Chlorine Dioxide Disinfection in Drip and Furrow Irrigation Systems

March 2014

Fall | 08

Team 2

[redacted]

Executive Summary

Onion growers in Malheur County, Oregon will be impacted by the Food and Safety Modernization Act which was proposed by the Food and Drug Administration. This proposal will limit levels of *Escherichia Coli (E. coli)* to 126 colony forming units (CFU) per 100mL of irrigation water. Oregon State University Ecological Engineering Department's senior design class was commissioned to create a feasible solution for disinfecting the irrigation water to an acceptable level. The design must be cost effective minimizing the impact to onion growers' profit margins. The disinfection system also needs to be practical for use in an agricultural setting. There are disinfection designs for both furrow irrigation and drip irrigation systems.

After consideration of sediment filtration, ozone, ultraviolet radiation, and chlorine dioxide (ClO_2) disinfection treatments, a ClO_2 disinfection system was selected (Appendix, C). ClO_2 inactivates the *E. coli* by disrupting the bacterial cell membrane. The ClO_2 will be made by combining hydrochloric acid and sodium chloride in an aqueous solution, and then injected in to the irrigation water. The ClO_2 disinfection system will be mobile, scalable, and practical for use in an agricultural setting for both furrow and drip irrigation systems. It was also the most cost effective technique when considering both furrow and drip irrigation systems.

Drip irrigation systems are comprised of a pump, four sand media filters, an injection point for chemicals and fertilizers, and drip tape. The design for this project will use a pump that pulls water from the head canal to the sand media filters which reduces the water's turbidity. A ClO_2 generation system will be used to combine hydrochloric acid and sodium chloride and then inject it continuously during irrigation into the drip system. To reduce the *E. coli* to 126 CFU from a maximum of 2,500 CFU required a dosage rate 1.6mg/l of ClO_2 with a contact time of one minute (Appendix F). This will result in 71 kg per season of chlorine dioxide for a forty acre field assuming a water flow rate of 500 gal/min (Appendix G). Drip tape will be used to distribute the disinfected irrigation water to the fields and ensures that the necessary contact time is satisfied.

The cost to implement the disinfection if the grower already owns a drip system will be approximately \$90/acre for the first year and \$15/acre annually each year after (Appendix L).

Furrow irrigation uses siphon tubes to move water from the head canal onto the field. The water will flow down the field in linear trenches called furrows and will be collected in the tail water ditch at the end of the field. The chlorine dioxide disinfection system design will use a pump and aluminum pipe to move the water from the head water ditch into four 300 gallon polyethylene holding tanks. The ClO_2 will be added before the first tank using the same generation system as for the proposed drip design. Furrow irrigation has a higher flow rate than drip at 1000 gal/min, which correlates to a higher ClO_2 demand. In total 320 kg per season of ClO_2 is needed to ensure a dosage rate of 1.6 mg/l at an increased contact time of 1.2 minutes (Appendix, G). The four tanks will be placed in series to create a plug flow reactor allowing for achievement of the full contact time necessary. The disinfected water will then be piped back into the head canal and siphoned out onto the field. This system can be disassembled and reassembled to follow crop rotations each season.

The total cost for the furrow irrigation system will be $275/acre per season. This was considerably higher than implementation of the disinfection system into drip, but was still found to be the most feasible option for a furrow irrigation system (Appendix L).

The environmental impacts of the ClO_2 system are minimal and the design will meet all regulatory standards. Malheur County growers already use ClO_2 for irrigation practices making it more readily acceptable to growers in the area. ClO_2 is the most practical solution for disinfecting irrigation water when considering both furrow and drip irrigation systems.

Abstract

The Food and Drug Administration is proposing a new regulation in regards to the quality of irrigation water applied to produce crops that may be consumed raw. The new regulation states that levels of *Escherichia Coli* cannot be above 126 colony forming units per 100 mL of irrigation water. Alternative treatment techniques were evaluated for effective compliance on onion farms found in Malheur County of Eastern Oregon. These alternative solutions include disinfection via ultraviolet radiation, ozone, and chlorine dioxide along with treatment via sediment filtration. After consideration of the alternatives, chlorine dioxide was found to be the best treatment choice for current farming practices in Malheur County. Within this area, irrigation techniques vary between pressurized drip systems and gravity fed furrow systems. The proposed design will be feasible for both types of distributions. The estimated cost per acre to implement the disinfection system with drip irrigation was approximately $90/acre for the first year and $15/acre annually each year after. The disinfection system for furrow required more machinery and must accommodate a higher flow rate making the cost estimate for furrow irrigation significantly higher than drip, a minimum of $275/acre. All cost estimates were based on an average field size of 40 acres. Chlorine dioxide has minimal environmental impacts and limited negative social implications. It is also the most economically feasible design that can be implemented in furrow and drip irrigation systems. The intent of this report is to document the alternatives initially considered while placing an emphasis on the final chosen design. The technical, economic, social, and environmental considerations for the final design are extensively discussed.

Table of Contents

1. Introduction

In Malheur County, Oregon, the second largest source of income is onions. Onions have been a major crop in this area for the last 100 years and many generations of farmers have made their living from the growth, sale, and distribution of these onions.

The Food Safety Modernization Act (FSMA) was a regulation proposed in 2013 which affected the cleanliness of irrigation water applied to raw edible food crops. This anticipated regulation will affect onion growers in Eastern Oregon. The proposed water quality standards limits the amount of *Escherichia Coli* (*E. coli)* bacteria to less than 126 colony forming units (CFU) per 100 mL of irrigation water for an average of five consecutive samples or 236 CFU/100mL in any one sample.

Onion farmers in Malheur County are divided between gravity fed furrow irrigation and drip irrigation systems. These methods relied on irrigation water that exceeded the proposed maximum *E. coli* levels. The senior design class in the Biological and Ecological Engineering Department (BEE) at Oregon State University (OSU) was commissioned to find a feasible solution to meet the water quality requirements of the FSMA.

Several disinfection technologies were evaluated to construct a feasible design solution. The technologies were ultraviolet radiation, ozone, sediment filtration, and chlorine dioxide. This report highlights all considered technologies and documents the final technology chosen. The final decision is explored in technical, economic, environmental, and social detail for implementation in furrow and drip irrigation systems

2. Alternate Solutions Considered

2.1 Methods

The BEE senior design class visited the OSU experimental research station in Ontario, Oregon to learn about current farming practices. Dr. Clint Shock, professor and manager of the station, shared his studies and personal experiences. Students were informed on furrow and drip irrigation, current practices of farmers in the area, water transport systems, and possible methods for filtration. Additional site information is available in Appendix A.

Preliminary research was conducted and each team member chose an alternate water treatment or irrigation technology to investigate further. Areas of research include furrow irrigation, drip irrigation, chlorine dioxide, UV, and ozone disinfection along with sediment filtration.

2.2 Decision Matrices

To select the most feasible technology that also met all regulatory standards a quantitative analysis or decision matrix was created that assigned numerical rankings to each technology. Categories for the rankings and the rankings themselves were determined based on design criteria and constraints (Appendix B). These were further broken down into five main categories of concern: regulations, technical, social, environmental, and economic. Pass/fail criteria were created ensuring that the technology received a score of "zero" if the regulations were not met, eliminating it from the list of possible options. For all other categories a score of zero indicated "failure", one was seen as "poor", two was "below the acceptable level", three was "acceptable", four was "above the acceptable level", and five was seen as "excellent". Economic regulations were weighted most heavily at 45% of the total because economics were determined to be the driving factor in the grower/client decision. Technical considerations were weighted at 30% because they were essential in making a feasible engineering design. The decision matrix and decision criteria can be seen in Figure 1 and Figure 2 respectively along with Appendix C. Chlorine dioxide received an overall score of 84.3%, which was higher than all other available technologies and thus was selected as the most feasible disinfection technique.

