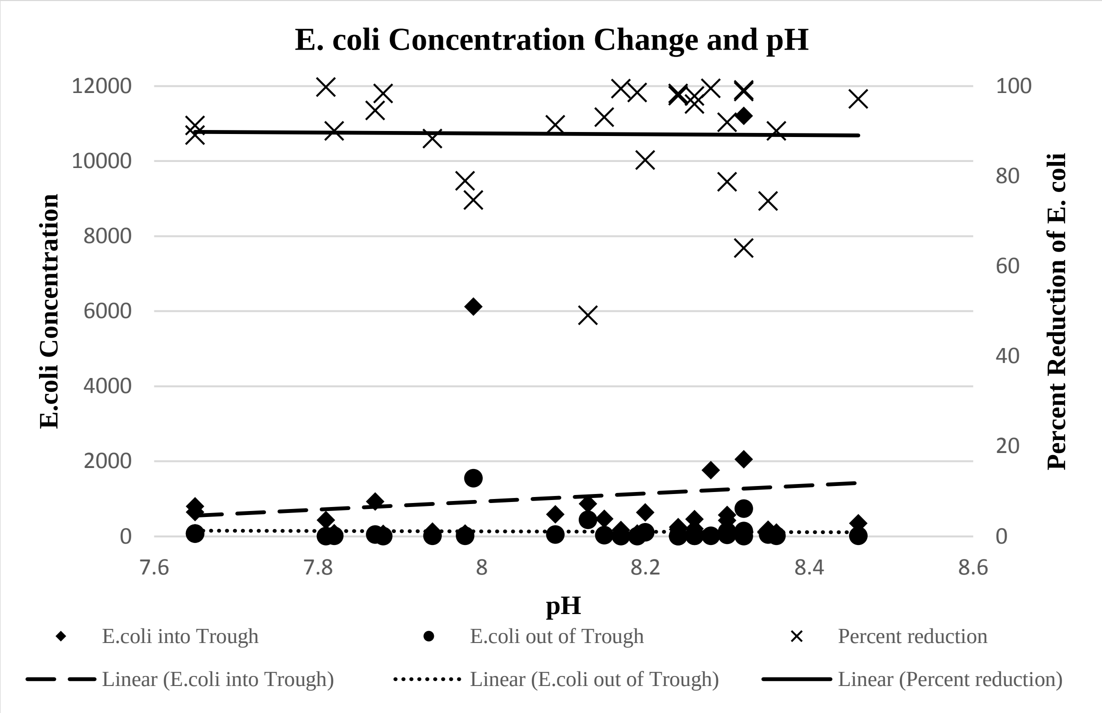

Figure 5.49 Relation between Water pH and E. coli Concentration Change in all Troughs in Scenario III

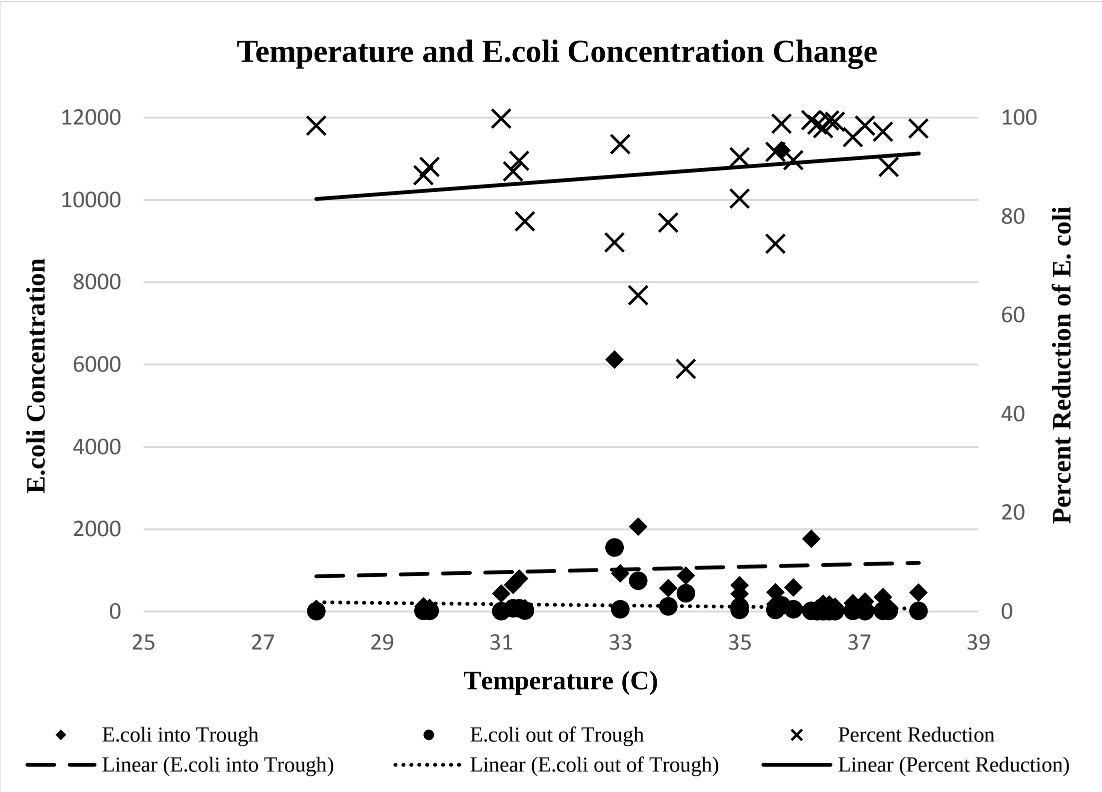

Figure 5.50 Relation between Water Temperature and E. coli Concentration Change in all Troughs in Scenario III

Discussion

In this scenario all troughs performed better than the previous scenarios. None of the troughs recorded negative values in *E. coli* reduction. This is due to the reduced targeted flow depth. Trough 1 performed better than the other troughs. *E. coli* concentration of 0 colony/100ml is expressed as 1 colony/100ml in the data tables above. This is done because when the end concentration is zero the percentage reduction will be 100%. And expressing a 100% reduction in log reduction is not possible.

Water temperatures in troughs reached 38° C during one event in trough 4. Water pH never recorded values below 4.0 or above 9.0.

5.3.3 SODIS Discussion

E. coli reduction is observed in all four troughs in all the scenarios. By observation, all four troughs performed better in scenario III in reducing *E. coli* concentration. A statistical analysis was performed on all the three scenarios for finding out the better performed scenario and trough in reducing the *E. coli* concentration. For this irradiation values are divided into three groups. Group 1 denotes the values between 0 W/m^2 and 600 W/m^2; group 2 denotes values between 601 W/m^2 and 750 W/m^2; group 3 denotes values between 751 W/m^2 and 900 W/m^2.

The effects of the different factors on the *E. coli* reduction is analysed at a significance level of 95%. A Box Cox transformation of the response variables was performed to make sure the residual's assumptions are maintained. With a p-value of 0.075, scenario and irradiation; trough and irradiation combinations are shown to be significant. Table 5-33 shows the ANOVA results obtained from Minitab. The significant features are Scenario, Trough, and the interaction between Scenario and

Irradiation Group, Trough and Irradiation Group. The associated p-values of their significance is highlighted in the table 5-33.

Table 5-33 ANOVA Results from Minitab

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Scenario	2	315495681	249546733	124773367	34.68	0.000
Trough	3	57768336	49811552	16603851	4.61	0.006
Irr Grp	2	8110314	6063429	3031715	0.84	0.436
Scenario*Trough	6	38100295	21397299	3566216	0.99	0.441
Scenario*Irr Grp	4	61232405	65511641	16377910	4.55	0.003
Trough*Irr Grp	6	44231871	44231871	7371978	2.05	0.075
Error	53	190702891	190702891	3598168		
Total	76	715641793				

The ANOVA shows that the factors mentioned above are significant. To better understand the levels at which the performance is significant, a pairwise Tukey test is performed on these factors. The results of the pairwise Tukey test are shown in Table 5-34 and 5-35. Grouping denotes the grading of the parameters. The grouping value A denotes most significant factor, grouping value, B denotes significance better than C and D. The Scenario III at Irradiation groups 1, 2 and 3 are the ones, which have statistically significant highest percentage reduction in the *E. coli* concentration. This is because of the reduced flow rate that resulted in attaining compared to other scenarios, which resulted in increased solar radiation penetrated in to deeper depth of water. Troughs 1 and 2 with maximum grouping value A are significant in reducing *E. Coli* when compared to troughs 3 and 4 who have maximum grouping value B. Scenario III which have reduced depth because of reduced flow rate when compared to previous scenarios. The time of exposure for scenario III is 5.0 hrs which is greater than scenario I and lower than scenario II. In the same way, flow depth attained in scenario III is lower than scenarios II and I. All three irradiation groups in scenario III attained a grouping value of A, which have not happened with the other two scenarios with respect to three irradiation groups. This proves that flow depth is also an important factor along with irradiation in reducing *E. coli* in water. Therefore, it can be stated that a low flow depth with a high irradiation value can help in better reduction of *E. coli.*

Table 5-34 Tukey Test Results for Scenario, Irradiance and E. coli Reduction

Scenario	Irr Grp	N	Mean	Grouping
III	3	12	8698.1	A
III	1	8	7721.9	A B
III	2	8	7321.4	A B C
II	1	4	6311.8	C D
I	2	16	4569.8	B C D
II	2	4	4246.4	C D
II	3	13	4015.3	D
I	1	10	2115.2	D
I	3	2	968.5	C D

Table 5-35 Tukey-Test Results for Trough Performance

Trough	N	Mean	Grouping
1	19	6362.7	A
2	21	5351.6	A B
3	20	4230.6	B
4	17	4485.4	B

5.4 Conclusion

Summary of Findings

Filter 1 and Trough 1 performed better in reducing *E. coli* concentration. Filter 1 performance increased gradually and the percentage drops is because of the frequent disturbance applied on the top layers of the sand for increased out flow rate from the filter. Trough 1 had reduced bacterial loading because of the sand filter (Filter 1) connected to the trough. This also helped in better performance of the trough in SODIS in reducing the *E. coli* concentration. pH and temperatures have never achieved the disinfection standards. Reduction of water depth from 8 inches to

3.5 inches, though the average receiving solar radiation decreased, increased the efficiency of all the four troughs. This is also demonstrated by the statistical analysis of the SODIS. *NPDES'* 2012 recreational water quality report states that an average 30-day *E. coli* concentration in water should not exceed 126 colonies/100ml to access water for recreation. Table 5-36 shows the average of the *E. coli* concentration at the outlet of troughs in scenario III. Troughs 2 and 4 performed better in achieving the targeted *E. coli* concentration for recreational water. However, when compared the amount of *E. coli* reduction trough 1 performed better than rest of the three. Table 5-37 shows the number testing events per filter and number of occasions a filter achieved the NPDES' limit on *E. coli* concentration in recreational water. Filter 1 performed better than rest of the three filters in achieving the limits in 9 occasions out of 18 testing events.

Research Contribution

The previous discussion illustrates that open channel SODIS can be an effective off-stream water treatment concept for reducing the *E. coli* concentration. SODIS can perform better if a filtration unit is installed prior to it. Optical inactivation of bacteria in water by sunlight is achievable with reduced suspended particles and lower flow depths. This is demonstrated in the scenario III, in which water depth was reduced from previous scenarios. The reduction in outflow rate from filters increased the retention time in filters, increased the filters performance, and reduced the suspended particles loading on SODIS system. In this study, system 1 that consists of Filter 1 and Trough 1 performed better than other systems.

Table 5-36 SODIS' Performance in Achieving NPDES RWQ Report 2012

Trough	1	2	3	4
Average *E. coli* Concentration (colonies/100ml)	290.71	36.71	141.3	80.3
No. of Occasions When Minimum *E. coli* concentration is achieved in 7 events	4	7	6	6

Table 5-37 Filters' Performance in Achieving NPDES RWQ Report 2012

Filter	1	2	3	4
Number of Testing Events	18	25	24	23
No. of Occasions When Minimum *E. coli* concentration is achieved	9	5	3	3

Environmental Education and Community Engagement

This project is one of the components of Beargrass Falls which is serving as a public display of renewable and sustainable urban runoff pollutant reduction concepts. Project is constructed on the bank of Beargrass creek near the MSD pumping station. Raw water used for this project is drawn from the Beargrass creek, an urban stream in Louisville metro area. The urban stream is highly polluted and access is restricted to public for recreational activities. Beargrass fall is developed as an educational and informational place to increase the awareness about urban stream protection in public. These concepts involve adoption of best management practices (BMPs) like pervious pavements (by MSD), rain garden and rain barrels (by University of Kentucky). These BMPs help in reducing the polluted rain water runoff getting into the urban streams and this helps in reducing the pollution levels in streams. In other way this project also helps in reducing the pollution but post pollution getting into the streams.

To achieve these educational sessions for students are being conducted by UofL Civil Engineering Dept. and Get Outdoors Kentucky. The sessions start with students going on canoe tour on Beargrass creek. Students were taught about history of Beargrass creek, urbanization effects on streams, and stress on ecology in streams due to pollution. The final step of this tour is visiting the park and learning about the sustainable concepts in reducing the pollution flowing into the creek. This project is located in the Butcher Town green way. The hikers, bikers and runners accessing the greenway stops at the park and learn about the sustainable concepts. International exchange student groups visited the park for learning the sustainable concepts.

5.5 Recommendations and Future Work

It is demonstrated that *E. coli* concentration reduction due to solar radiation can be increased by reducing water depth. This project used the semi-circular troughs for SODIS. An increased water surface area and decreased water depth can effectively increase the *E. coli* reduction. Usage of an half elliptical shaped trough can increase water surface area exposed to sun light than the semi-circular trough and reduced water depth helps in increasing the solar radiation effects at deeper depths. *E. coli* is used as the indicator of biological water quality. Analysing water samples for bacteria other than *E. coli* can help in testing the system's efficiency in changing the other bacterial concentrations. Filters' performance can be increased by increasing the retention time of water in filter. This can be achieved by reducing the inflow and outflow. Reduction of inflow also helps in reducing the overflow of water from the filters. And also introduction of sedimentation chamber prior to filtration can reduce the loading on filters. A combination of filtration and SODIS can achieve better reduction of *E. coli*. This project considered *E. coli* as water quality indicator. It will be better to analyze water samples for other bacterial and virus concentrations. As the raw water used for this project is drawn from Beargrass creek, which is a polluted urban stream and water is polluted with all the possibilities from biological (sewer over flows, dry leaves. etc) to chemical (gasoline from street surface, fertilizers from gardens and back yards. etc), usage of better quality raw water for treatment can result in achieving the better purification and better output water quality.