	Technical Alternative →		Test case	Sediment Filter	Chlorine dioxide	Ozone	UV	Do nothing
Regulatory		Weight						
Meets all regulations		1	1	1	1	1	1	0
Compatibility		1	1	1	1	1	1	1
Technical								
Mature		8	5	3	4	3	3	5
Scalable		8	5	5	5	5	5	2
Mobility		8	5	2	5	5	5	5
Operation and maintenance		6	5	3	3	1	3	5
Overall Technical Score		30	20	13	17	14	16	17
Environmental								
Soil impact		5	5	3	3	3	3	3
Crop impact		5	5	3	3	3	3	3
Run off impact		5	5	3	3	3	3	3
Overall Environmental Score		15	75	45	45	45	45	45
Social								
Grower acceptance		5	5	3	3	2	3	5
Community acceptance		5	5	4	2	2	4	5
Overall Social Score		10	50	35	25	20	35	50
Economic								
Annual cost/acre		45	5	3	5	2	1	5
Overall Economic Score		45	225	135	225	90	45	225
Overall Score								
		100	370	228	312	169	141	0
Scores Normalized to 100		100	100.0	61.6	84.3	45.7	38.1	0.0

Figure 1: Decision matrix used to evaluate available technologies

Scale	Description	Economic	Maturity	Scalable	Mobility	Operation and maintenance	Environmental	Grower acceptance	community acceptance
0	Fail	>900		Cannot work for irrigation	Cannot move water				
1	Poor	>300	Not used for disinfection	Can only work for either small fields (<10 or large farms >80 acres)	Can move/ distribute water with extreme modifications and high expense	Costly, regular, labor intensive, or hazardous operation	net negative	Never used in irrigation, can damage crops, or hazardous to operator	Dangerous
2	Below acceptable level	300-160	Used for disinfection but not commonly and not necessarily for irrigation	Will only work for 40 acre fields	Can move/distribute water with many modifications and expense	Regular, labor intensive, training intensive, or hazardous operation	slight net negative	Potentially damaging to crops, potentially dangerous to operator, and not commonly used	Potentially dangerous
3	Acceptable	140-160	Used commonly for disinfection but not necessarily for irrigation	Can be used for 20-60 acre fields	Can distribute water with modifications	Yearly or less maintenance requirements and simple operation which can be preformed by grower or laborer with simple training or few potential hazards	No net effect	Not potentially damaging to crops or grower, is used but not a common practice in farming	Not dangerous and limited environmental impacts
4	Above Acceptable Level	100-140	Used for disinfection and experimentally in irrigation	10-80 acre fields	Can move/disabuse water without modifications	Yearly or less than yearly maintenance simple operation with minimal training not hazardous	net positive	Is used in farming practices	Not dangerous no negative environmental impact
5	Excellent	<100	common practice in disinfection and irrigation	Can be scaled to any sized field	Can move/distribute water without modifications	Less than yearly maintenance, no addition operation training, no hazards	very positive	Saves water, soil, increases yield, or is economically beneficial in another way, is a common practice in farming	Not dangerous with positive environmental impact

Figure 2: Decision criteria and ranking scale for design criteria

From the four available technologies, ClO_2 was found to be the most feasible choice for disinfection over sediment filter, ozone, and ultraviolet radiation treatments. Categories from a technical standpoint were created to assess maturity, scalability, mobility and operation & maintenance. Using chemicals to achieve disinfection was seen as a mature technology from its use in drinking water and wastewater disinfection. It is also already in use for irrigation practices (Shock, 2013). Since the necessary disinfection level is a function of the chemical dosage, chlorine dioxide scored an "excellent" in scalability. ClO_2 will be generated on-site using two chemicals and can easily be moved from field to field via a trailer or truck. For this reason it scored an "excellent" in mobility. Yearly maintenance of the generation system and regular cleaning give this technology an "acceptable" score in operation & maintenance.

Impact of ClO_2 on soil structure, crop uptake of water and nutrients, or erosion from runoff was found to be neutral. For this reason, an "acceptable" score was given in all three environmental categories.

The addition of chemicals to water or natural systems can be perceived as negative to growers and the community. The practice of adding chemicals to irrigation water could cause concern about the long-term negative effects. Due to this, chlorine dioxide scored "acceptable" in grower acceptance and "below acceptance level" in community acceptance.

Chlorine dioxide is the least expensive out of the available technologies and scored highest in annual cost per acre. Chlorine dioxide is the most cost effective disinfection technology available and meets all other necessary regulations. The economic considerations were weighted most heavily.

2.3 Sediment Filtration

Research and field tests confirmed that sediment filtered *E. coli* to an acceptable level for the regulation proposed in the FSMA. A study conducted by Dr. Clint Shock at the OSU experiment center evaluated the efficiency of bacterial removal through a test sediment filter. This study influenced the filter design

Field sizes evaluated for the sediment filter design calculations ranged from 10-60 acres. Irrigation flow rates for furrow ranged from 200-1500 gal/min corresponding to a filter area size range of 0.5-4 acres at a water level of 3 feet. The irrigation flow rates for drip ranged from 120-720 gal/min and correspond to filter sizes of 0.3-2 acres at a water level of 3 feet (Appendix D). The annual cost of a sediment filter was approximately $130 per acre (Appendix E).

The environmental impacts of a sediment filter were minor. The soil used for filtration would need to be taken from the surrounding areas. This could cause ecosystem disturbances and possible damage to the soil structure and profile; this impact was estimated to be minimal. The sediment filter would also collect suspended sediments helping to improve local water quality by decreasing suspended solids.

Sediment filters met the regulatory, economic, social, and environmental criteria for this design but was not mobile. The typical five year field rotation for onions meant sediment filters would need to be installed on each field making the design too expensive. Due to the fact that the design was immobile, it is deemed infeasible for disinfecting irrigation water in Malheur County.

2.4 Ultraviolet Radiation

The feasibility of the implementation of an ultraviolet radiation treatment to the current farming practices in Malheur County, Oregon is evaluated as a solution to the new FDA regulations regarding farm-to-table crops. Ultraviolet radiation sufficiently disinfects contaminated water by rearranging and destroying genetic material via ultraviolet light bulbs that emit short electromagnetic waves (Ellner, 2013). The result is mass cell inactivation preventing the reproduction of subsequent bacterial cells.

The main benefit of this technology is its use of light to inactivate microorganisms, meaning that no chemicals are used in the process to achieve effective treatment. As a result, the formation of harmful chemical byproducts is completely eliminated. The lack of chemicals used also minimizes groundwater contamination.

The environmental impacts of a UV radiation treatment design stem from the energy intensive nature of this system. The bulbs needed for this system operate at high intensities and require constant power to be effective. They run on electric, which is unavailable in the fields and a portable generator that converts gas to electricity would be necessary.

The social acceptance of UV radiation water treatment system is fairly high. It does not employ the handling, generation, or distribution of chemicals, making it appealing to farmers. However, UV radiation is not a mature technology for agricultural settings as it is widely used in municipal and wastewater treatment plants but not within farms.

Capital costs alone for a UV radiation system is upwards of $400/acre annually for a 40 acre farm. This number is based on a 20 year farm loan valued at a 5% interest rate. This cost estimate is based off UV cost estimates done by the Environmental Protection Agency (EPA) (Wastewater, 1999). On top of capital costs, other expenses must be addressed. One of the main constraints of UV radiation technology is that turbidity levels must be less than 2 Nephelometric Turbidity Units (NTU). To achieve this low turbidity level, water filtration prior to UV exposure is required. The necessity of a pre-filtration system increases cost for this system. Ultimately, the cost of a UV disinfection system is roughly 50% of the farmers' annual profit of $929/acre. Due to this high cost, issues with filtration, and increased maintenance the implementation of this system was rendered infeasible.

2.5 Ozone

Ozone (O_3) is a strong oxidizing compound that can be used for the disinfection of water via oxidation reactions. It is a highly unstable molecule that when introduced to contaminated water, effectively inactivates pathogens by disrupting the organism's cell membrane. Once the cell membrane has been damaged, the bacteria cease to function properly and therefore cannot reproduce for continual contamination.

The process of generating ozone imitates the natural process that occurs when lightning strikes Earth. This process is duplicated on site by sending high voltages through dry air ensuring that no toxic chemicals are necessary. No harmful byproducts are created in the generation. Ozone also leaves no traces of chemical residue in the water after all disinfection reactions have occurred. This is one of the environmental benefits of using this compound for disinfection.

Ozone is very effective in water disinfection because of its highly reactive composition. Ozone has an oxidation reduction potential (ORP) that is 1.5 times the ORP of chlorine (Solomon et al, 2013). ORP is a measure of disinfection efficacy and allows comparison of different treatments. This high ORP is effective against most bacteria, including *E. coli*.

Social acceptance of ozone is expected to be fairly low. Though ozone is a natural compound, once produced it becomes highly corrosive, rendering it hazardous. Due to its high instability, it is not safe to transport and it must be generated onsite. This greatly increases the operations and maintenance for growers because extensive training of staff is required. This system is not mature in agricultural settings.

The following cost estimate for implementing ozone disinfection technology is from cost estimates from EPA (Wastewater, 1999). Capital costs alone for an ozone system used in an agricultural setting are about $600/acre/year. This is based on a 40 acre farm and a 15 year farm loan valued at 5%. It is likely cost would go down with further investigation of various treatment designs, but the reduction would not be enough to create cost effectiveness. On top of capital cost, other costs must be addressed. Many ozone water treatments involve a pre-filtration for water with high levels of suspended solids. Irrigation water in Ontario would require filtration, increasing the total cost per acre again. Annual operating costs need to be considered as well, such as power consumption, training, and various repairs for equipment.

Ozone can be an environmentally conscious disinfection solution on a small scale. The energy intensive nature of this treatment, however, renders it much less environmentally friendly when large quantities of water must be treated as is the case for the farms within Malheur County. It is not currently mature design for water treatment in agriculture and is not cost effective to implement. For these reasons it is deemed infeasible for implementation with current farming practices in Malheur County.

3. Chlorine Dioxide

After consideration of the alternatives, chlorine dioxide was found to be the best treatment choice for current farming practices in Malheur County based on a quantitative analysis and team discussions. The intent of the rest of the paper is to investigate the implementation of a chlorine dioxide disinfection system into both drip and furrow irrigation systems.

3.1 Chlorine Dioxide Chemistry

Unlike other chlorine compounds, ClO_2 had the ability to reside in water without hydrolysis. This means that it existed as a dissolved gas (White 2010).

The oxidation potential of ClO_2 was dictated by the amount of electrons that the compound would consume as its oxidation-reduction reaction occurs. This value allowed for the comparison of chlorine compounds in regards to their strength of oxidation and disinfection. For ClO_2, the half reaction that dictates this was the following (Davis 2010):

$$(1)\quad ClO_2 + 2H_2O + 5e^- \rightleftharpoons Cl^- + 4OH^-$$

Five electrons were consumed in this redox reaction. Using this value to calculate percent available chlorine, ClO_2 has a value of 260% available chlorine in comparison to free chlorine gas (Cl_2), which has 100% available chlorine. This means that ClO_2 is 2.6 times more powerful of as an oxidant than free chlorine and the highest of all the chlorine compounds (Davis 2010). In actuality, ClO_2 is rarely reduced completely to the chloride ion, so this value is not fully realized. The typical reaction in water is as follows (Davis 2010):

$$(2)\quad ClO_2 + e^- \rightleftharpoons ClO_2^-$$

There are multiple ways to generate chlorine dioxide using different acids in reaction with sodium chloride. In this design, hydrochloric acid is combined with sodium chloride to produce ClO_2.

3.2 Inactivation Methods and Dosages

Chlorine Dioxide is effective at deactivation of viruses, bacteria, and protozoans. ClO_2 used a process of bacterial cell membrane disruption to create a large influx of potassium ions into the cell. In conjunction with the reduction of the bacterial cell's respiration rates the cell will be inactivated. The inactivation of viruses was caused by the reaction of ClO_2 with viral capsid proteins rendering it inactive (Aieta et al. 1986).

According to literature, the dosage rate for a 2-log inactivation of *E. Coli* ranges from 0.75 mg/L to 10 mg/L with a contact time of one minute, a temperature of 20ºC, and a pH of 7 (Aieta et al. 1986; Huang et al. 1997; Siemens 2008; Tchobanoglous, 2003). Inactivation times for viruses and bacteria vary from 2 mg*min/L to 27 mg*min/L on average (Davis 2010). Inactivation for protozoans can be upwards of 200 mg*min/L at temperature of 20ºC and pH of seven (White 2010). A range of pH values from 2-10 and temperatures have little effect on the efficacy of the disinfection (Aieta et al. 1986).

3.3 Byproduct Generation

Usually with the use of chlorine compounds, the formation of trihalomethanes (THM) and haloacetic acids (HAA) was not an issue unless the water contains bromide (Li et al. 1996). The irrigation water in Eastern Oregon used does not contain a significant amount of bromide (Warmsprings Water Quality). The main disinfection byproducts formed are chlorite ions and chlorate ions.

4. Design

4.1 Technical Considerations

A ClO_2 generation system was recommended to be incorporated into both drip and furrow irrigation systems in order to meet proposed FSMA regulations.

As stated in the introduction, the allowed levels of *E. Coli* in irrigation water are 126 CFU per 100 mL. Using data collected from the Warmsprings Watershed District, the worst-case scenario bacterial coliform loads were used to calculate the amount of inactivation to reduce levels to acceptable limits. With an initial value of roughly 2500 CFU and using the following equation (Davis 2010):

$$(3) \quad -\log\left(\frac{N_f}{N_0}\right) = \text{inactivation number}$$

N_f is the number of max CFUs as per regulation (126) and N_0 is the initial number of CFUs (2500). The log inactivation number is calculated to be 1.3. The dosage of chlorine dioxide needed to obtain this amount of inactivation can be found from this value (Appendix F).

The water in the area is assumed to have a pH value of around 8 with a temperature of 20ºC at standard atmospheric pressure (STP) (Warmsprings Water Quality). The log inactivation number, calculated as 1.2 for *E. coli* average maximums of 2000 CFU. To provide a factor of safety for occasional *E. Coli* outbreaks, which can reach values above 2500 CFU, a log reduction of 1.3 was used. From these assumptions the dosage rate in literature was recorded to be anywhere from 0.5 mg*min/L to 10 mg*min/L (Aieta et al. 1986; Huang et al. 1997; Siemens 2008; Tchobanoglous, 2003). A dosage rate of 1.6 mg*min/L corresponding to a 1.3 log inactivation with a 1 minute contact time was chosen. Dosage feed rates will vary depending on the flow of water to be treated, which is discussed in following sections.

Figure 3: The chlorine dioxide generation system sold by CH20.

4.2 Integration

Due to the fact that in Treasure Valley onion farmers use both furrow and drip distribution, designs for the incorporation of a chlorine dioxide generation system in to current farming practices were made and shown in sections below.

4.2.1 Integration with a Drip Irrigation System

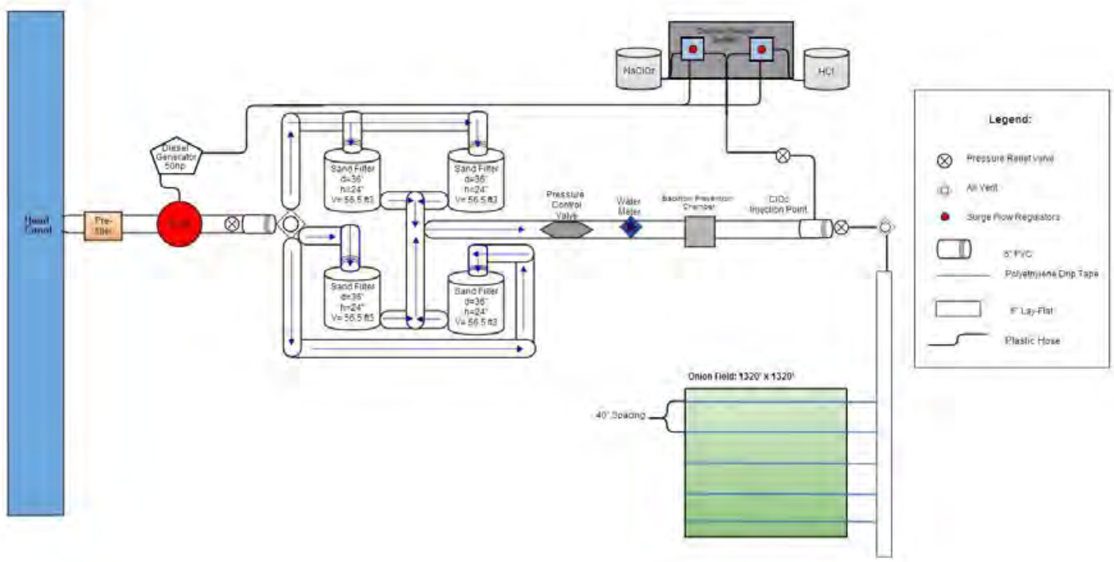

Figure 4: Implementation of a chlorine dioxide disinfection system with drip irrigation

Integrating ClO_2 into a drip system was simple because not only do farmers already have the drip distribution system in place, the apparatus itself contains an existing chemical injection. Water enters the system and will be filtered for large debris by a prefilter or grit screen before it passes through the pump. Then it will be filtered again for remaining particles larger than 75 microns via a series of sand media filtration tanks. The chemicals will then be integrated into the system after the water had passed through the filters, but before the water is distributed to the field via the layflat pipes and drip tubes (Figure 4). Hydrochloric acid and sodium chloride will be delivered in barrels and combined using the chlorine dioxide generation system. The chlorine dioxide generation system will be placed onto the trailer that holds the entire drip filtration and pump system and will run off of the same diesel-powered 50hp generator that powers both the pump and the electrical power switch. This ensures that the entire system will be mobile.