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APPENDIX A

STATISTICAL ANALYSIS RESULTS

A.1 General Linear Model: Percent Reduction of *E. coli* by Filters

Method

Factor coding	(-1, 0, +1)

Box-Cox transformation

Rounded λ	1.4218
Estimated λ	1.4218
90% CI for λ	(1.07830, 1.79530)

Factor Information

Factor	Type	Levels	Values
Filter	Fixed	4	1, 2, 3, 4

Analysis of Variance for Transformed Response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Filter	3	501597	167199	5.04	0.003
Error	86	2854762	33195		
Total	89	3356359			

Model Summary for Transformed Response

S	R-sq	R-sq(adj)	R-sq(pred)
182.195	14.94%	11.98%	6.94%

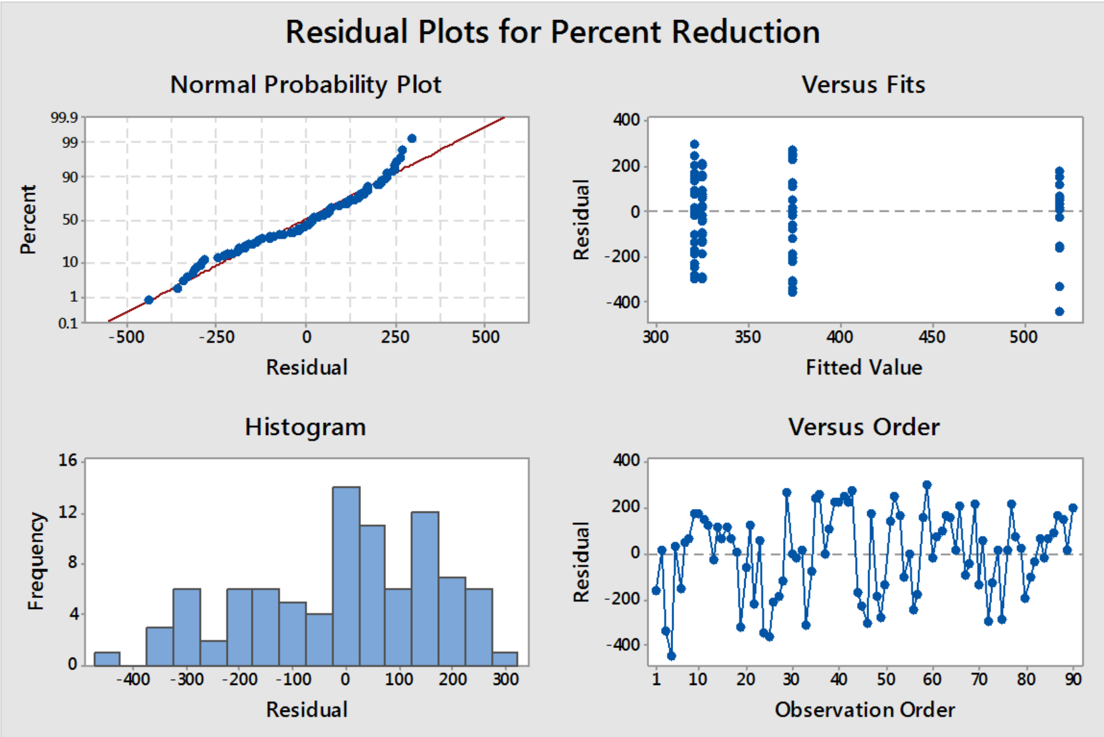
Coefficients for Transformed Response

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	385.0	19.4	19.88	0.000	
Filter					
1	134.4	36.0	3.73	0.000	1.63
2	-10.6	32.2	-0.33	0.744	1.53
3	-63.6	33.1	-1.92	0.058	1.5z

Regression Equation

Percent Reduction^1.4218 = 385.0 + 134.4 Filter_1 - 10.6 Filter_2 - 63.6 Filter_3
- 60.2 Filter_4

Residual Plots for Percent Reduction



Comparisons for Percent Reduction

Tukey Pairwise Comparisons: Response = Percent Reduction, Term = Filter

Grouping Information Using the Tukey Method and 90% Confidence

Filter	N	Mean	Grouping
1	18	81.2633	A
2	25	64.5554	B
4	24	58.4153	B
3	23	57.9762	B

Means that do not share a letter are significantly different.

A.2 General Linear Model: Log Reduction

Method
Factor coding (-1, 0, +1)

Box-Cox transformation
Rounded λ 0.5
Estimated λ 0.415773

90% CI for λ (0.253273, 0.581273)

Factor Information

Factor	Type	Levels	Values
Filter	Fixed	4	1, 2, 3, 4

Analysis of Variance for Transformed Response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Filter	3	1.376	0.45883	6.90	0.000
Error	86	5.717	0.06648		
Total	89	7.094			

Model Summary for Transformed Response

S	R-sq	R-sq(adj)	R-sq(pred)
0.257840	19.40%	16.59%	11.53%

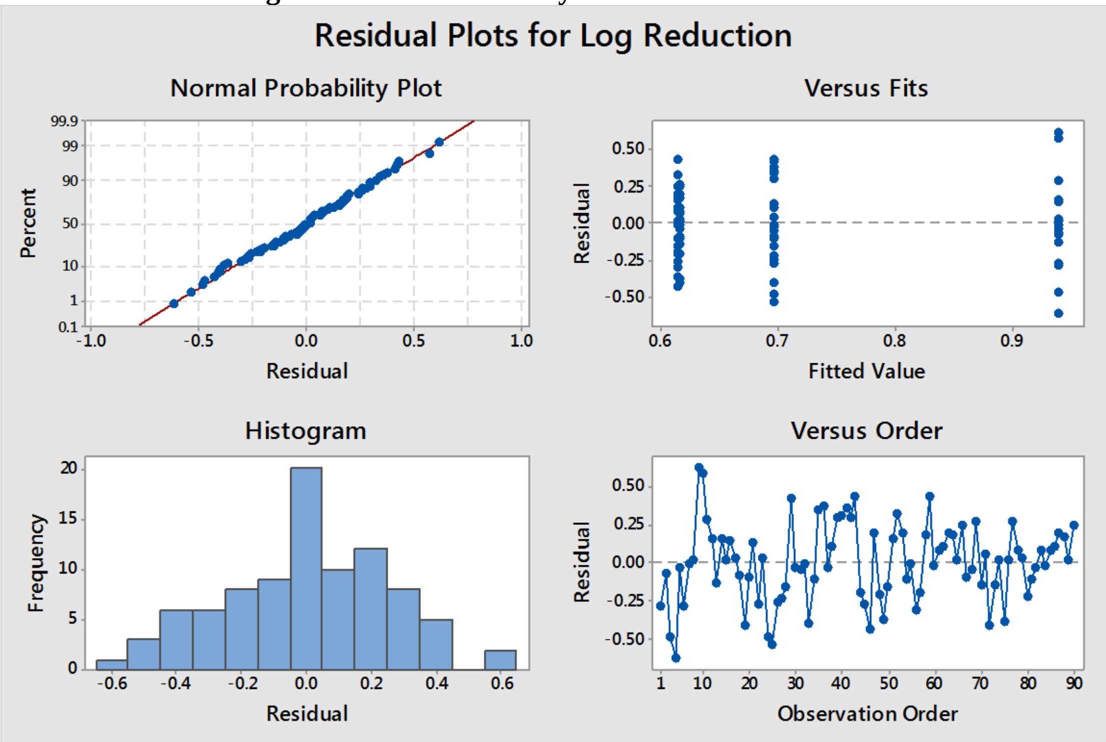
Coefficients for Transformed Response

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.7172	0.0274	26.17	0.000	
Filter					
1	0.2233	0.0510	4.38	0.000	1.63
2	-0.0198	0.0456	-0.43	0.665	1.53
3	-0.1023	0.0469	-2.18	0.032	1.55

Regression Equation

Log Reduction^0.5 = 0.7172 + 0.2233 Filter_1 - 0.0198 Filter_2 - 0.1023 Filter_3
- 0.1012 Filter_4

Residual Plots for Log Reduction of *E. coli* by Filters



Comparisons for Log Reduction

Tukey Pairwise Comparisons: Response = Log Reduction, Term = Filter

Grouping Information Using the Tukey Method and 90% Confidence

Filter	N	Mean	Grouping
1	18	0.884643	A
2	25	0.486361	B
4	24	0.379458	B
3	23	0.378171	B

Means that do not share a letter are significantly different.

A.3 General Linear Model: Percent reduction of *E. coli* by SODIS

Method

Factor coding	(-1, 0, +1)

Box-Cox transformation

Rounded λ	2
Estimated λ	1.82657
90% CI for λ	(1.34307, 2.34107)

Factor Information

Factor	Type	Levels	Values
Scenario	Fixed	3	1, 2, 3
Thorousgh	Fixed	4	1, 2, 3, 4
Solar Radiation	Fixed	3	1, 2, 3

Analysis of Variance for Transformed Response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	2	304133625	152066812	31.39	0.000
Thorousgh	3	57025931	19008644	3.92	0.012
Solar Radiation	2	8110314	4055157	0.84	0.437
Error	69	334267462	4844456		
Lack-of-Fit	26	171494333	6595936	1.74	0.052
Pure Error	43	162773129	3785422		
Total	76	715641793			

Model Summary for Transformed Response

S	R-sq	R-sq(adj)	R-sq(pred)
2201.01	53.29%	48.55%	41.45%

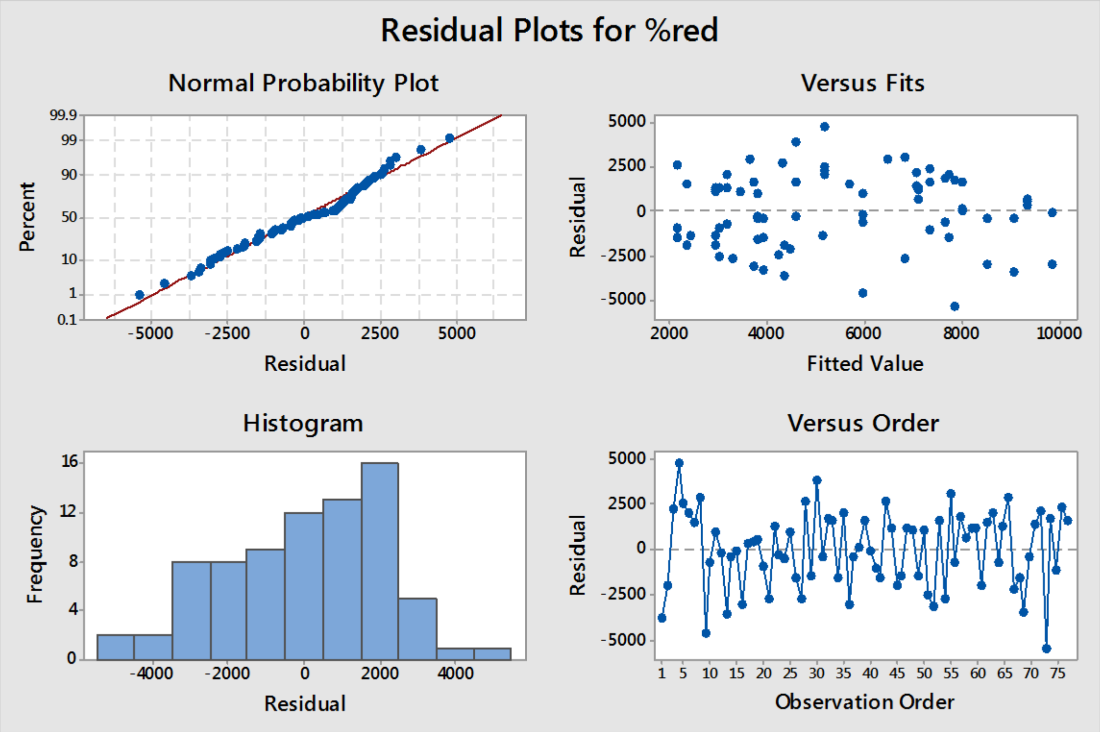
Coefficients for Transformed Response

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	5341	256	20.87	0.000	
Scenario					
1	-2004	398	-5.04	0.000	1.83
2	-693	405	-1.71	0.092	1.64
Thorousgh					
1	1398	438	3.19	0.002	1.42
2	48	424	0.11	0.909	1.40
3	-829	433	-1.92	0.060	1.42
Solar Radiation					
1	-360	376	-0.96	0.342	1.42
2	444	370	1.20	0.235	1.56

Regression Equation

Percent reduction^2 = 5341 - 2004 Scenario_1 - 693 Scenario_2 + 2697 Scenario_3 + 1398 Thorousgh_1 + 48 Thorousgh_2 - 829 Thorousgh_3 - 618 Thorousgh_4 - 360 Solar Radiation_1 + 444 Solar Radiation_2 - 84 Solar Radiation_3

Residual Plots for Percent reduction



Comparisons for Percent reduction

Tukey Pairwise Comparisons: Response = Percent reduction, Term = Scenario

Grouping Information Using the Tukey Method and 90% Confidence

Scenario	N	Mean	Grouping	
3	28	89.6542	A	
2	21	68.1717		B
1	28	57.7635		B

Means that do not share a letter are significantly different.

Tukey Pairwise Comparisons: Response = Percent reduction, Term = Thorousgh

Grouping Information Using the Tukey Method and 90% Confidence

Thorousgh	N	Mean	Grouping	
1	19	82.0895	A	
2	21	73.4099	A	B
4	17	68.7225		B
3	20	67.1717		B

Means that do not share a letter are significantly different.

Tukey Pairwise Comparisons: Response = Percent reduction, Term = Solar Radiation

Grouping Information Using the Tukey Method and 90% Confidence

Solar Radiation	N	Mean	Grouping
2	28	76.0558	A
3	27	72.5003	A
1	22	70.5770	A

Means that do not share a letter are significantly different.

A.4 General Linear Model: Log reduction of *E. coli* by SODIS

Method

Factor coding	(-1, 0, +1)

Box-Cox transformation

Rounded λ	0.195768
Estimated λ	0.195768
90% CI for λ	(0.00926810, 0.383268)

Factor Information

Factor	Type	Levels	Values
Scenario	Fixed	3	1, 2, 3
Thorousgh	Fixed	4	1, 2, 3, 4
Solar Radiation	Fixed	3	1, 2, 3

Analysis of Variance for Transformed Response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	2	0.65219	0.32609	28.44	0.000
Thorousgh	3	0.13624	0.04541	3.96	0.012
Solar Radiation	2	0.02798	0.01399	1.22	0.302
Error	69	0.79129	0.01147		
Lack-of-Fit	26	0.35727	0.01374	1.36	0.181
Pure Error	43	0.43403	0.01009		
Total	76	1.62384			

Model Summary for Transformed Response

S	R-sq	R-sq(adj)	R-sq(pred)
0.107089	51.27%	46.33%	39.02%

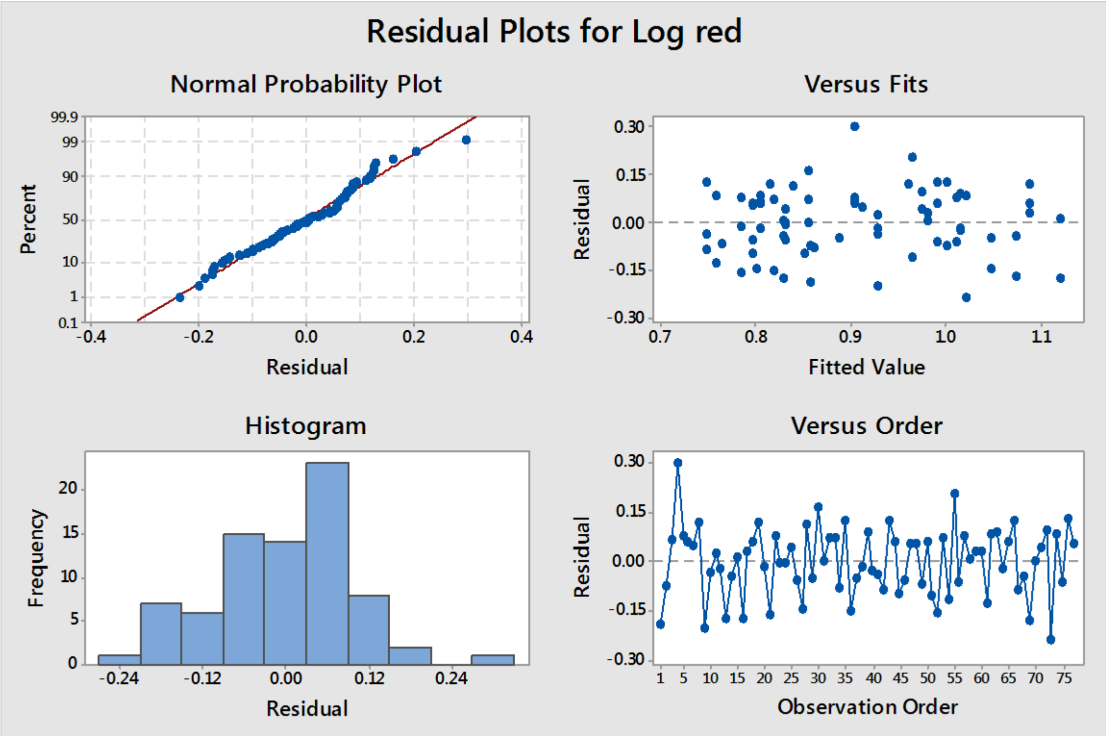
Coefficients for Transformed Response

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.8997	0.0125	72.26	0.000	
Scenario					
1	-0.0905	0.0194	-4.67	0.000	1.83
2	-0.0351	0.0197	-1.78	0.080	1.64
Thorousgh					
1	0.0700	0.0213	3.29	0.002	1.42
2	-0.0027	0.0206	-0.13	0.898	1.40
3	-0.0386	0.0210	-1.83	0.071	1.42
Solar Radiation					
1	-0.0208	0.0183	-1.14	0.258	1.42
2	0.0262	0.0180	1.46	0.150	1.56

Regression Equation

Log red^0.195768 = 0.8997 - 0.0905 Scenario_1 - 0.0351 Scenario_2 + 0.1255 Scenario_3 + 0.0700 Thorousgh_1- 0.0027 Thorousgh_2- 0.0386 Thorousgh_3- 0.0288 Thorousgh_4 - 0.0208 Solar Radiation_1 + 0.0262 Solar Radiation_2 - 0.0054 Solar Radiation_3

Residual Plots for Log red



Comparisons for Log red

Tukey Pairwise Comparisons: Response = Log red, Term = Scenario

Grouping Information Using the Tukey Method and 90% Confidence

Scenario	N	Mean	Grouping	
3	28	1.13562	A	
2	21	0.47562		B
1	28	0.33908		B

Means that do not share a letter are significantly different.