Using the data on drip irrigation scheduling provided by Dr. Clint Shock, the chemical feed rate was calculated to be 1.6 mg of ClO_2 per liter. This number was calculated using the drip irrigation flow rate of 500 gal/min. These values yielded a dose of 280 g/hr of ClO_2. This was then used to calculate total ClO_2 needed for an entire season. Assuming a 2.5 month long growing season and a required 8-hour irrigation set every 1.5 days, the total amount of chlorine dioxide that was required per season was 71 kg of ClO_2

(Appendix G). The required retention time of 1 minute for disinfection of *E. coli* was achieved between the time the water was dosed with chemicals and the time it exits the drip tape onto the crop root zone.

Figure 5: The sand media filtration system used in drip irrigation. This equipment is sold by Clearwater Supply locally in Malheur County.

4.2.2 Integration with a Furrow Irrigation System

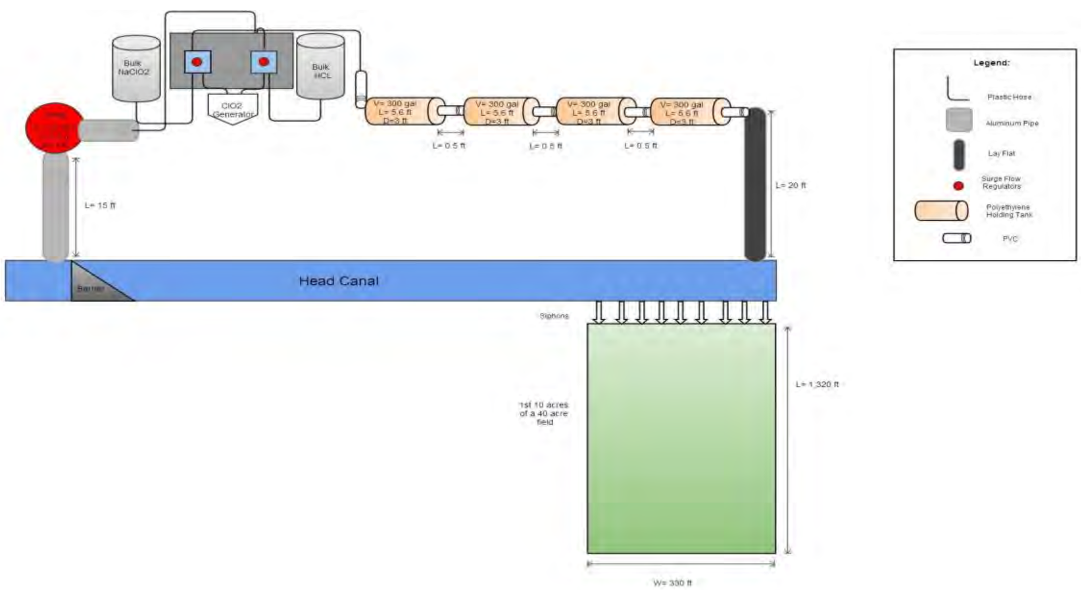

Figure 6: Design schematic for chlorine dioxide treatment system in furrow irrigation with a plug flow reactor system

Integrating a ClO_2 disinfection system into a furrow irrigation distribution system required a different approach than the drip system did. This is because an entirely new system had to be designed. It was not possible to simply scale up from what was already in practice for current furrow irrigation systems as was done with the drip system.

The proposed system for furrow will use a pump to pull water out of the field's head canal which will then be injected with a dose of 1.6 mg/L ClO_2 from the generation system which manufactures ClO_2 onsite using hydrochloric acid and sodium chlorite. The chlorine dioxide generator will run off of power from a diesel generator, which the farmers are assumed to already own. Once treated, the water will be pumped through a series of four high-density polyethylene tanks. The water should reside in the tank system for at least 1.2 minutes, which was the acceptable contact time for the dosage chosen (Liu, 2013). The treated water will then be released from the holding tanks and fed back to the head canal through lay flat where it can then be siphoned and applied to the field via furrows.

Furrow irrigation has a flow rate of 1,000 gal/min to ensure that the onions are properly irrigated. Typically, in the Treasure Valley area an irrigation schedule of one 12-hour set every day (1/4 of the field is irrigated every day, therefore a whole field is irrigated in four days) was used. For a whole season of irrigation approximately 320 kg of chlorine dioxide will be needed (Appendix G).

Initially, four sand media tanks were considered for implementation to decrease organic loading and other suspended solids that could interfere with adequate treatment of the water. However, after a cost analysis was done for this proposed implementation, it was deemed to expensive to employ (Appendix H). As a result, the proposed design does not include a pretreatment filtration system to ensure ClO_2 disinfection efficacy.

Other methods were considered to increase the efficiency of the disinfection technique. According to Dr. Hong Liu, of Oregon State University, an increase in the retention time of the chlorine dioxide with the raw water can decrease the effect of organic loading on its disinfection efficacy (Liu, 2013). Using this knowledge, a series of tanks were designed to increase the contact time. Due to the complex nature of organic matter and chlorine dioxide interactions a log inactivation of 1.3 was used again to ensure that sufficient disinfection occurs. This log inactivation incorporates maximum spikes in bacterial colony forming units of the raw water. This applied factor of safety ensured that the raw water will be treated to acceptable levels should the organic loading be unusually high.

With a flow rate of 1000 gpm and a minimum retention time of 1.2 minutes, the total volume needed for the holding tank series was 1,200 gallons (Appendix I). This volume was distributed across four smaller holding tanks to act as a plug-flow reactor as seen in Figure 7. Each of the four tanks holds a volume of 300 gallons and should be as skinny and as long as possible to best achieve a plug-flow reactor set-up (Levenspiel, 1999).

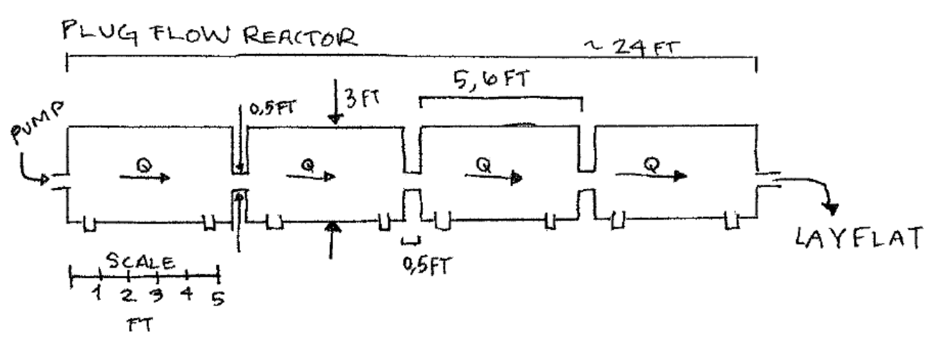

Figure 7: Scale drawing of the plug flow reactor used in the Furrow irrigation system. Each tank is 300 gallons in volume.

This system will be mobile, meaning it can be broken apart, put onto the bed of a regular truck, and set up on site. The weight of the machinery in the truck was deemed negligible when no water is present in the system. The weight of each holding tank is roughly 100 pounds and the pump weighs 1,125 pounds. The holding tanks will be on a concrete slab and the pump would be mounted on a trailer so it is easily transportable making the whole system extremely easy for farmers to move from field to field at the end of the season.

The pump used to pull the water from the head canal and pressurize the system is a 1000 gpm 24 hp trash pump. To ensure that the pump could tolerate the backpressure created by the junction and frictional losses throughout the plug flow reactor system, losses in pressure for each of these components were calculated. Because the tanks will be made of polyethylene, which is a very smooth material, and our system is only about 24 ft long, frictional losses were assumed to be negligible. Losses due to junctions, inlets and outlets, of each tank along with the frictional losses of the layflat were calculated using the head loss equations below (Ecological Fluid Dynamics),

$$(4)\ \ Head\ loss\ from\ Junctions\ (h_L) = K_e \frac{V_1^2}{2g}$$

$$(5)\ \ Headloss\ from\ friction\ (h_L) = f\,\frac{L}{D}\frac{V^2}{2g}$$

The velocity can be calculated based on the flow rate and diameter of each tank section. The loss from four inlets and four outlets, totaling the whole system, was 0.65 ft or 8 inches. The head loss resulting from the 15 feet of agricultural grade lay flat after the plug flow reactor is 1.7 feet. This had a total of 2.38 feet of head loss for the total system (Appendix J). As shown in Figure 8 below, when the pump curve for a 1000 gpm 24 hp trash pump was compared to the loss as a function of flow rate, it was clear that the back pressure created by the plug flow reactor system was not large enough to restrict pump operations (Koshin, 2014).