Tukey Pairwise Comparisons: Response = Log red, Term = Thorousgh

Grouping Information Using the Tukey Method and 90% Confidence

Thorousgh	N	Mean	Grouping	
1	19	0.854503	A	
2	21	0.573941	A	B
4	17	0.493536		B
3	20	0.465841		B

Means that do not share a letter are significantly different.

Tukey Pairwise Comparisons: Response = Log red, Term = Solar Radiation

Grouping Information Using the Tukey Method and 90% Confidence

Solar Radiation	N	Mean	Grouping
2	28	0.674836	A
3	27	0.565027	A
1	22	0.517024	A

Means that do not share a letter are significantly different.

APPENDIX B

PRESENTATION

Community Engagement, Environmental Education, And Public Outreach in Sustainable Engineering – A Collaborative Demonstration Project For Water Treatment Using Natural Processes And Sustainable Materials

Ph.D. Defense

By Venkata D. Gullapalli

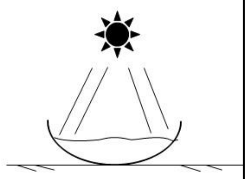
Advisor: Dr. Mark N. French

OUTLINE

- Research Statement
- Water Treatment
  - Filtration
  - Disinfection
- System construction and operation
- Results and discussion
- Future work

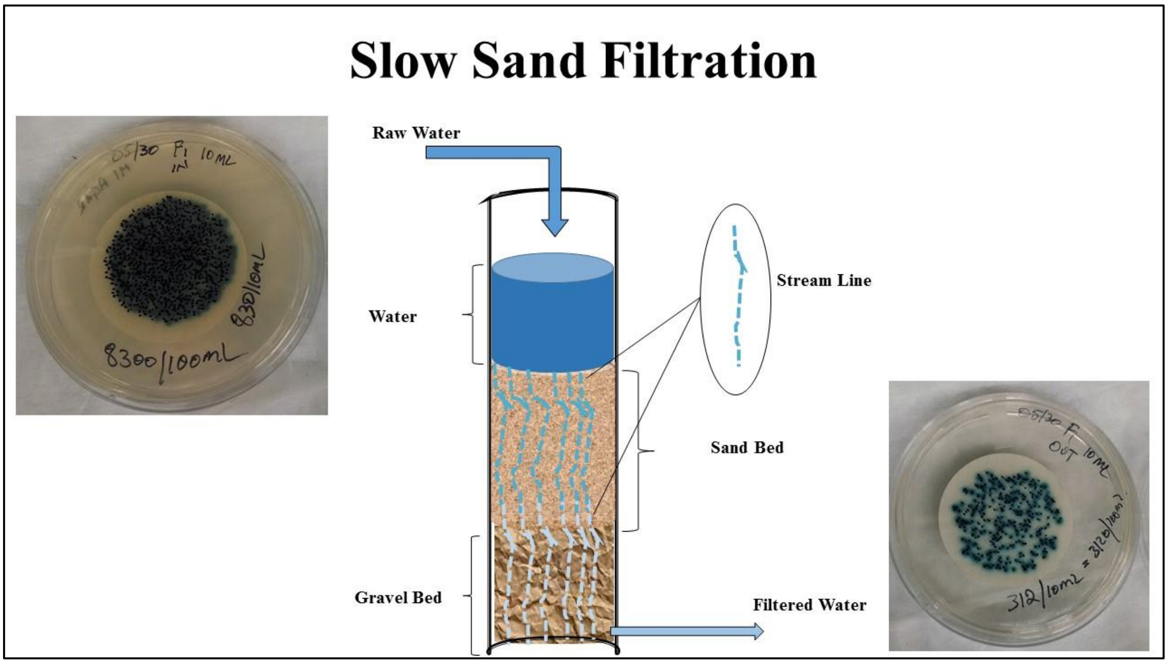
RESEARCH STATEMENT

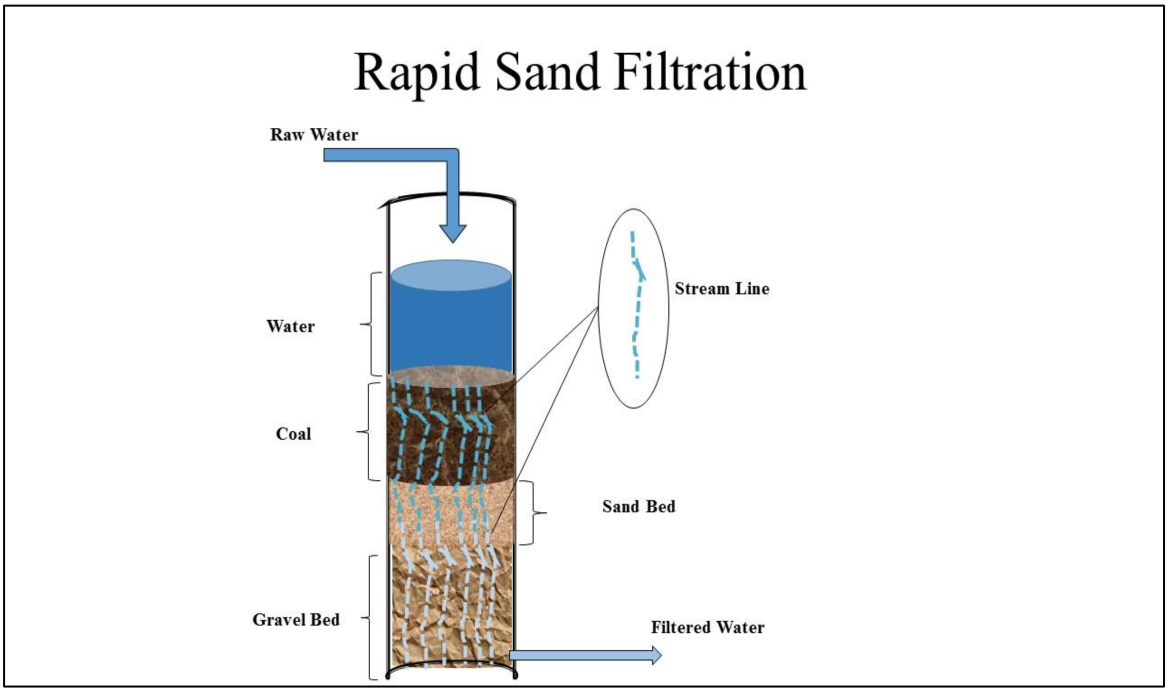
- Project tested:
  - Optical inactivation capacity of Sunlight in reducing Escherichia coli (*E. coli)* concentration in open channel flowing water
  - Filters' efficiency in reducing *E. coli* concentration in water
  - Achieving of National Pollution Discharge Elimination System (NPDES) 2012 recreational water quality report



Filtration

- Removes suspended particles and Bacteria over the time
- Types:
  - Slow sand filters
    - Uses sand and gravel
  - Rapid sand filters
    - Uses sand, gravel and activated charcoal or anthracite

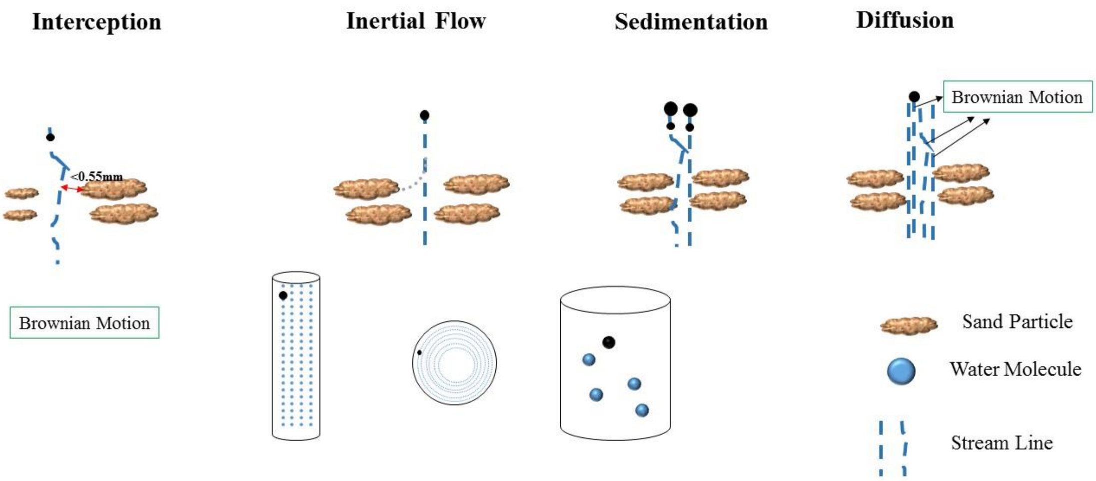

Slow Sand Filtration
Raw Water
Water
Stream Line
Sand Bed
Gravel Bed
Filtered Water
8300/100mL
312/10mL

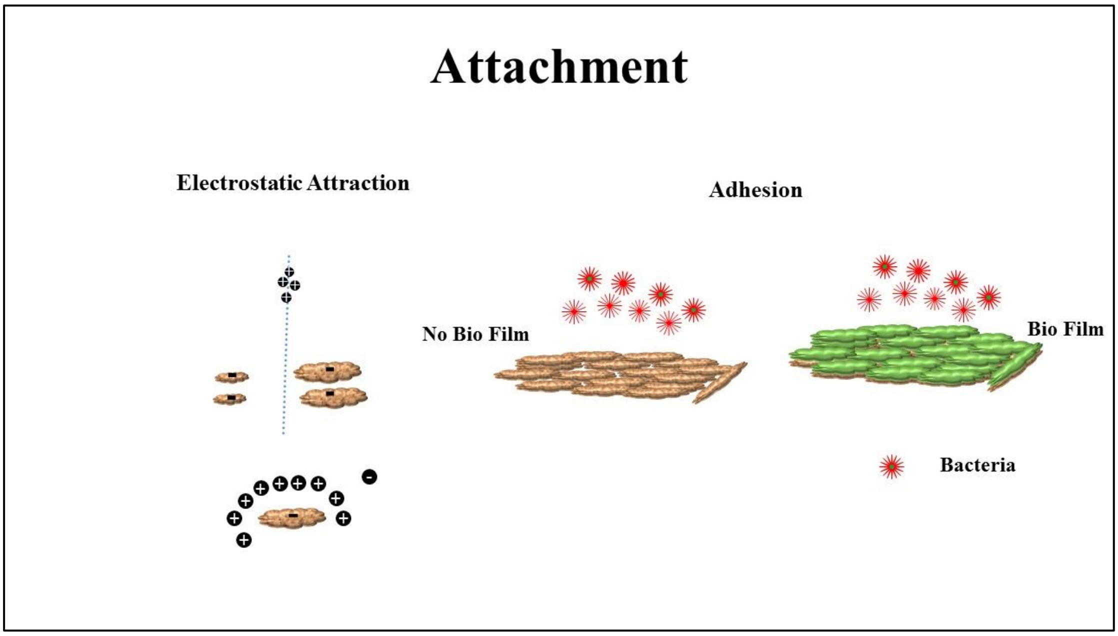

Rapid Sand Filtration
Raw Water
Water
Stream Line
Coal
Sand Bed
Gravel Bed
Filtered Water

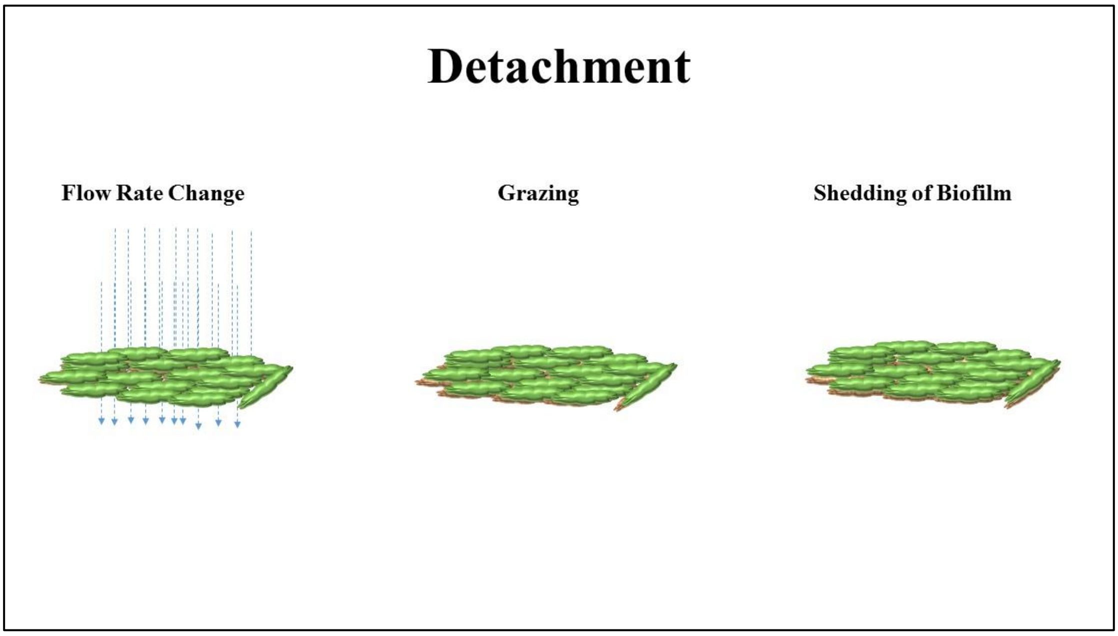
Filtration Mechanism

- Transport
- Attachment
- Detachment

Transport




Attachment
Electrostatic Attraction
Adhesion
No Bio Film
Bio Film
Bacteria


Detachment
Flow Rate Change
Grazing
Shedding of Biofilm

Slow and Rapid Sand Filters Difference

	Slow Sand	Rapid Sand
	Oldest and Economical	Expensive and replacing the slow sand filters
Serving Communities	Good for smaller communities	Can serve Larger communities
Power Consumption	Minimum to zero power consumption	Required
Operation	Easy to operate	Technical support required
Space for construction	Large space requirements	Not as much as for slowsand
Clogging issues	Happens frequently	Happens less frequently

Disinfection

- Final step of water treatment
- Clears bacterial and/or viral concentrations in water
- Methods involve
  - Chemical
    - Chlorination
    - Ozone
  - Non-chemical
    - Boiling
    - Membrane filtration
    - Ultra Violet (UV)

Chemical Disinfection

- Chlorination
  - Addition of Chlorine to water
    - Gaseous
    - Liquid
    - Solid
  - Reaction

$$Cl_2 + H_2O \rightarrow HCl + HOCl$$

- Hypochlorus Acid (HOCl) dissolves bacterial cell walls and make them harmless

Chemical Disinfection

- Ozone
  - Better performer than chlorine
  - Powerful oxidising agent
    - Releases hydrogen peroxyl and hydroxyl for oxidation
  - Disintegrates cell wall in bacteria
  - Highly unstable
  - In house generation is expensive

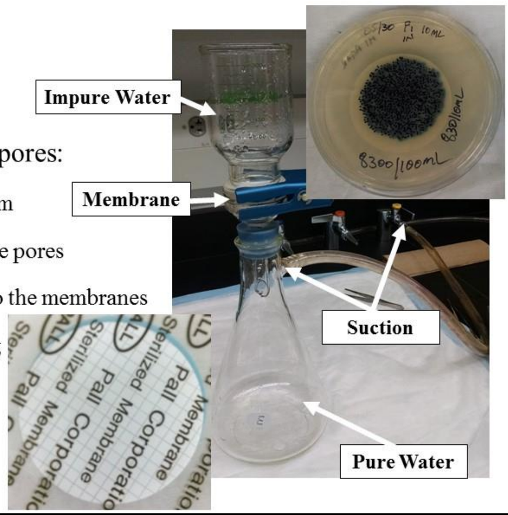
Non-Chemical Disinfection

- Boiling
  - Age old technique
  - At present used during the boil-water emergency
  - Heating water to the boiling point results in disinfection
    - Boiling time depends on the elevation of the site from sea level

Pic Ref: http://www.sswm.info/category/implementation-tools/water-purification/hardware/point-use-water-treatment/boiling

Non-Chemical Disinfection

- Membrane Filtration
  - A physical barrier with micro or nano pores:
    - Pores traps the impurities bigger than them
    - Bacteria, and virus also gets trapped in the pores
    - Requires pressure driven water flow on to the membranes
    - Automation for filtering and self cleaning



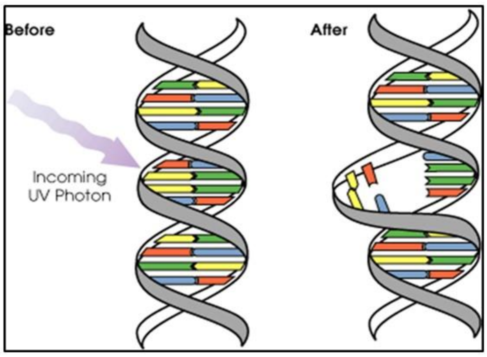
Non-Chemical Disinfection

- UV Disinfection
  - Uses artificial UVC radiation for disinfection
    - 285 nm radiation
    - Synthetic UV light bulbs
      - Inert gas, and liquid mercury
      - Mercury atoms gets excited to higher energy state after collision of free electrons and ions with the gaseous mercury atoms
    - Amount of UV light produced is influenced by the concentration of mercury atoms in the lamp

Disinfection Mechanism

UVB & UVC Disinfection

- Pyrimidine dimers are formed when bacterial DNA absorbs UVB or UVC

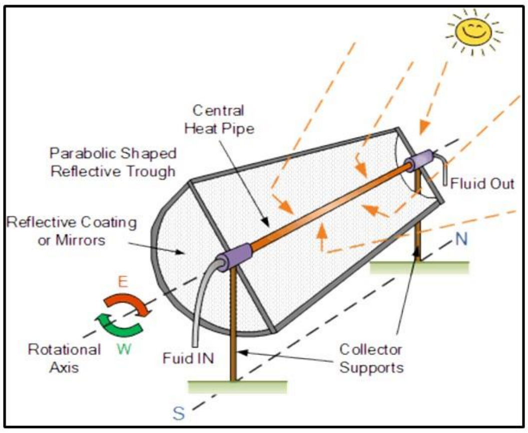


- Makes Bacteria incapable of reproducing
- Inability of reproduction makes it less pathogenic

Pic Ref: http://www.bath.ac.uk/

Solar Disinfection (SODIS)

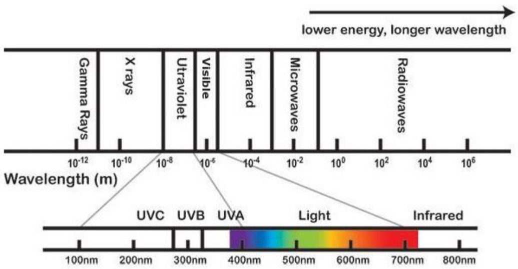
- Uses UVB, UVA, and IR radiations for disinfection
- Thermal Inactivation
- Optical Inactivation
- Combined Thermal and Optical Inactivation

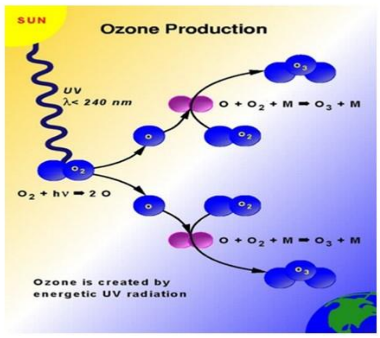


Pic Ref: http://www.alternative-energy-tutorials.com/

Solar Radiation

- Electromagnetic Radiation emitted by sun
- UV, Visible, IR
- 100% of UVC, 90% OF UVB and 10% of UVA blocked by Stratospheric Ozone





Newman, P. A., 1999, "SAGE III Ozone Loss and Validation Experiment, SOLVE A NASA DC-8, ER-2 and High Altitude Balloon Mission".

SODIS System

Thermal Inactivation

- Process of Inactivating bacteria by application of heat
- IR radiation helps in warming up the water
- Maintaining 50-60 °C temperature for 6 hr reduces the Bacterial concentration by 99.9%

SODIS

Optical Inactivation

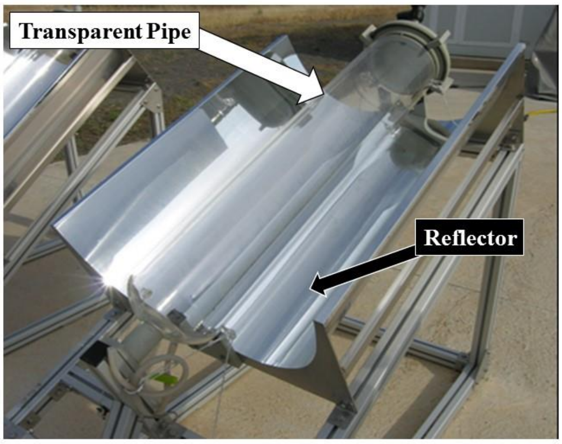
- UVB and UVA in solar radiation
  - UVB responsible for changing natural strain same as UVC in artificial UV disinfection
  - UVA responsible for generating Reactive Oxygen Species (ROS)
    - singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radical
  - ROS damages DNA and reduces the pathogenic effect of bacteria

SODIS

Combined Thermal and Optical Inactivation

- Thermal inactivation + Optical inactivation
- Mechanism in most of the SODIS systems

SODIS Systems

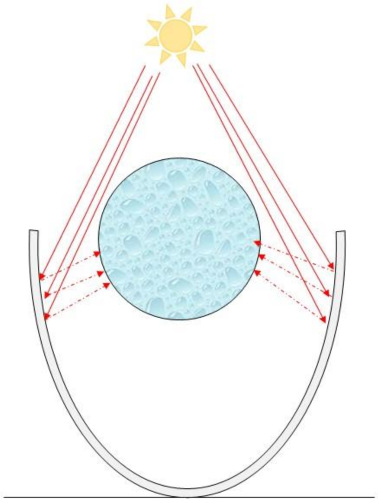


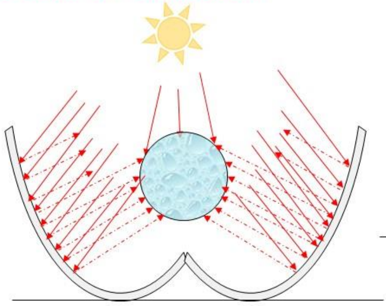
- Apparatus
  - Transparent circular pipes or PET bottles
    - Restrict heat loss
  - Reflectors
    - Concentrate the radiation

Pic Ref: http://www.colm-coffey.com/sodis/

SODIS Systems

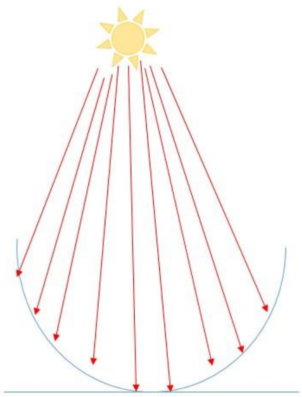
- Apparatus
    - Pipe material may obstruct UVB or UVA radiation
  - Reflectors
    - Concentrate the radiation
    - Requires expert supervision for construction



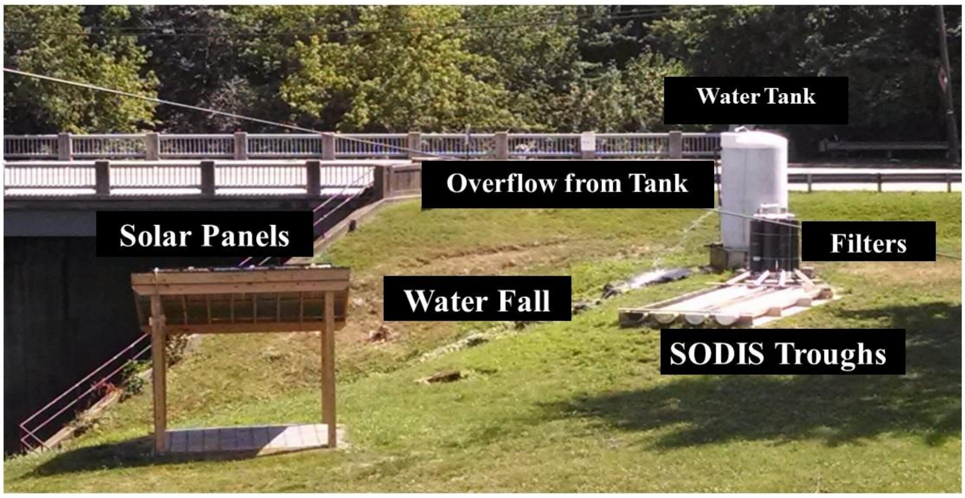


Project Significance

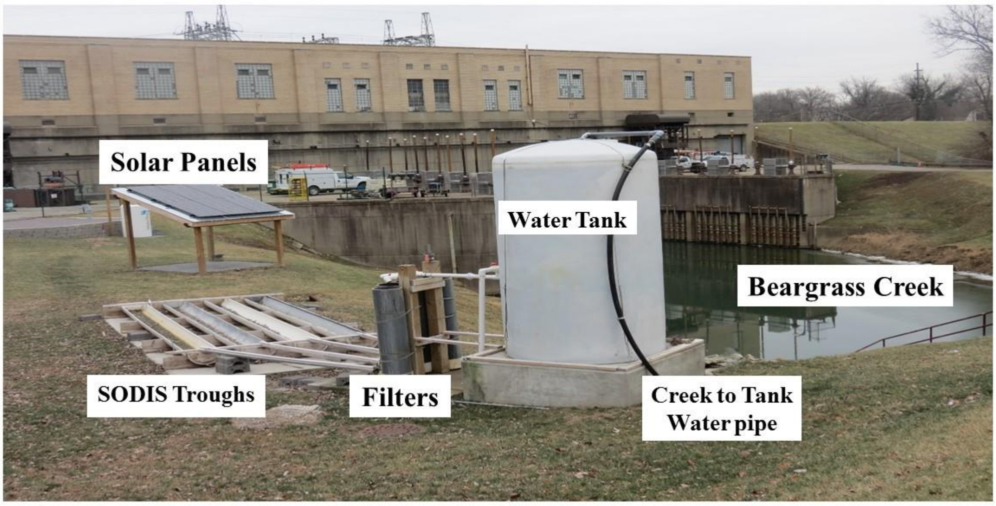
- Tested Optical inactivation capacity of sunlight
- Open channel can use both UVA and UVB radiations
- Semi-Circular troughs
    - Can increase the surface area exposed to sunlight



Project Components



Project Components



Solar Panels

- Six solar panels
  - Mounted on a gazebo
- Powers the pump installed in creek

Filter Materials

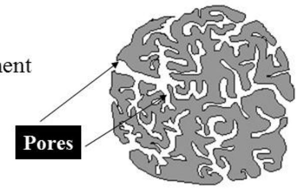
Sand

- Commonly available medium
- Successful in reducing suspended solids
- Successful in reducing bacterial concentration post Biofilm formation
- Preference should be given to local sand

Filter Materials

Activated Charcoal

- Common material used for removing taste and odour
- Impurities filtration dependent on the pore size
- Prepared from
  - Coconut shells, peanut shells, and wood products
  - Produced through
    - Carbonization
    - Gas or Chemical Treatment
    - Crushed



Filter Materials

- **Crushed Oyster Shells**
  - Proved as good reducers of Ammonical Nitrogen in water
  - Used as calcium supplement in Chicken industry
  - Particle size makes it to replace a coarser particle in filter

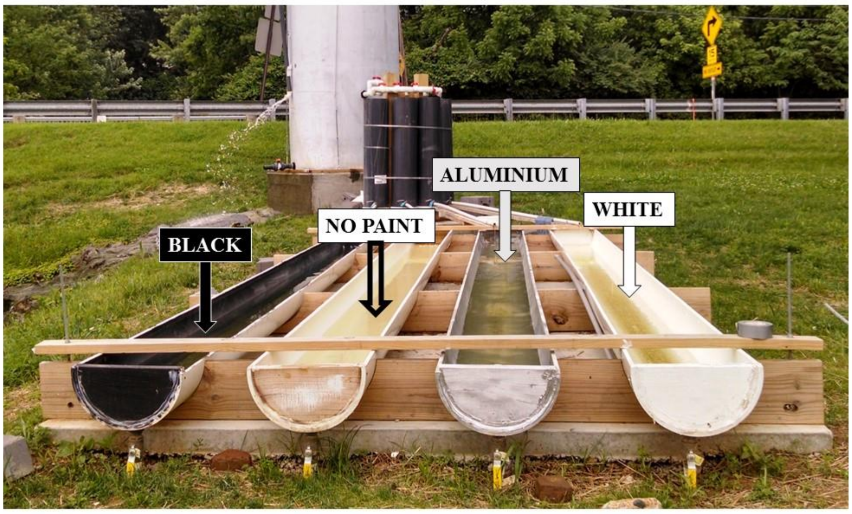
Filters

- Four filters
  - 20 feet long 1 foot dia schedule 80 pvc pipe
- Water from tanks flow into filters gravitationally
- Filtered water flows into SODIS troughs
- Water samples collected pre and post filtration

Filters

Filter	Filter Media
1	Gravel – 11″; Oyster Shells – 7″; Sand – 3.5″
2	Gravel – 11″; Oyster Shells – 6″ Activated Charcoal – 3.5″
3	Gravel – 11″; Activated Charcoal – 7″
4	Gravel – 11″; Oyster Shells – 7″