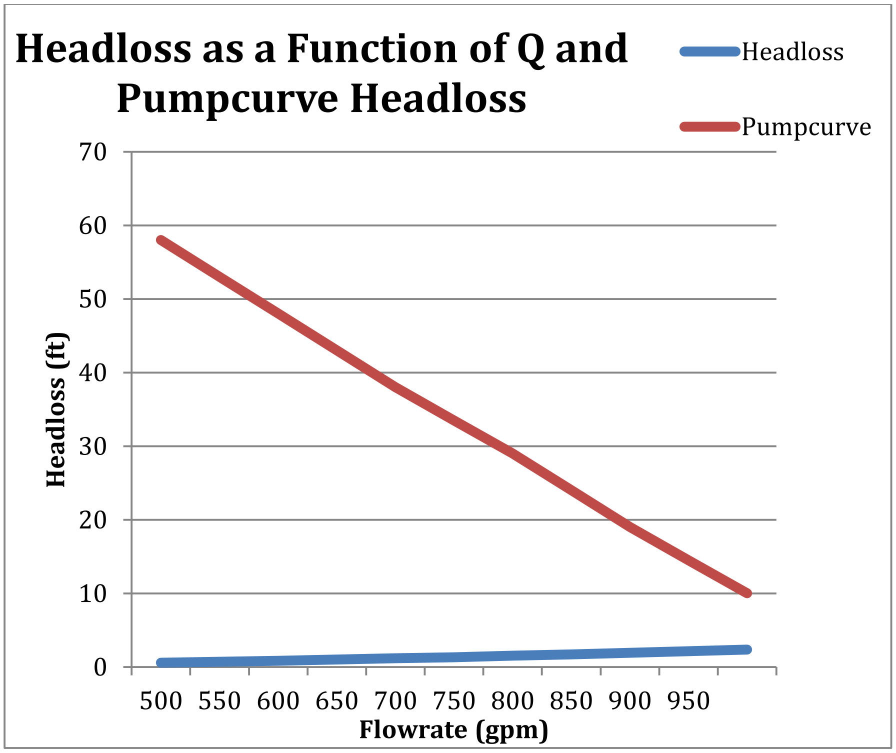

Figure 8: Head loss and pump curve as a function of flow rate.

All four tanks will be constructed of High Density Polyethylene with ½ inch walls to ensure that tanks are resistant to both chemical exposure and increased pressure from the pump (Plastic Storage Tanks).

5. Regulatory Considerations

Chlorine dioxide regulations were not currently specified for use in irrigation water. The U.S. Food and Drug Administration's code of federal regulations Title 21, Volume 3 revised on April 1, 2013 stated that ClO_2 was safe to use as an additive given that certain guidelines will be followed. The sodium chlorite additive used in the ClO_2 generation process must be made using the following methods: "treating an aqueous solution of sodium chlorite with either chlorine gas or a mixture of sodium hypochlorite and hydrochloric acid." The EPA supported the use of chlorine dioxide in agricultural settings. The EPA stated that chlorine dioxide should not be discharged into bodies of water or into sewer systems unless it was permitted by the National Pollution Discharge Elimination System (NPDES) (USA, 59).

Through lab analysis, the U.S. Environmental Protection Agency has determined that risk for operation will be reduced if the handler wears gloves to limit dermal exposure. The hazard from inhalation was deemed negligible (USA, 22). The current Occupational Safety and Health Administration (OSHA) allowed an exposure limit of 0.1 ppm for chlorine dioxide over an eight hour period. Since the chlorine dioxide will be distributed outside, this limit will not be surpassed in the proposed irrigation water disinfection design. This ClO_2 system met all regulatory standards.

6. Economic Considerations

6.1 Economics for Implementation with Drip Irrigation

The initial cost of the generation apparatus used to create chlorine dioxide was \$3,000 and annual maintenance was \$100. The power requirement associated with this apparatus was 110 volts at 10 amps for a total of 1100 watts. (Keith Saunders, 2013). For a drip irrigation system, the chemical cost is \$12 per acre (assuming a 40 acre field). (Appendix K) The first year will cost \$90 per acre, which will include the initial cost of the apparatus, chemicals, and maintenance. The assumption was made that power will be supplied from generator already in place on site and was negligible compared to the power requirement of the drip distribution system. In subsequent years, the total operational cost per acre is equal to \$15 for the same size field, which includes maintenance, and chemical costs (Appendix L). This was a reasonable yearly cost per acre, and initial investment in the technology was small enough that a grower could avoid taking a loan. In addition, these values were both lower than the maximum yearly cost of \$100-\$150 per acre that farmers were willing to pay, according to Dr. Clint Shock. The expected lifetime of the ClO_2 generation system is five years. (Keith Saunders, 2013).

6.1.1 Net Present Value for Drip Irrigation

The net present value (NPV) of the ClO_2 water treatment system was easiest to understand when compared to the NPV of the entire irrigation system. All expenses were estimated using a furrow irrigation budget sheet released by the University of Idaho (Thorton et al, 2011) and adjusting the values to better suit a drip irrigation system. Dr. Clint Shock informed the senior design class on the site visit that using drip irrigation increases the onion yield by 20% in comparison to furrow irrigation. Additionally, drip irrigation cuts the fertilizer costs by 50% and pesticide costs by 20% compared to furrow irrigation. This helps combat some of the expensive machinery and materials that are part of the initial costs of drip irrigation, such as drip tape and drip tape machinery. Adding a chlorine dioxide water treatment system was relatively inexpensive when a drip irrigation system was already in place, because the water is filtered to decrease the organic loading and the system is pressurized, both of which are system requirements for chlorine dioxide generation. Thus, the only extra costs found were the chemicals needed for chlorine dioxide generation and the chlorine dioxide generation system. These costs can be seen in Table 1 on the next page. The difference in the NPV between a drip system with and without a chlorine dioxide treatment is about \$6,000; see Appendix M for further information on a detailed drip irrigation net present value analysis.

Chlorine Dioxide System Annual Expenses (Drip Irrigation)		Annual Income (Drip Irrigation)		Chlorine Dioxide System Initial Costs (Drip Irrigation)	
Chemicals	$480	Onion Yield	$218,000	ClO2 Generation System	$3,000
Total	**$480**		**$218,000**		**$3,000**

Table 1: The major chlorine dioxide design costs compared to onion gross income for a drip irrigation system.

6.2 Economics for Implementation with Furrow Irrigation

The cost of integration in the furrow irrigation system was significantly more than the cost of integration into a drip system. All initial machinery costs were calculated using a 5%, 10 year loan with payment on an annual basis ("Loan Payment Calculator", 2013). All other costs were set to an average field size of 40 acres and are given in units of per acre, per season. Growers in Malheur County are likely not willing to pay more than $150 per acre per season to implement a water treatment system (Shock, 2013). Current furrow irrigation net profit per acre per season is about $930 (Thorton et al., 2011).

The ClO_2 generation system had an initial cost of $3,000 (Saunders, 2013). This generation system is powered using a diesel generator which yields fuel costs of $25.20 an acre per season (Appendix N). It is assumed that the farmers will have a diesel generator already, as most farms do. The chemical cost for this generation system was $33 per acre (Appendix K). The costs associated with maintenance for this system were $100 per season, which was $2.50 per acre (Saunders, 2013). Each of the four, 300 gallon tanks cost about $400, which yielded a total cost of $1,600 for the tank system ("325 Gallon Horizontal Leg Tank", 2013).

The minimum power needed for this pump was 1.66 horsepower (Appendix O), however flow rate must still be satisfied. With research on various pumps and costs, the most economical and feasible option was a 24 horsepower trash pump running on gasoline that can accommodate a 1,000 gallon per minute flow. The estimated cost for this pump is $9,000. This was a horsepower is about 15 times more powerful than necessary; however a 24 horsepower pump is used in industry to accommodate a 1,000 gpm flow rate. Its dimensions are 8 feet long by 4 feet wide by 4 feet high and it weighs 1,125 pounds ("IPT Pumps, 2013). A corresponding pump curve efficiency of a 24 horsepower pump meets 1,000 gallons per minute at about 10 feet of head, which will be sufficient head for this system as mentioned above (Koshin, 2014). This pump can be transported with ease despite its weight because it is trailer mounted. Although diesel is commonly used for agricultural pumps, the gasoline pumps researched use the same amount of fuel per hour as the diesel and gasoline is less expensive than diesel. The only problem with this pump is that it consumes 2 gallons of gasoline per hour and only can hold 12 gallons of gasoline. The irrigation set time for furrows was 12 hours, as previously mentioned, so the gasoline would need to be replenished half way through the irrigation set. Currently, the cost of gas was approximately $3.30 per gallon (Lowest Regular Gas Prices", 2013) and in one season, the gas-associated costs for the pump are $5,940. This amounts to $148 an acre. The price of gas fluctuates greatly on a regular basis so this cost will be likely to fluctuate as well.