Solar Disinfection



Open Channel Flow SODIS

Trough	Paint	Purpose
1	White	Best reflector, Cheap reflecting agent
2	Spray painted Aluminum Finish	Better reflector than White but expensive
3	None	Left unpainted for control
4	Black	Absorbs more heat than other materials

Project Operation

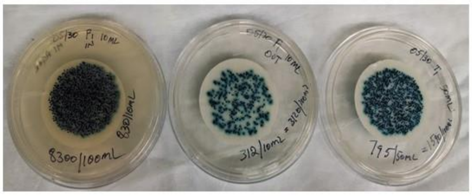
- Operated in TWO phases
  - Phase I - STATIC BATCH
    - Troughs filled with filtered water
  - Phase II - DYNAMIC
    - Troughs filled up-to a targeted depth over a period of time

Water Sample Collection

- Garb sampling
- 12 samples per event
  - 4 samples pre filtration
  - 4 samples post filtration/SODIS inlet
  - 4 samples post SODIS
- Samples transported to lab in a cooler bag
  - In 45 minutes after collection
  - Maintained temperature 1-4 °C

Water Sample Analysis

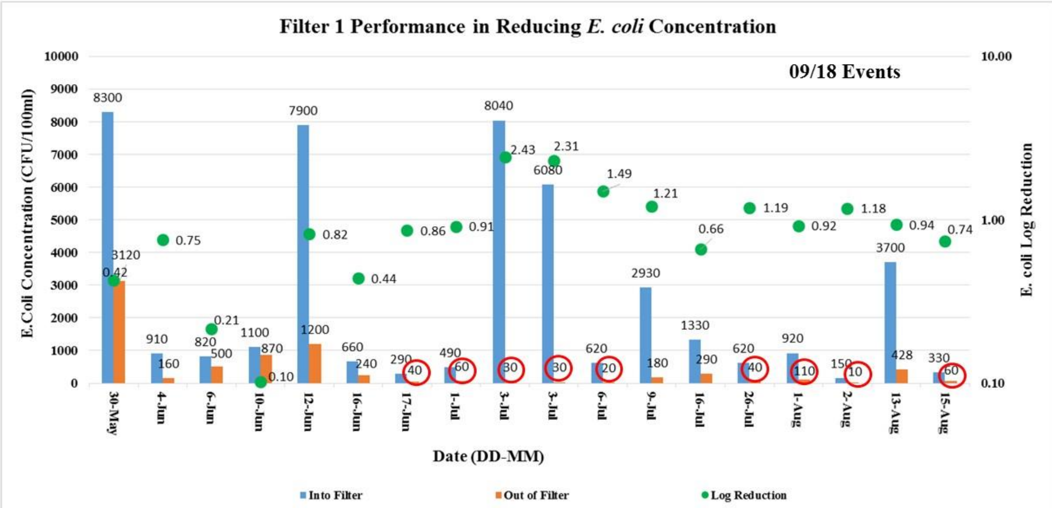
- Physical Analysis
  - pH, DO, Temperature, and TDS
- Microbiological Analysis
  - *E. coli*
  - Used MI Agar (*EPA* method 1604)



E. coli as Water Quality Indicator

- Gram Negative bacteria
- Common inhabitant of intestinal tract of warm blooded animals
- Can survive outside of the host
- Testing the medium can help in finding out the contamination
- Testing for *E. coli* is economical and less technical when compared to other strains of bacteria

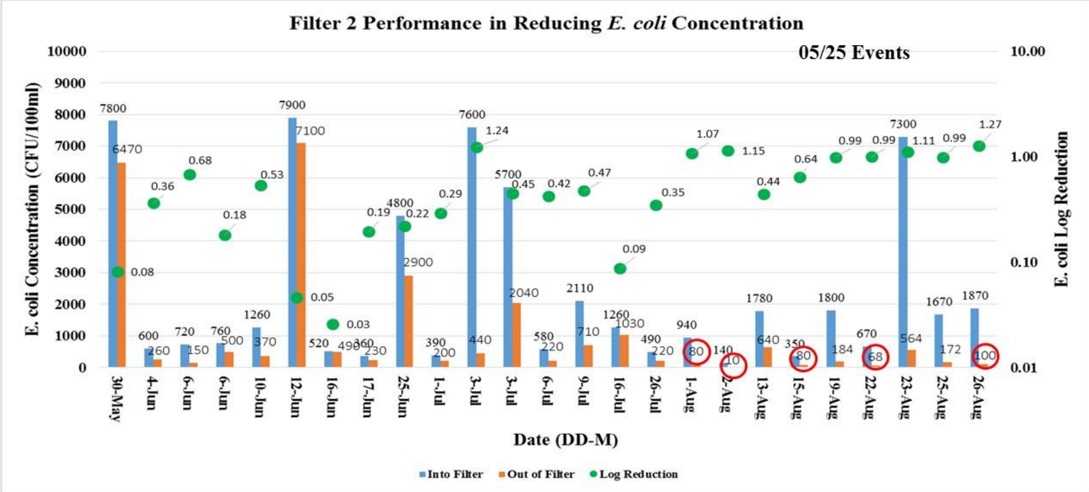
Filter #1



Discussion

- Performance in reducing *E. coli* concentration improved over time
  - Development of bio film *Schmutzdecke* and low pore size
- Usage of fine grain sand sometimes resulted in blockage of the filter
- Helped in reducing the *E. coli* loading on solar disinfection system
  - Achieved NPDES' 2012 instream *E. coli* limits --- 9 out of 18 times

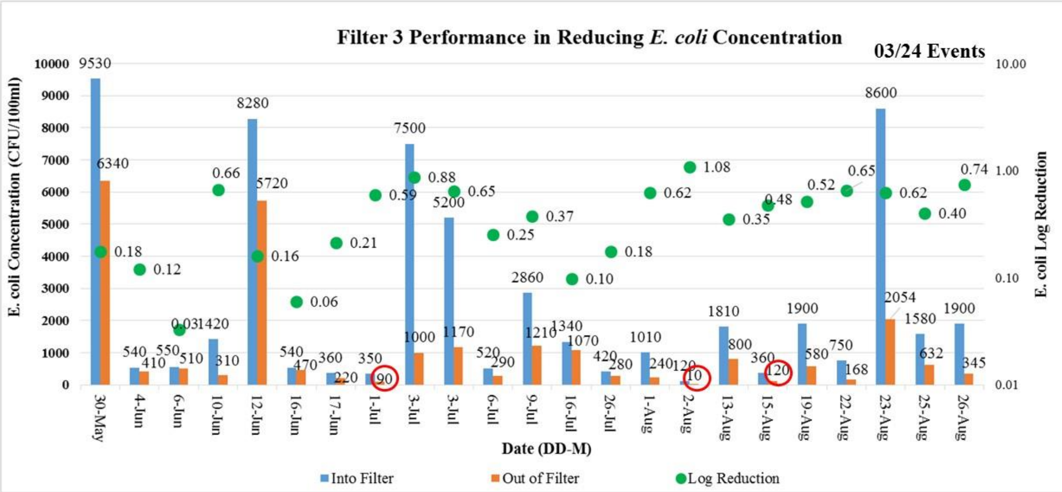
Filter #2



Discussion

- No blockage of filter observed
  - Activated charcoal and Oyster Shells
- Achieved NPDES' 2012 instream *E. coli* limits --- 5 out of 25 times

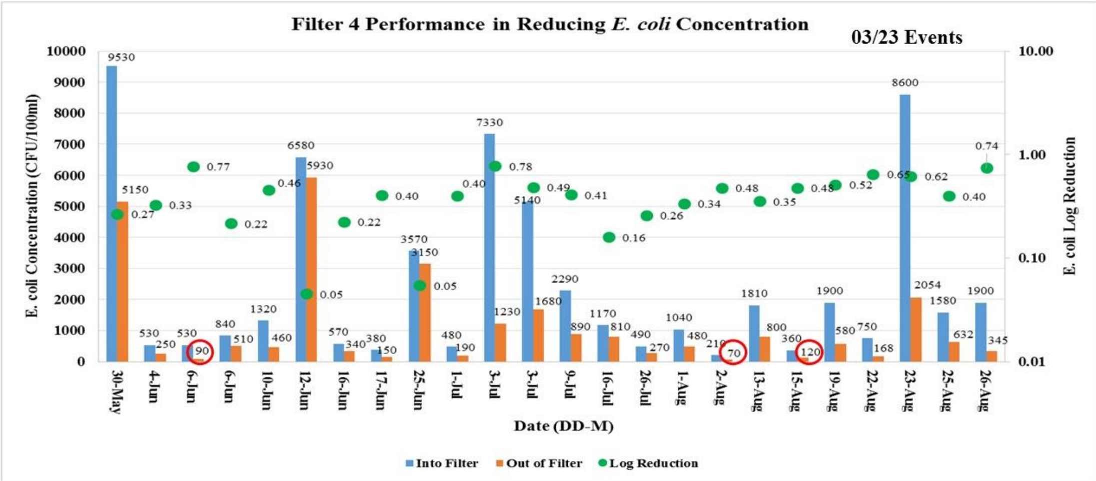
Filter #3



Discussion

- No blockage of filter observed
  - Activated charcoal created high pore size and no development of Bio-Film
- Achieved NPDES' 2012 instream *E. coli* limits --- 3 out of 24 times

Filter #4



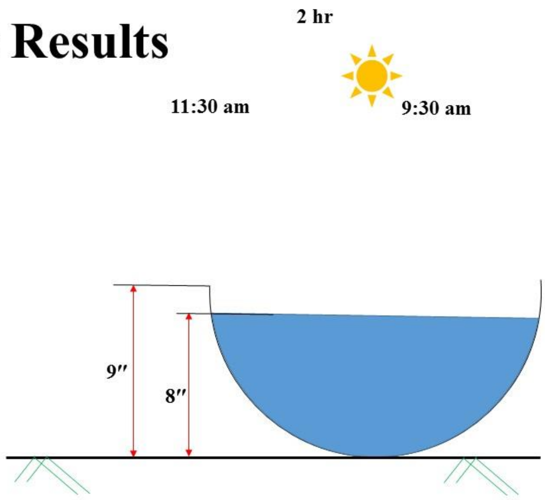
Discussion

- No blockage of filter observed
  - Crushed Oyster shells created high pore size and no development of Bio-Film
- Achieved NPDES' 2012 instream *E. coli* limits --- 3 out of 23 times

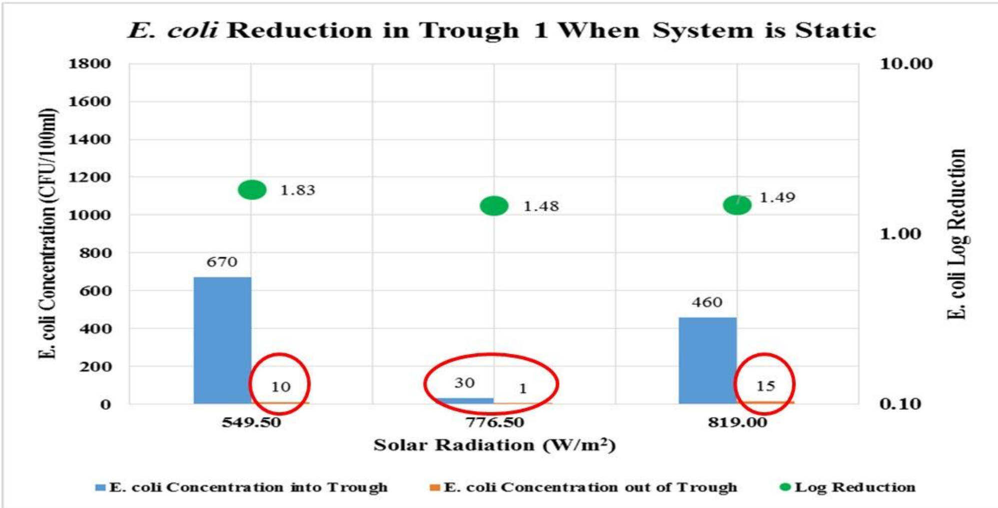
SODIS Results

Phase I

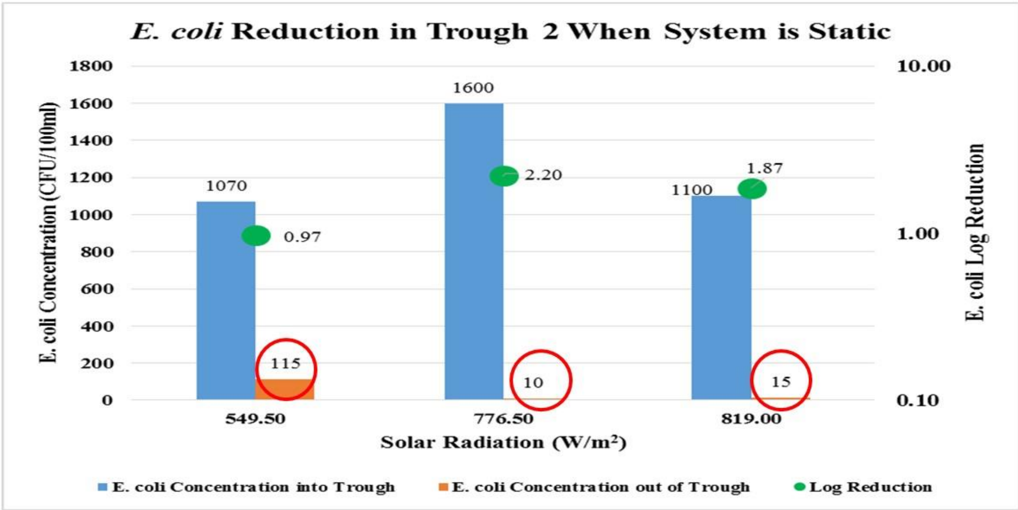
- Static Batch System
  - Troughs filled up to 8 inches
    - 113 gallons of water
  - Exposed to sunlight for 2 hr



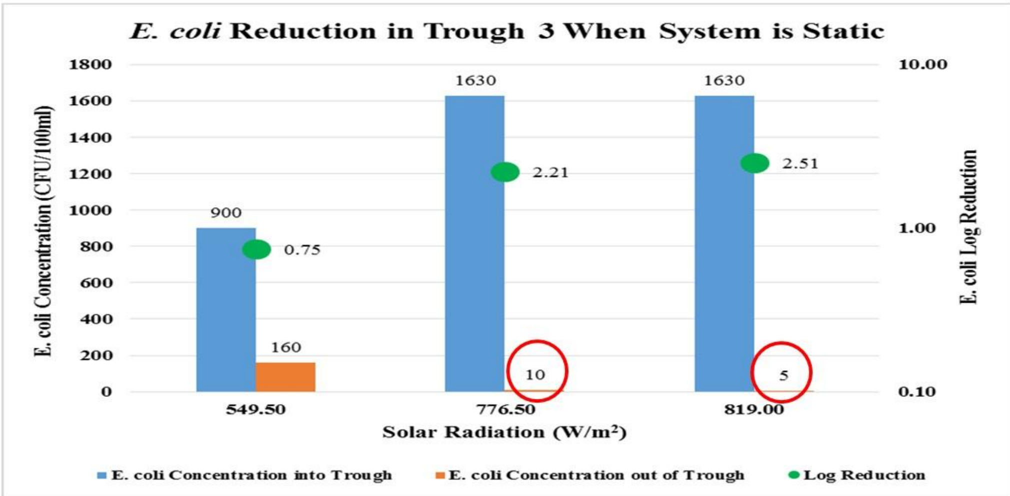
Trough #1



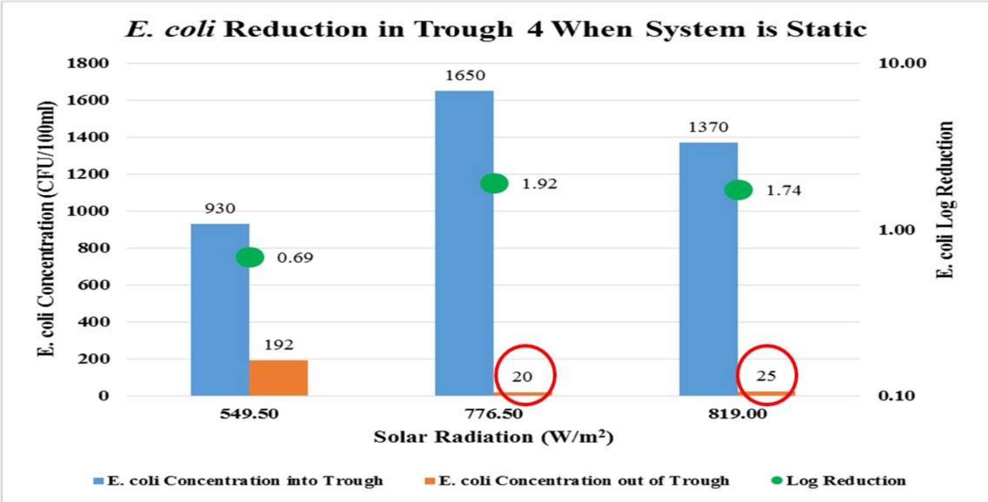
Trough #2



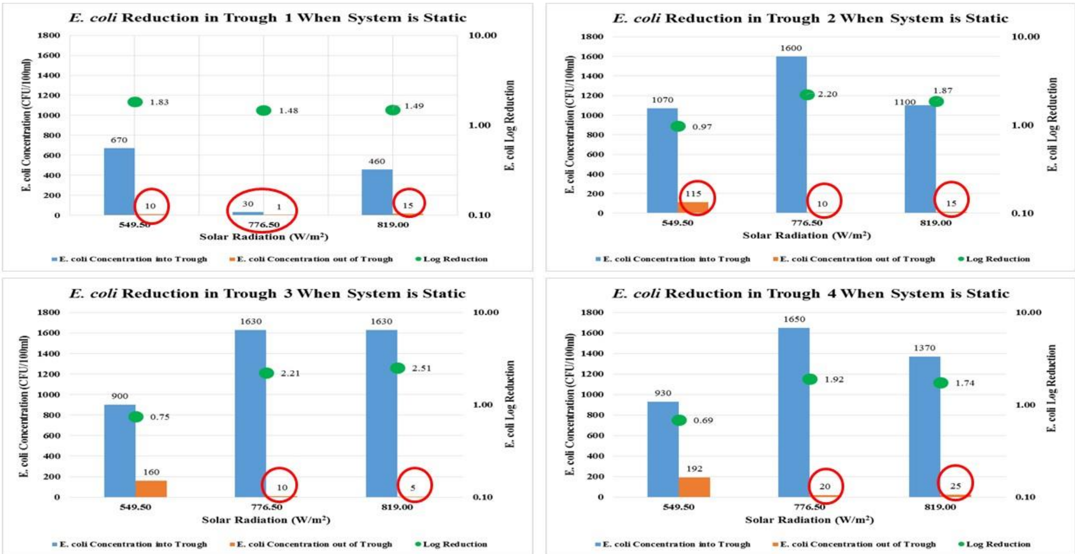
Trough #3



Trough #4



Analysis

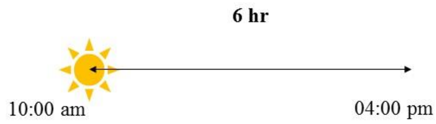


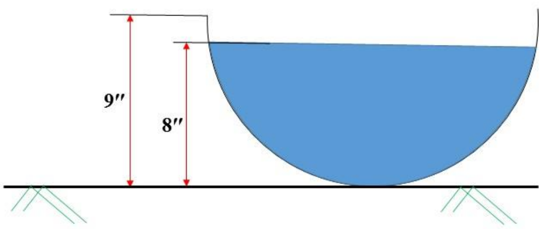
Results and Discussion

- All 4 performed good in reducing *E. coli*
- Trough 3 performed better
- Proved that *E. coli* can be reduced in open channel
- Takes more time but financially viable

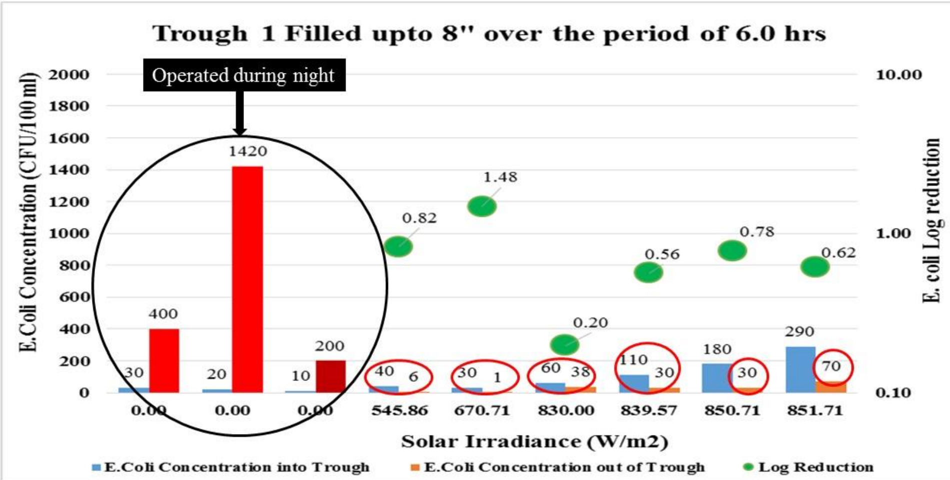
Phase II – Scenario ii

- Continuous Flow System
  - Troughs filled up to 8 inches in 6 hr
  - 18.8 gal/hr

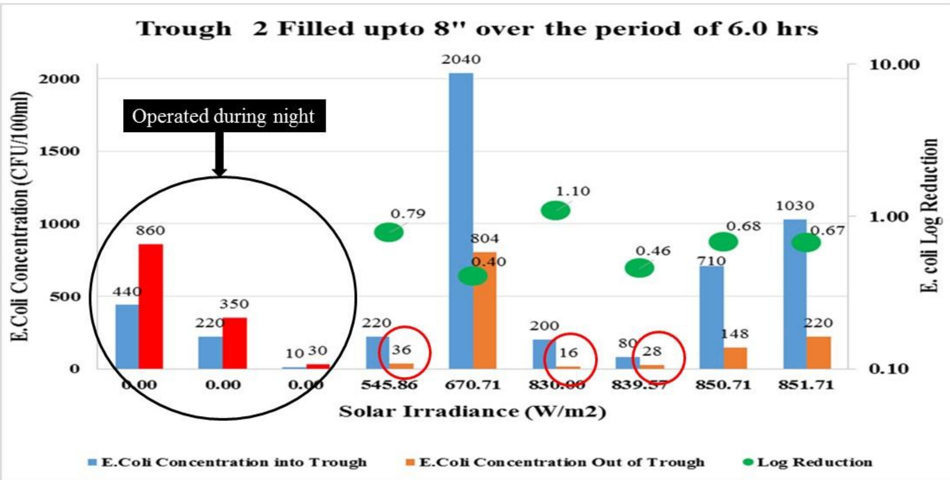




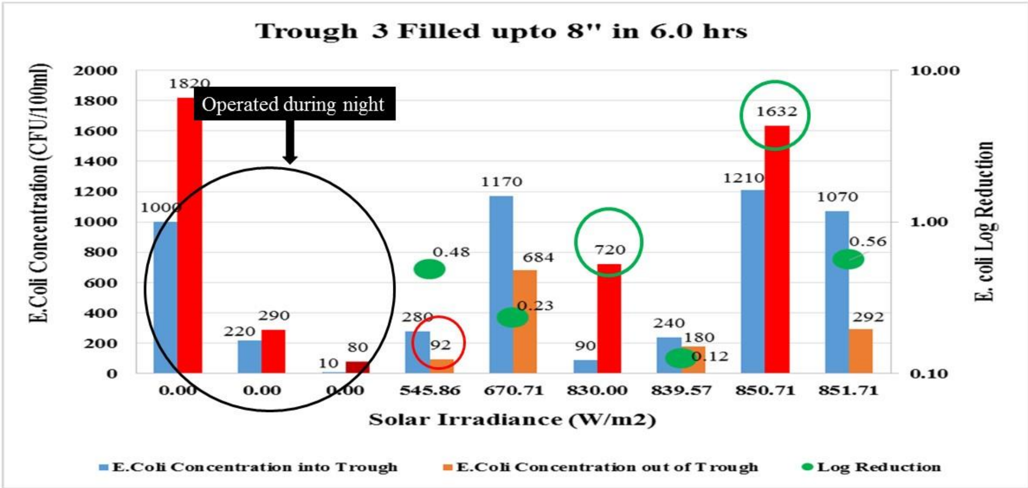
Trough #1



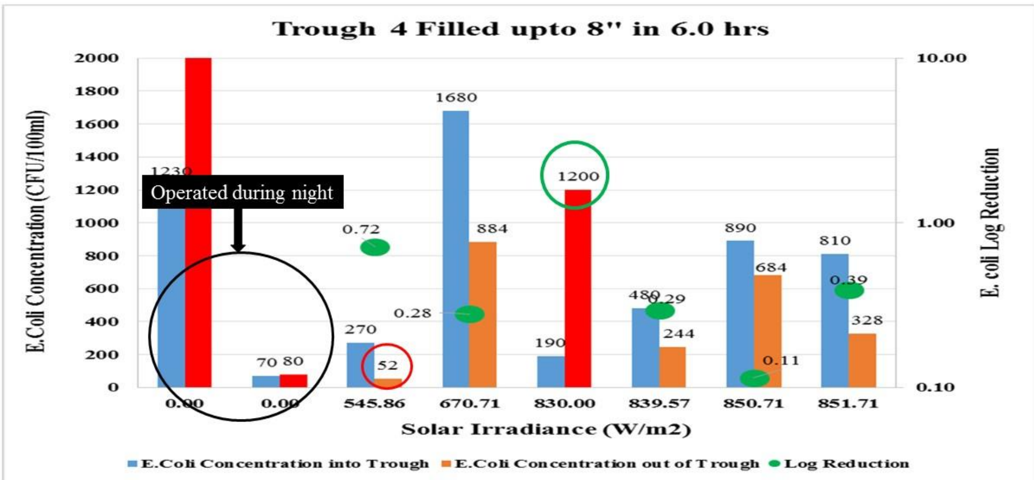
Trough #2



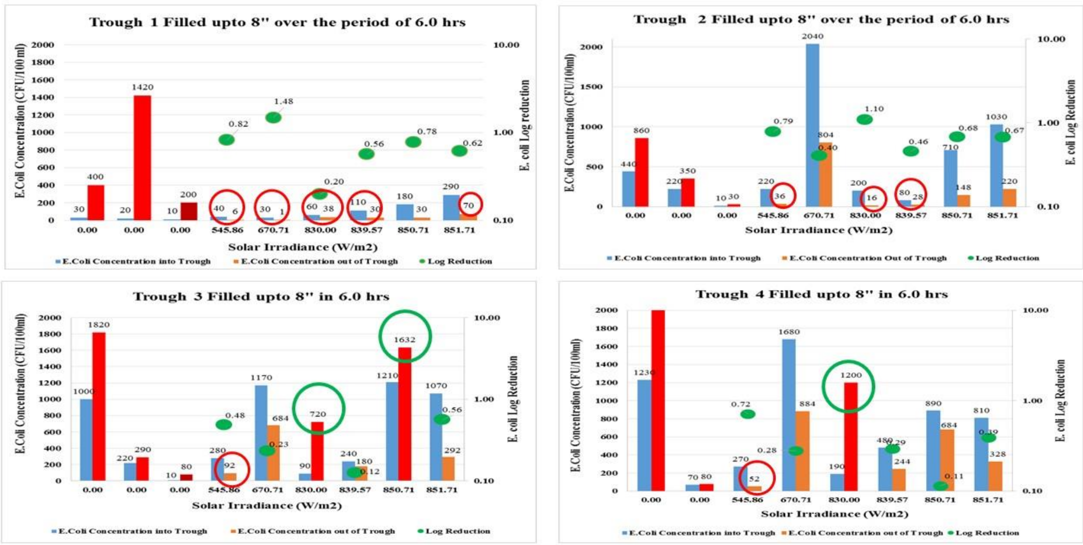
Trough #3



Trough #4



Analysis

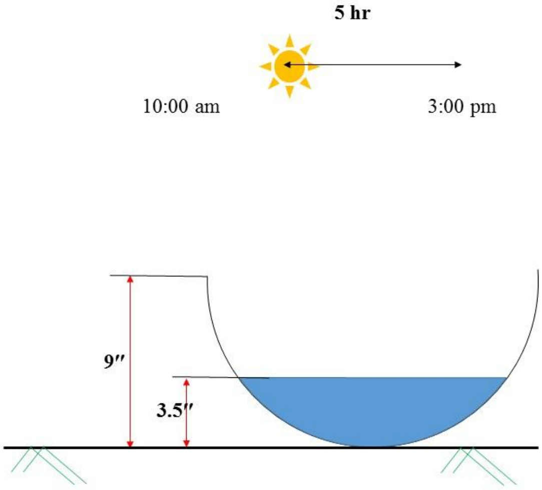


Results Discussion

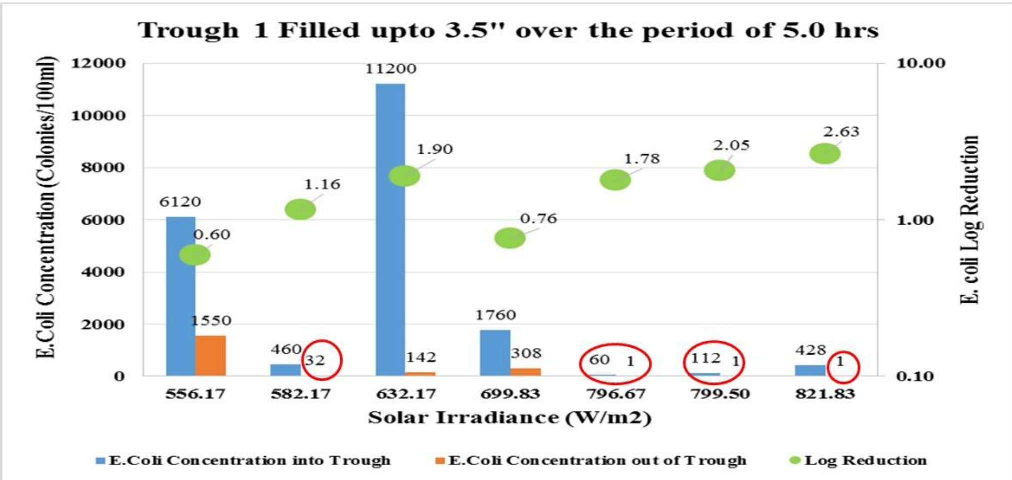
- SODIS was tested during nights for 3 events
  - To check whether *E. coli* reduction is done due to sunlight or not
  - Observed increase in *E. coli* concentrations
- Trough 1 performed better than the others