A ClO_2 treatment system integrated into a furrow irrigation system cost $275 per acre per season (Appendix L). This cost was considerably higher than the target $150 per acre per season that farmers are willing to pay. However, using NPV analysis, this system is still worth about $435,000 compared to its NPV of $506,000 without the implementation of the chlorine dioxide system. After evaluating the alternatives, a chlorine dioxide treatment system was the only feasible option for disinfection of *E. coli* for furrow irrigation.

6.2.1 Net Present Value for Furrow Irrigation

There is relatively little heavy machinery necessary for furrow irrigation, which is why many growers in Malheur County are currently using this technique. This irrigation system is not classically pressurized and does not have any way to decrease organic loading in irrigation water, which are both necessary design components for a chlorine dioxide system. To ensure that the water is pressurized to flow through the plug reactor system, a pump will be necessary. The pump was a large cost at about $9,000 and the fuel costs associated with running this pump for 12-hour irrigation sets was over $6,000 per season. The chlorine dioxide generation system sold by CH_20 that this design incorporated cost $3,000. More chemicals were needed to generate chlorine dioxide for furrow irrigation because of the high water flow rate. These chemicals could cost over $2,000 per season, depending on the availability of discounted chemicals sold in bulk. This is considered the maximum cost for chemicals. The holding tanks necessary to achieve a plug flow reactor system cost $1,600. Lastly, piping is necessary to take the water out of the head canal, using aluminum pipe, for treatment and then to return the treated water to the field, using flexible layflat. Furrow irrigation does not normally have the need for piping, so this was an additional cost of about $500. These design costs are illustrated in Table 2 on the next page. These extra design components for a ClO_2 system, along with the lower efficiency of furrow irrigation compared to drip irrigation deducted $70,000 dollars from the NPV of furrow irrigated onions. See Appendix M for further information on a detailed furrow irrigation net present value analysis.

Chlorine Dioxide System Annual Expenses (Furrow Irrigation)		Annual Income (Furrow Irrigation)		Chlorine Dioxide System Initial Costs (Furrow Irrigation)	
Chemical	$2,205	Onion Yield	$181,900	Holding Tanks	$1,640
Fuel	$6,940			ClO2 Generation System	$3,000
				Pump	$9,000
				Layflat	$50
				PVC	$45
				Aluminum Pipes	$375
				Cement Slab	$440
Total	**$9,145**		**$181,900**		**$14,650**

Table 2: The major chlorine dioxide design costs compared to onion gross income for a furrow irrigation system.

6.3 Sensitivity Analysis

A sensitivity analysis is a technique used to determine how sensitive an output is to a change in any input, while all other inputs remain constant. A sensitivity analysis was conducted on all the necessary parameters involved in the proposed chlorine dioxide system designs for both furrow and drip irrigation systems. The analysis was based off the calculated NPV of each proposed system and accounts for any fluctuations in the market or in the design itself.

A ±25% sensitivity on total cost for each major component (fuels, pipes, pumps, tanks, concrete, etc.) was calculated. The analysis was completed for furrow and drip systems and the resulting +25% and -25% numbers were graphed and are shown in Figures 9-12 below. These sensitivity analyses are valuable because they help when assessing risk. They provide knowledge on the components of each system that are the most sensitive to economic change.

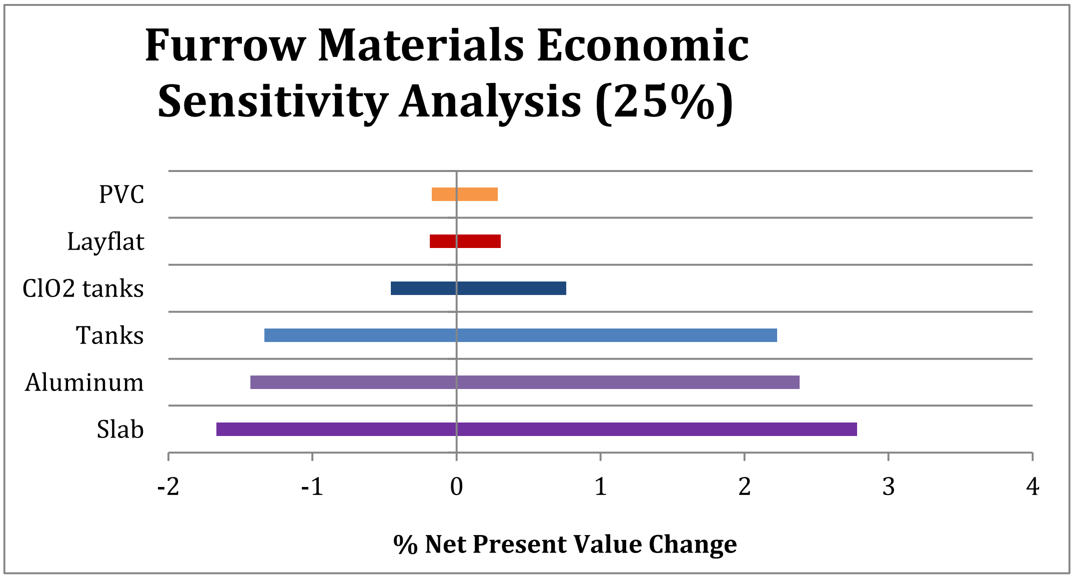

Figure 9: Sensitivity Analysis for the materials involved in furrow irrigation system.

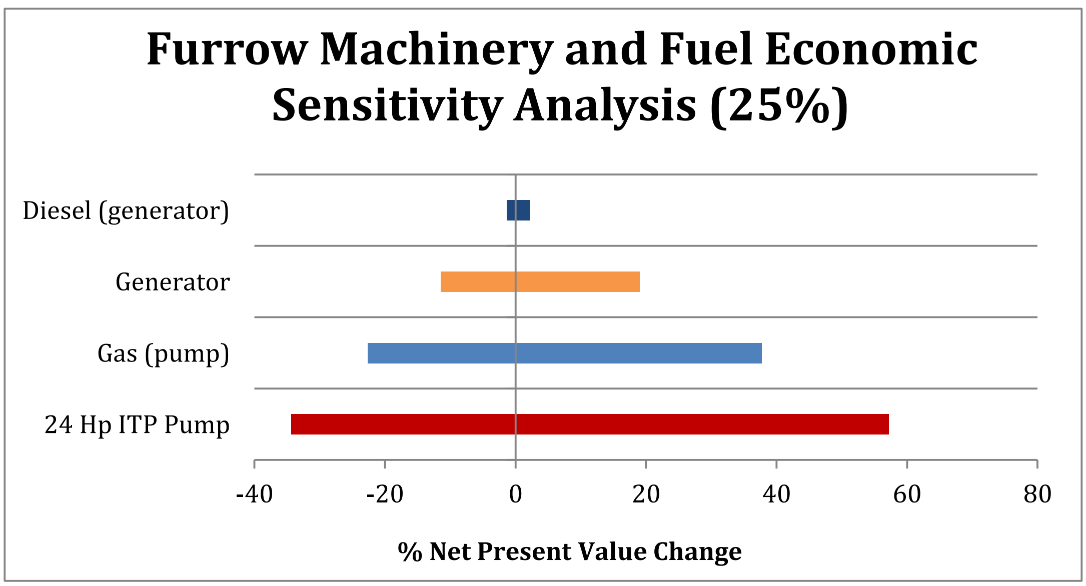

Figure 10: Sensitivity Analysis for the machinery and fuel involved in furrow irrigation system

Two graphs were created for the furrow system as opposed to one because of the significant difference in the percent change of the NPV for specific parameters. Due to high initial costs, the diesel generator, the gas powered pump and the fuel for both were graphed separately. It was apparent after examining each graph that within Figure 9 the concrete slab, the aluminum piping, and the 300 gallon tanks were the most sensitive to economic change. In Figure 10, the pump and the fuel required to power the pump were the most sensitive parameters. It should be noted that both graphs display the same information, but due to the large scale discrepancies the difference is seen easiest when the two graphs are separated, as above.

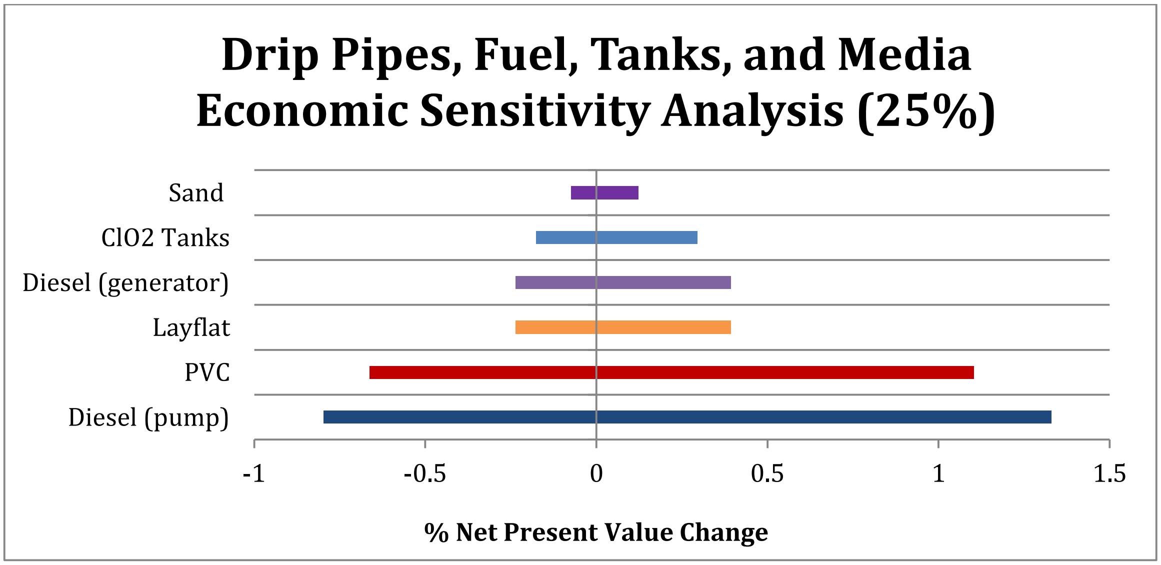

Figure 11: Sensitivity Analysis for the materials and fuel involved in drip irrigation

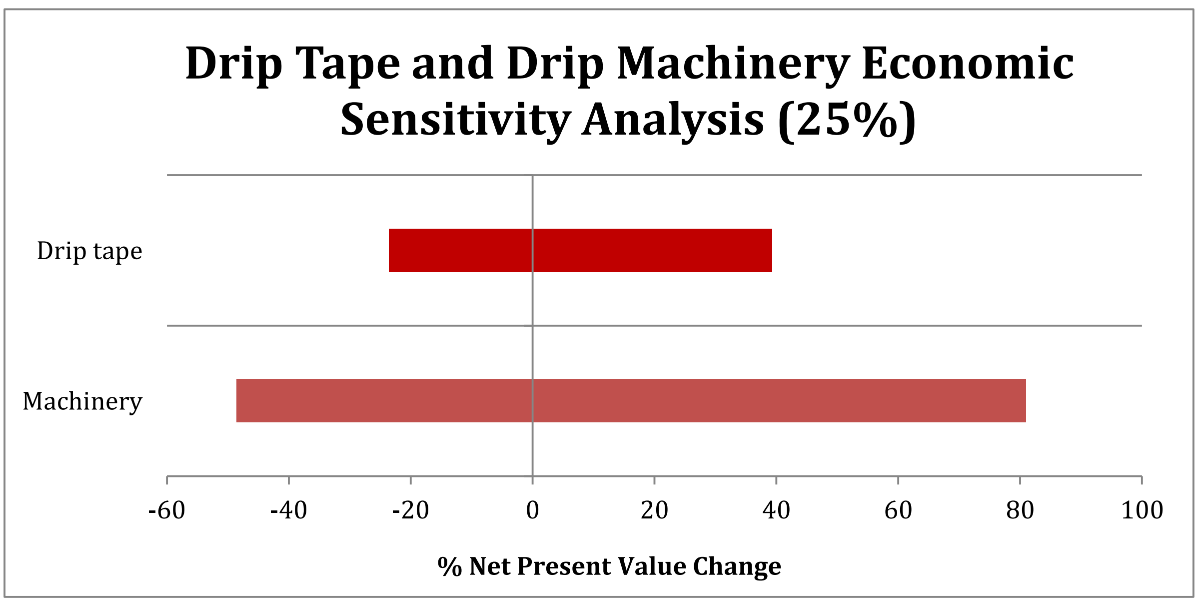

Figure 12: Sensitivity Analysis for the tape and machinery involved in drip irrigation

Two graphs were created for the drip system for the same reasons that two graphs were created for the furrow system. In Figure 11, it is obvious that the fuel necessary to power the pump along with the PVC piping were the most sensitive to economic change. Figure 12 shows that the machinery involved in the drip system was a more sensitive parameter than the drip tape. As previously noted the graphs were again split for viewing purposes.

7. Environmental Considerations

Since chlorine dioxide is a volatile chemical when exposed to sunlight and atmosphere, that once irrigation water containing chlorine dioxide was applied to the field, any excess will volatilize to chlorine and oxygen gas (World Health Organization, 2002). The chlorate and chlorite concentrations remaining in the irrigation water are ionic and will not volatize. Due to the increased flow necessary for furrow irrigation the total application of chlorine dioxide to the field was greater. This means that there will be more chlorate and chlorite ions present in the soil. The concentration of these ions must be monitored more closely in furrow systems than drip systems. Salt is another by-product and the amount produced is minimal. This results in little to no soil contamination.

7.1 Life Cycle Analysis

A Life Cycle Analysis (LCA) is a tool used to evaluate the impacts of products, processes, and activities. This tool can help determine the impacts of the production of components that were used in the disinfection system design. This project was evaluated with Carnegie Mellon University Economic input-output life cycle assessment online program. Categories evaluated were greenhouse gas emissions measure in CO2e, economic impact in dollars, and energy use in trillion joules (Appendix P)

The drip tape had the largest production for greenhouse gas emissions, economics, and for energy use (Figures, 13-15). Drip tape can be recycled but seldom is in practice because there generally is a fee for this service. It was recommended that the drip tape be recycled at the end of each season to reduce the waste and impact. Although drip tape has the largest production impact, drip irrigation systems reduced water use, soil erosion, and runoff of irrigation waters. These environmental benefits are not considered in the LCA analysis but should be taken into consideration when choosing an irrigation system.

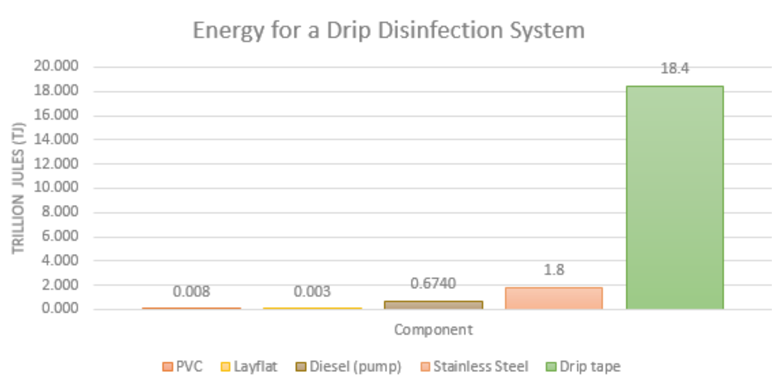

Figure 13: Energy for a Drip Disinfection System

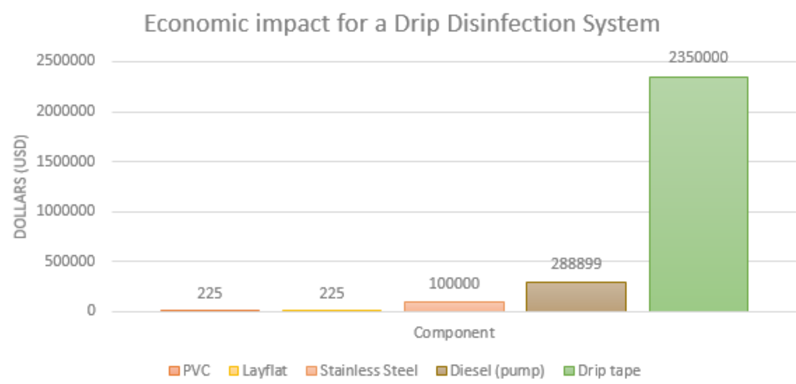

Figure 14: Economic Impact for a drip disinfection system.

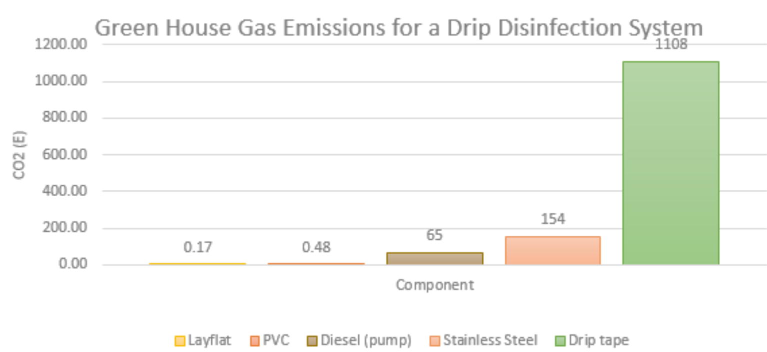

Figure 15: Greenhouse Gas Emissions for a drip disinfection system.