Phase II – Scenario iii

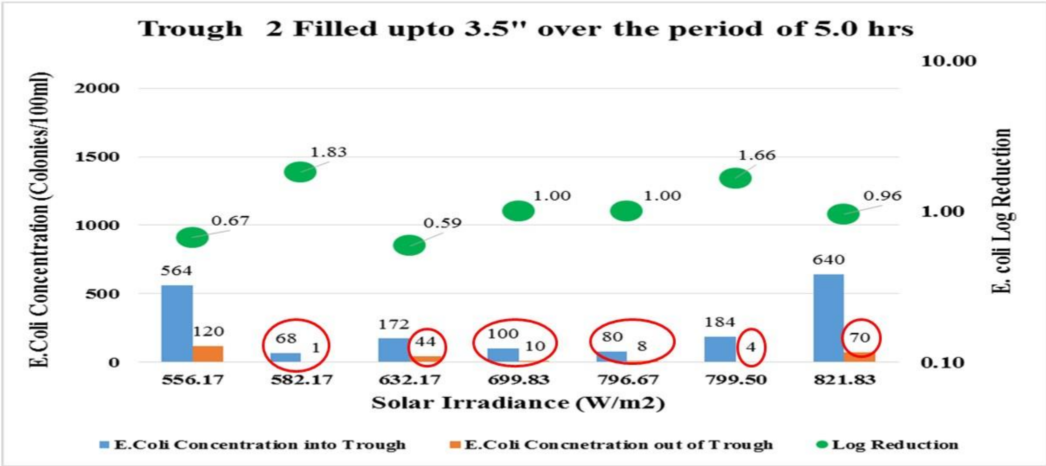
- Continuous Flow System
  - Troughs filled up to 3.5 inches in 5.0 hr
  - 7.3 gal/hr



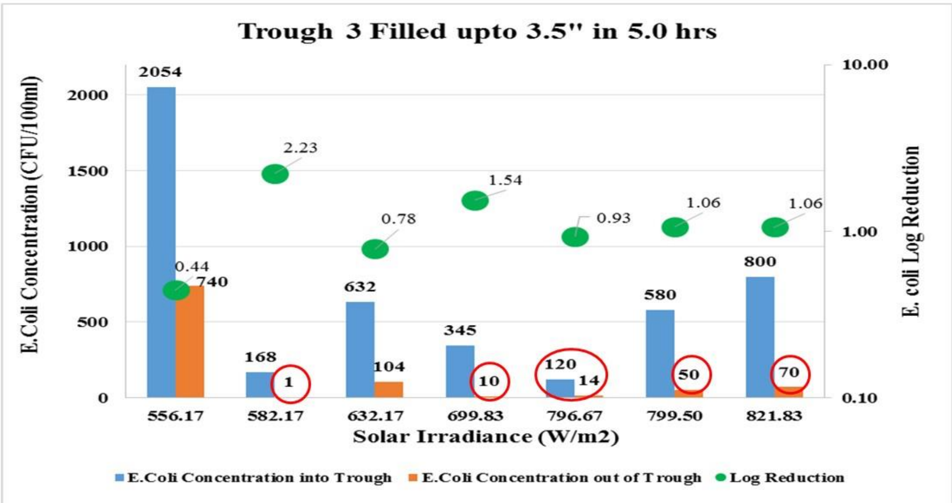
Trough #1



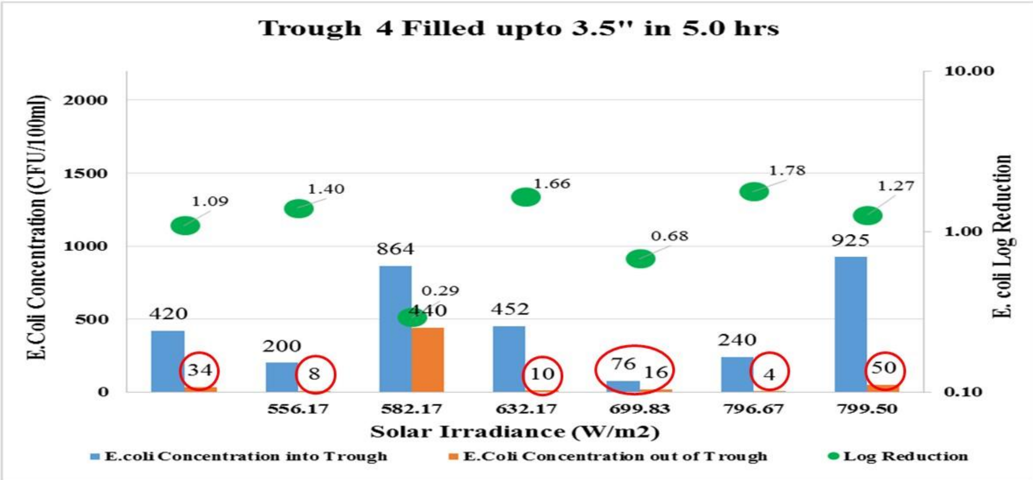
Trough #2

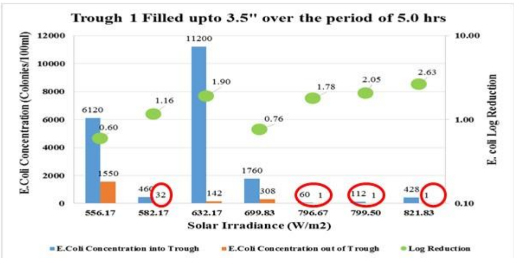


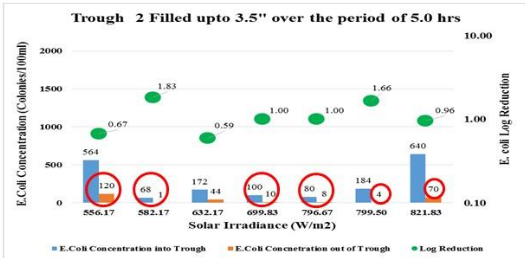
Trough #3

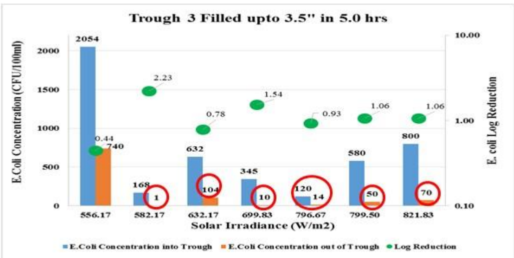


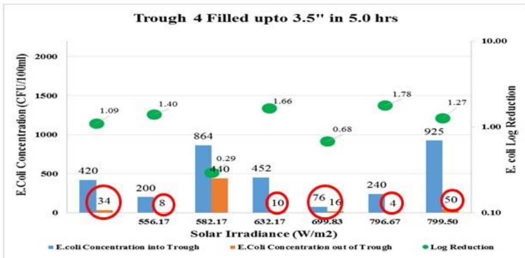
Trough #4


Trough 4 Filled upto 3.5" in 5.0 hrs
E.Coli Concentration (CFU/100ml)
E. coli Log Reduction
2000
1500
1000
500
0
10.00
1.00
0.10
1.09
1.40
1.66
0.68
1.78
1.27
0.29
420
34
200
8
864
440
452
10
76
16
240
4
925
50
556.17
582.17
632.17
699.83
796.67
799.50
Solar Irradiance (W/m2)
E.coli Concentration into Trough
E.Coli Concentration out of Trough
Log Reduction


Trough 1 Filled upto 3.5" over the period of 5.0 hrs
E.Coli Concentration (Colonies/100ml)
E. coli Log Reduction
Solar Irradiance (W/m2)
E.Coli Concentration into Trough
E.Coli Concentration out of Trough
Log Reduction


Trough 2 Filled upto 3.5" over the period of 5.0 hrs
E.Coli Concentration (Colonies/100ml)
E. coli Log Reduction
Solar Irradiance (W/m2)
E.Coli Concentration into Trough
E.Coli Concnetration out of Trough
Log Reduction


Trough 3 Filled upto 3.5" in 5.0 hrs
E.Coli Concentration (CFU/100ml)
E. coli Log Reduction
Solar Irradiance (W/m2)
E.Coli Concentration into Trough
E.Coli Concentration out of Trough
Log Reduction


Trough 4 Filled upto 3.5" in 5.0 hrs
E.Coli Concentration (CFU/100ml)
E. coli Log Reduction
Solar Irradiance (W/m2)
E.coli Concentration into Trough
E.Coli Concentration out of Trough
Log Reduction

Results Discussion

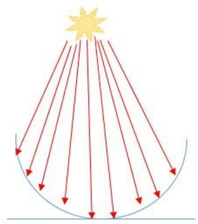
- Better performance than previous scenarios
  - Low flow conditions increased water retention time in filters
  - Input loading is low
  - Targeted depth reduction helped in increased solar IR penetration
- None of the troughs recorded *E. coli* increment
- Trough 1 performed better than others

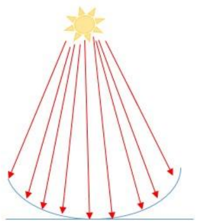
SODIS Discussion

- All 4 troughs are successful in reducing *E. coli*
- All 4 performed better in Phase II Scenario iii
- Trough 1 performed better than others
  - ANOVA and Tukey test results proved this

Future Work

- Replacing Semi-circular troughs with half elliptical shape
  - Increases the surface area of exposure
- Increase the retention time in filters
- Water analysis for other bacteria and virus





Thank You…!!!

Appendix C

Draft of Article Published in Sustain Magazine

Reducing E.Coli Concentrations in Urban Streams

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Professor of Civil and Environmental Engineering
University of Louisville

Venkata Gullapalli
Doctoral Candidate
University of Louisville

Introduction

Historically urban streams were used for recreational activities and as centers for education. Because of urbanization, urban streams have been neglected and abused by changing the natural alignment, installing combined sewer overflows, not controlling polluted storm water runoff and more. These factors made urban streams polluted and limited their use as recreational spaces. Researchers are investigating efficient techniques for increasing in-stream water quality. This involves both in-stream and off-stream techniques for reducing the pollution levels in urban stream water. In-stream techniques involve modification of channel slope, shape and removal of impervious channel lining, which reduces soil erosion, and increases habitat for aquatic life and plants, which in turn creates a natural balance for stream health. Off-stream techniques involve storm water harvesting through the use of rain gardens, pervious pavements, rain barrels and infiltration basins.

Water purification on the other hand involves filtration and disinfection. Filtration removes suspended particles in water and bacteria. Disinfection involves reducing bacterial and viral concentrations in water through the addition of chemicals, or passing water through germicidal irradiation. Research is showing that using naturally available materials for filtration and sunlight as germicidal agents for disinfection makes the treatment system sustainable and results in zero disinfection by-products release.

This project studied the feasibility of using a sustainable water treatment concept as off-stream enhancement of stream water quality. The authors tested four different filter combinations for filtration and an open channel flow concept for solar disinfection. The project is installed at the Beargrass Falls, a park for public education on water conservation, storm water runoff reduction and sustainable power sources. Educational sessions are being conducted with students from local schools at all grade levels and also to the general public. Beargrass Falls is located at Karen Lynch Park, a Jefferson county park located in District 9, Louisville, Kentucky.

Pilot Project

A pilot water treatment project is being tested as an off-stream technique for reducing the *E. coli* concentration in water. This project was constructed and operated on the bank of Beargrass creek, an urban stream in Louisville metro with a drainage area of 60 sq. miles. Water is drawn from Beargrass Creek using a solar pump, and then stored in a tank which is constructed to flow through filters. A post filtration mechanism exposes the water to sunlight by passing it through an open channel setting. The water then flows back into the creek through a waterfall. Figure 1 shows the project setup with components labelled. Which are classified into four categories:

Pumping water into storage tank

Six solar panels are installed to power the submersible pump that is installed in the creek. The pump sucks water into a storage tank that is 35 feet above the water level of the creek. The over flow water is channeled back into the creek through a concrete water fall which creates a ripple effect and helps to increase the

Dissolved Oxygen (DO) concentration in the water. The storage tank serves as a settling reservoir to catch sediment in the water. Figure 2 shows the PV-panels setup for powering the pump.

Filtration

A one foot diameter, 20 foot long schedule 80 PVC pipe was cut into four 5 foot long pipes and filled with filter materials in different proportions. Water flows gravitationally into the filters and is controlled individually at the inflow of each filter. Figure 3 shows the Filter arrangement. Filter materials used in this project are sand, crushed oyster shells, and activated charcoal.

Sand - Sand filters are good in reducing the suspended particles and bacterial concentrations in water over the course of time because of the development of a biofilm called *Schmutzdecke* in the top few millimetres of the fine sand layer. *Schmutzdecke* is formed in the first few days of filter operation depending on the flow into the filters. It consists of different species ranging from bacteria to protozoa (*Huisman, L 1974*). A fine particulate sand is used in this pilot study to reduce as much of the total suspended solids (TSS) as possible.

Oyster Shells - Oyster shells are used because of the rich calcium content in them where they are being used as the calcium supplement in the chicken industry. In addition, they are good at reducing the NH3-N (Ammonical nitrogen) concentrations in water (*Liuin, Yao-Xing 2010*). Because of their size, commercially available oyster shells can also be used as a coarse particle in filters eliminating the need for gravel often used in filters. Gravel in filters does not have the effectiveness in water purification that oyster shells do. Replacing a portion of gravel with some material of similar particle size and a better water treating agent can help in improving the filter performance. But total replacement of gravel with Oyster shells isn't a better option because it takes a longer time to dissolve a pebble than an oyster shell. Crushed oyster shells can best fit in this filter zone 1) the particle size is similar to gravel; 2) the price for a 50lb bag of shells is only $10; 3) and they are as good at reducing agents of NH3-N compounds in water as well as reducing total phosphorus concentrations (*Liuin, Yao-Xing 2010*).

Activated Charcoal - Activated charcoal has been used as a filter material for treating odor and taste of the potable water (EPA). The mechanism involved in activated charcoal filtration is absorption. Because of its high porosity, it provides a large surface area to which contaminants can be trapped. Granular activated charcoal, derived from burning of coconut shells was used in this project. Early on, activated charcoal was used as a filtering material for absorbing a wide range of chemicals (EPA), however, research studies show that it can also effectively adsorb *E. coli* bacteria depending on the retention time (*Katsiani, N 2000*). In addition, its particle size makes it a perfect match to be added to the filter between very coarse and finer material.

Figure 1. Project setup.

Figure 2. Solar panels for powering the water pump.

Figure 3. Filter arrangement showing inflow and outflow controls.

American Water Works Association's manual for designing slow sand filtration was used in constructing the slow sand filters used in this study. Filters are designed to reduce the suspended solids in water so that sunlight can pentrate the water. The mechanism involved in setting up a filter is placing coarser material in the bottom and gradually decreasing the grain size to finer material at the top. This helps to control the finer particles entering into the plumbing and clogging it (*Hendricks, D., et al., 1992*).

Solar Disinfection (SODIS)

Solar disinfection (SODIS) is the process of cleaning water by exposing it to sunlight. Two 18 inch diameter, 10 foot long pvc pipes were cut into two half cylinders then placed in a rectangular base with the semi-circular ends open. Each half cylinder was painted with different colors, either reflective paint or heat absorbing paint. Water moving out of the filters flows into separate troughs filled to the desired depth, and flows out through the outlet. Table 1 gives details about the painted surfaces and the reasons for using them.

Solar Radiation

Solar radiation is the electromagnetic radiation emitted by the sun. It consists of several bands, however, the significant band of radiation used for water purification is divided into five regions in ascending order of wavelengths (*Naylor, M. F., et al., 1995*). These band regions are UVC (100 – 280 nm), UVB (280 – 315 nm), UVA (315 – 400 nm), Visible Light (380 – 780 nm), IR (700 - 106 nm). Stratospheric oxygen absorbs all the UVC and 90% of the UVB radiation and 5-10 % of UVA reaching earth's surface allowing UVA and UVB to be effective for disinfection (*Amaro-Ortiz A., et al., 2014*). As we know, the primary cause for temperature increase in the atmosphere is infrared radiation.

Table 1.

Trough	Paint	Purpose
1	White	Best reflector, Cheap reflecting agent
2	Spray Painted Aluminum Finish	Better reflector than White but expensive
3	None	Left unpainted for control
4	Black	Absorbs more heat than other materials

Reflection of solar radiation from ground surfaces, including the sea, is normally low (<7%) but is higher for fresh snow (fresh snow can reflect up to 80 per cent of incident solar radiation). This shows that more than 7% of solar radiation is not reflected from the water surface but is absorbed into the water. Penetration of solar radiation into water is dependent on the turbidity levels in the water. Altitude is another factor that affects solar radiation. Each 1 km increase in altitude increases the ultraviolet flux by about 6%, meaning that places on the Earth's surface below sea level are relatively poorer in receiving solar radiation than sites that are at sea level or at higher elevations (*Cutchis, P., 1991*). The Louisville region's elevation ranges from a high of about 761 feet to a low of 382 feet above sea level (*elevations and distances in the United States, USGS*) and so suffices as a suitable location for using natural UV irradiance for water disinfection.

Disinfection by Solar Radiation

Descriptions of solar disinfection of water have existed in communities on the Indian sub-continent for nearly 2000 years. In the distant past, drinking water was placed outside in open containers to be "blessed" by the sun (*Baker, M.N.T.M., 1981*). *Downes and Blunt (1877)* showed that sunlight is effective in reducing or killing bacteria. Disinfection by sunlight happens because of the UV radiation and infrared radiation present in solar radiation (*Mbonimpa, E. G., et al., 2012*). Inactivation of the bacteria under solar radiation happens due to three mechanisms: 1) thermal inactivation, 2) optical inactivation, 3) combined thermal and optical inactivation.

Thermal Inactivation - Thermal inactivation is the process of destroying bacteria by application of heat. This is one of the oldest techniques for water disinfection. This significantly improves the microbiological quality of water, but does not fully remove the potential risk of waterborne pathogens especially if water temperatures do not reach the boiling point (Rosa et al. 2010). Infrared radiation is not visible to the naked eye, but the heat produced by radiation in wavelengths beyond 700nm is sensed as heat. The infrared radiation absorbed by water is responsible for increasing its temperature. Microorganisms are sensitive to heat, and water can experience a bacterial reduction of 99.9% prior to reaching the boiling point. In solar disinfection, water is retained in airtight containers to increase the water temperature.

Optical Inactivation - Optical inactivation of bacteria is a process of destroying bacteria by application of optical irradiation. UVA, and UVB reaching the earth's surface plays a major role in optical inactivation of bacterial populations. This concept is good when applied to zero turbid water where sunlight can pass to deeper levels and effectively reduce the bacterial count.

The basic mechanism involved in UVB and UVC disinfection is formation of pyrimidine dimers. When bacterial DNA absorbs UVB or UVC radiation, thymine base pairs in genetic sequences bond to each other and form pyrimidine dimers. This disrupts the structure of the DNA strand, causing reproductive enzymes to be unable to copy (*Goodsell D.S., 2001*). Formation of pyrimidine dimers results in making the bacteria incapable of reproducing which in turn reduces the infection capacity of the bacteria. Unable to multiply, pathogens no longer pose a health risk and soon die. UVB (wavelength of 280-315 nm) in the germicidal range (200-300 nm) is capable of causing DNA damage.

Although the UVA wavelengths (315-400 nm) are not sufficiently energetic to directly modify DNA bases, they play an important role in the formation of reactive oxygen species (ROS) such as singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radical (*Jagger, J 1981; Eisenstark, A 1987; Lloyd, R. E. et. al. 1990; Sammartano, L.J., 1987*). Once formed, these ROS can also cause damage to DNA. Additionally, sunlight can be absorbed by natural exogenous photosensitizers present in surface waters (humic acids and chlorophyls), which in turn can react with oxygen to produce ROS (*Blough, N.V. et al. 1995; Schwartzenbach, R.P., et. al., 2003*) which exerts a disinfecting effect.

Several SODIS systems, or reactors, were developed considering UVB or UVA radiation and IR. When solar radiation is used as the source for disinfection, UVA is abundantly available in natural sunlight and is able to penetrate deeply into the water(*Lee, Z et. al. 2013*).

Combined Thermal and Optical Inactivation - Inactivation of bacteria by applying both thermal (heat) and optical irradiance is called combined thermal and optical inactivation. The Combined thermal and optical inactivation is the mechanism involved in most solar disinfection systems. These systems are effective when used as both solar UV and IR for disinfection.

This research project was developed based on the optical inactivation mechanism. To achieve this, the system was designed as an open channel flow, and because of the materials used in making it transparent, this contributed to the elimination of solar UV filtration.

Aeration

Water from the tank over flow and post solar disinfection unit flows back into Beargrass Creek through a water fall. This creates ripples and which puts the water in contact with the atmospheric oxygen and results in increased dissolved oxygen concentrations in the water.

Water Sampling and Testing

Water samples were collected and analysed for microbial and physical parameters. Twelve samples were collected during each test run. Samples pre- and post-filtration and samples at the end of SODIS system were collected for analysis, and also tested for *E. coli* concentration.

Pilot Plant Operation and Results Discussion

The pilot project was operated in two phases. In phase 1, the system was operated static in which troughs were filled with water up to 8 inches and exposed to sunlight for 2.0 hours, after which the water was released to the water fall. The phase 2 system was operated as a continuous flow system, where water is allowed to flow into troughs until the desired depth is achieved in targeted time. In this phase, different scenarios based on water depth and exposure time were tested. In one scenario, water was tested with a flow rate of 32.43 gal/hr maintained in the troughs for 3.5 hrs to achieve a water depth of 8.0 inches. In another, water depth in the troughs is restricted to 3.5 inches and the troughs are filled up to 3.5 inches over the period of 5.0 hrs. The depth is maintained for effective penetration of sunlight to the bottom of the troughs. The flow rate into the troughs was maintained at 7.3 gal/hr.

E. coli reduction was observed in all four troughs and filters. As each was observed, all 4 troughs performed satisfactorily, however, filter 1 and trough 1 performed better than the rest of the three filters and troughs in reducing *E. coli* concentration.

Conclusion

NPDES' 2012 recreational water quality report states that an average 30-day *E. coli* concentration in water should not exceed 126 colonies/100ml to access water for recreation. In this study, Filter 1 and Trough 1 performed better in reducing *E. coli* concentrations. Filter 1 performance increased gradually over a period of time. Filter 1 performed better than the other three filters in achieving the limits in 10 occasions out of 18 testing events. Table 2 shows the number of testing events per filter and number of occasions a filter achieved the NPDES' limit on *E. coli* concentration for recreational water. Trough 1 had reduced bacterial loading because of the sand filter (Filter 1) connected to the trough which also helped to improve performance of the trough in SODIS in reducing the *E. coli* concentration.

Table 2.

Filter	1	2	3	4
Number of Testing Events	18	25	24	23
No. of Occasions When Minimum *E. coli* concentration is achieved	10	5	3	3

Trough	1	2	3	4
Average *E. coli* Concentration (colonies/100ml)	290.71	36.71	141.3	80.3
No. of Occasions When Minimum *E. coli* concentration is achieved in 7 events	4	7	6	6

Future Work

This pilot research concluded that a mechanism of this kind can reduce the *E. coli* concentrations in urban streams. Scaling up the mechanism will require more hours of testing. The research was conducted in the summer and under clear sky conditions. Tests will need to be conducted under winter sunny conditions. This project used the semi-circular troughs for SODIS. Increasing water surface area and decreasing water depth will result in increased *E. coli* reduction. Use of a half elliptical shaped trough can increase water surface area exposed to sunlight than the semi-circular trough and reduced water depth which helps increase the solar radiation effects at deeper depths. The filters' performance can be enhanced by increasing the retention time of water in the filter which is achieved by reducing the inflow and outflow.

Mark N. French, PhD, PE, is Professor of Civil and Environmental Engineering at the University of Louisville and served as Department Chair from 2002-2004. Mark's current areas of research focus is sustainable water treatment for drinking water to meet needs of people and industry while limiting adverse environmental impacts. Mark's research includes real-time rainfall-runoff, forecasting and managing water quality in reservoirs, sustainable water supply and wastewater treatment systems, waterway transportation logistics, and methods of effective teaching and learning in engineering. Dr. French teaches courses in mechanics, hydraulics, surface hydrology, water treatment, groundwater flow (classroom and online), and international service learning for engineering students (with travel to the Philippines). He is a faculty mentor for the Brown Fellows Scholar program at the University of Louisville, and has served on the engineering faculty in the Kentucky Governor's Scholar Program. Mark is a registered Professional Engineer (PE) in Kentucky, and has a PhD from the University of Iowa, Iowa Institute for Hydraulic Research, MS from Massachusetts Institute of Technology, and MEng and BS from the University of Louisville.

Venkata Gullapalli is completing his PhD in the Civil and Environmental Engineering Department at the University of Louisville. Venkata's research focus is on sustainable water treatment methods and his research director is Dr. Mark N. French. During his tenure as a Doctoral candidate, Venkata designed, built and operated a green engineering pilot water treatment plant as a component of the environmental sustainability display at a metro-Louisville park in the Butchertown neighborhood. As part of his work, Venkata hosted many educational field trips by regional high school classes and the general public on water treatment, where he addressed the important role of urban streams for storm water management and clean water impacts on natural habitats. Venkata's experience includes work with the Level 1 triage of Alternative Response Technologies for abatement, containment, and remediation of oil flow due to the BP Deepwater Horizon explosion, Gulf of Mexico. His interests include green engineering and non-chemical water disinfection concepts, and sustainable concepts for urban stream revitalization. Venkata is a LEED Green Associate professional, has a Bachelor of Technology degree in Civil Engineering from Acharya Nagarjuna University, India and Master of Science degree in Civil Engineering from University of Louisville.

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CURRICULUM VITA

Venkata D. Gullapalli

Motivation

To work in a creative environment that uses my skill and experience to the fullest and gives adequate exposure and scope to emerging and evolving technologies.

Education

University of Louisville

Louisville, Ky

- Ph.D. in Civil Engineering April 2015

  Advisor: Dr. Mark N. French

  Research Project: Green Water Treatment Project

- Master of Science in Civil Engineering August 2008

  Advisor: Dr. Mark N. French

  Research Project & Masters Thesis: Reuse of treated filter wash water as source of flow augmentation

Acharya Nagarjuna University April 2006

Guntur, India

- Bachelor of Technology in Civil Engineering

Research Experience

University of Louisville

Louisville, Ky

Water Treatment Using Sustainable Engineering Concepts May 2012 – TD

Partners: Kentucky Institute for Environmental Sustainable Design (KIESD), MSD Louisville, District 9 Louisville, Get out Doors Kentucky

A pilot water treatment project was designed and being tested, which uses naturally available materials for water filtration, and solar radiation for disinfection. This pilot project is a part of Beargrass Falls, a sustainable and educational project.

Duties:

- Reviewed past and present techniques and research projects in water treatment
- Pilot project design, construction, maintenance and operations
- Testing different reflective surfaces to find out the effective and viable reflective material
- Designed and developed standard operating procedures (SOPs) for conducting laboratory analysis
- Certified for performing Biosafety level2 (BSL 2) analysis
- Collected and tested water samples for bacterial concentration, pH, DO, Temperature, TDS, TSS, Conductivity and Nutrients

Reuse of Treated Filter Wash Water as Source of Flow Augmentation

Feb 2007 - Aug 2008

Partners: Center for Infrastructure Research, Louisville Water Company, Metropolitan Sewer District (MSD) Louisville, KY

This project tested the feasibility of treated filter backwash water as source for stream flow augmentation

Duties:

- Reviewed NPDES, KPDES and Clean Water Act to check the pollution release regulations and drinking water standards
- Collected and tested water samples from Beargrass Creek (Louisville, KY), and filter wash water from Louisville Water Company
- Reviewed water quality reports from historical records
- Reviewed water flow quantities in Beargrass creek from historical records
- Conducted field work for pipe line locations and stream discharge points for storm sewer outlets
- Prepared technical report summarizing project feasibility

Acharya Nagarjuna University
Guntur, India
Estimation of accident rate on NH9
Vijayawada, India
Central Road Research Institute, New Delhi, India
This project involves counting the vehicles manually, measuring speeds of vehicles by using speed guns and reporting the data to Central Road Research Institute for design references.
Seismic Design of Buildings
Vijayawada, India
Undergraduate final project
This project tested and analyzed the feasibility of incorporation of international seismic design standards into Indian design standards.

Professional Experience and Activities

Instructor
Beargrass Falls Park,
Louisville Ky

- Conducted informative sessions on water and its importance
- Sessions conducted for community partners and students
- Teaching materials prepared for diverse audience ranging from general public to middle school students
- Sessions conducted to students attending Health and wellness program with city of Louisville, Lincoln Foundation

Engineer May - July 2010
Net Results Inc. Louisville, KY
Performed Level 1 triage of Alternative Response Technologies for abatement, containment, and remediation of oil flow due to the BP Deepwater Horizon explosion, Gulf of Mexico.

Software Security Systems Engineer Sept. 2008 – Apr. 2010
Ebullient Services Inc. Arlington, TX
Developed front end security gateway for organizational user accounts. Planning, and designing of security systems using SUN IDM and data base tools.

Teaching Experience

University of Louisville Louisville, KY
Graduate Teaching Assistant Aug. 2010 - TD
Civil and Environmental Engineering Department

- Assisted in grading and teaching Courses

- Assisted in developing research proposals for external grants

Courses: CEE 205: Statics (Fall 2010, Spring 2011, Summer 2011)
CEE 370: Engineering Hydraulics (Spring 2012, 2013, 2014)
CEE 422: Steel Design (Fall 2013)

Certifications & Training

LEED Green Associate 31st July 2014 – 30th July 2016
United States Green Building Council
University of Louisville
Louisville Ky
Graduate teaching Academy (GTA) Aug. 2011 – Jan. 2012

- Trained for developing course structures
- Trained for improving interaction with students
- Trained for developing and acquiring latest teaching techniques

Grant Writing Academy (GWA) Aug. 2013 – Jan. 2014

- Trained for searching, developing, and submission of proposals for extramural grants
- Trained for developing budget

Department of Environmental Health and Safety
NIH Guidelines program; Biosafety Training (BSL1/BSL2); OSHA Training

Awards

Speed Graduate Scholarship Fall 2007; Spring 2008
CODRE Scholarship 2012-2013
Martha & Frank Diebold Award April 2014
Nominated for Community Engagement Award 2014 in student category

Computer Skills

Proficient in MS Office, AutoCAD, STAAD-Pro, HCS, TNM, ANSYS, HEC-RAS, WMS, HMS, Arc MAP, Solid Works, Data Base tools, Photoshop, Adobe Flash

Posters/Presentations

Gullapalli, Venkata D., French, Mark N., and Rockaway, Thomas D. "Stream Flow Augmentation Using Treated Filer Wash Water", World Environmental & Water Resources Congress, Palm Springs, California, May 22-26, 2011.

Gullapalli, Venkata D. and French, Mark N., "Treated Filter Backwash Water as Source of Streamflow Augmentation" 27th Annual WateReuse Symposium, Ft. Lauderdale, Florida, September 9-12, 2012.

Gullapalli, Venkata D. and French, Mark N., "Natural Methods for Treating and Disposing of Industrial Waste Water for Urban Stream Restoration", KY/TN Water Professional Conference, Louisville, KY, July 2013.

Gullapalli, Venkata D. "Green Concepts in Water Treatment", UofL Sustainability Scholars Roundtable, University of Louisville, November 20th 2014.

Gullapalli, Venkata D. and French, Mark N., “Solar UV Disinfection of Open Channel Flowing Water” 14th annual conference National Council for science and the environment, Washington D.C., January 28-30, 2014.

Memberships

Member of ASCE Louisville student chapter

Student Member KY Science Foundation

24 PDHs by attending professional conferences and meetings