For a furrow irrigation system aluminum has the largest greenhouse gas emissions, economic impact, and energy use (Figures 16-18). The values were still lower than drip in all categories except for the economic impact. Aluminum piping was used in the design for pulling the water from the head ditch into the pumping system. Layflat cannot be used for suction and aluminum was more durable than PVC. Since chlorine dioxide is not present in the head ditch waters, the material did not need to be polyethylene therefore aluminum was used. The use of aluminum should be minimized by having the pump and disinfection system as close to the head ditch as possible. This will minimize the resources used in producing the aluminum piping.

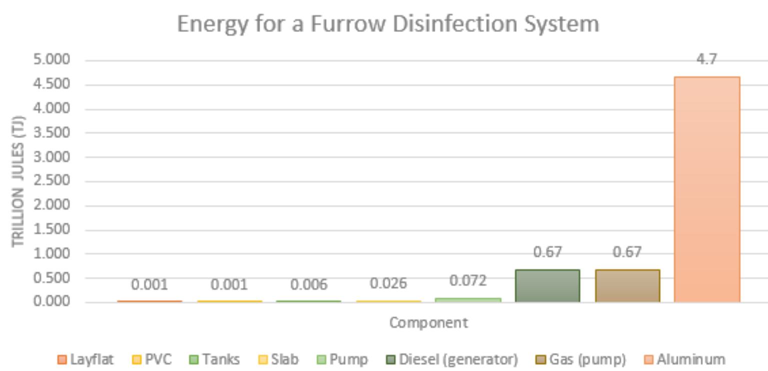

Figure 16: Energy required to construct a furrow disinfection system

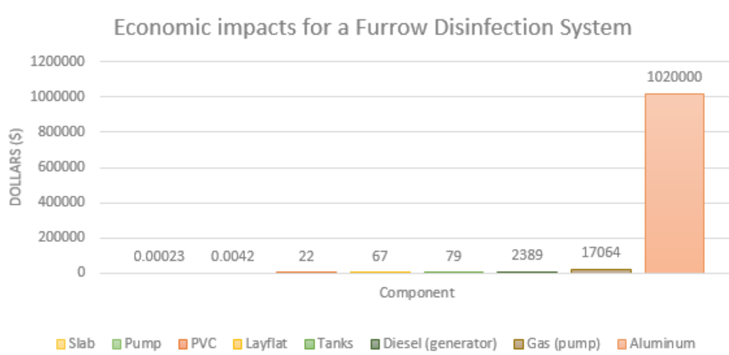

Figure 17: Economic Impacts of a furrow disinfection system.

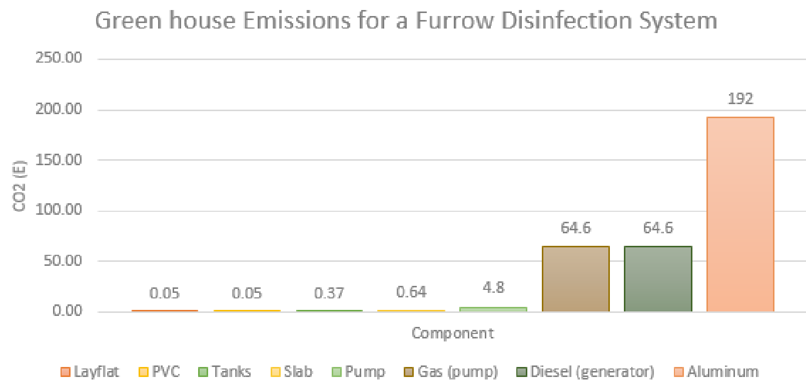

Figure 18: Greenhouse Gas Emissions for a furrow disinfection system.

8. Social Considerations

There are some safety concerns when using chlorine dioxide. It is a gaseous and volatile chemical, and should not be exposed to air. Thus the design calls for a holding tank for furrow irrigation systems, and the need for a pressurized distribution for drip irrigation systems. Chlorine dioxide will be generated on site due to its explosive nature when pressurized and packaged (White 2010). Care must be taken to ensure that exposure to chlorine dioxide will not occur as irritation to lungs, eyes, and skin can result (EPA 1999). Exposure to acids used in the creation of chlorine dioxide can also cause harm to lungs, eyes, and skin so special precautions must be taken.

According to CH_2O, minimal training will be required for farmers to learn how to operate the chlorine dioxide generation system. Approximately one hour of instruction time will be necessary (Saunders, 2013). Typically water quality samples were taken and analyzed to calculate exact dosage values needed to create the desired inactivation of pathogens. Then, the system will be calibrated to accommodate these pathogenic loads.

It was believed that because the proposed chlorine dioxide disinfection system can be implemented in both furrow and drip systems, this design will be widely accepted. Farmers in the area that are using drip irrigation already employ this technology to clear drip tape of algae and minerals. This allows for an easy transition from the occasional use of chlorine dioxide to "shock" the system to full time disinfection. Farmers that use furrow irrigation are most likely aware of the technology and its uses in drip meaning that the idea of using it to disinfect will not be a foreign concept.

9. Discussion

Creating designs for integrating chloride dioxide treatment in to both furrow and drip irrigation originally posed a large challenge. The technologies are completely opposite in almost all respects. Integration into a drip irrigation system is uncomplicated; the chlorine dioxide system is already in place to clear drip tape of algae and minerals, all that is needed to treat the water itself is a scale up of the dosage rate. Integration into a furrow system is more complicated due to the fact that organic loading from unfiltered raw water can decrease the efficacy of the chlorine dioxide treatment. Increasing the contact time of the chemical and the raw water, a technique that has been seen to decrease the organic load's impact, solved this problem. Other concerns with the furrow system were the head losses throughout the system due to junctions and ensuring that the tanks and connections can handle the pressure from the water flowing through the system.

Economically, the two systems are different as well. The proposed design for furrow irrigation costs $275/per acre for a 40-acre field and includes the whole system designed from scratch. The cost for the proposed drip irrigation system has a cost of $90/per acre for the first year, followed by a cost of $15/per acre for the subsequent years. For the drip system it is assumed that the original drip distribution machinery is already in place. This is where the discrepancy in cost stems from; furrow integration requires a whole new system as where drip irrigation involves adjustments to the system already in place. In addition, the necessary flow rates of water and irrigation schedules ensures that chemical cost will be much higher in the furrow design. Furrow irrigation requires 1000 gpm of water for 12 hours every day during the season. In comparison drip irrigation has a flow rate of 500 gpm with irrigation sets 8 hours in duration every 1.5 days. The volume of water used for the two systems differs, causing the amount of chemical needed and total chemical cost to differ as well.

Environmentally speaking, furrow and drip systems are much more similar than the categories stated above. For both systems the main concern is the amount of chlorate and chlorite ions deposited in the soil as waste after the disinfection process takes place. It is unknown quite how these species will interact with the soil chemistry. Furrow irrigation uses a larger amount of chemical per season so extra precautions must be taken to monitor the levels of ions. This means that with furrow irrigation there could be a larger accumulation of chlorate and chlorite in comparison to drip irrigation. In terms of the life cycle analysis both systems are similar there as well. Furrow's main concern is its large greenhouse gas, energy, and carbon dioxide contribution that stems from the aluminum piping used. Drip tape was the major contributor to greenhouse gas, energy, and carbon dioxide for the drip irrigation system. Other components were not as large of contributors.

Socially, in terms of ease of farmers and safety, both systems are similar. Designs for both furrow and drip irrigation are proposed ensuring that all farmers in the Treasure Valley area will be able to use chlorine dioxide as a disinfectant treatment. Each system is safe, mobile and scalable based on farm field size and location of field, making it convenient and easy for growers to rotate crops. Chlorine dioxide is already used in drip irrigation meaning that the scale up and switch to furrow irrigation should not be an extremely large issue for farmers in the area.

10. Conclusion

After consideration of all alternatives, chlorine dioxide was chosen as the final design for disinfection. Chlorine dioxide is an economically, technically, environmentally, and socially feasible solution to effectively lower *E. coli* populations to the desired treatment levels proposed by the FDA. Within Malheur County, chlorine dioxide is a viable disinfection option for both drip and furrow irrigation systems. It is relatively inexpensive to implement within drip irrigation and slightly more expensive for implementation in furrow irrigation. The estimated cost per acre to implement the disinfection system with drip irrigation is approximately $90/acre for the first year and $15/acre annually each year after. The disinfection system for furrow requires more machinery and must accommodate a higher flow rate making the cost estimate for furrow irrigation somewhat higher than drip at about $275/acre/year. Although the disinfection system for furrow is higher than the ideal $150/ac/yr, it is the most cost effective of the alternatives considered. The use of chlorine dioxide for disinfection created no harmful disinfection byproducts and insignificant amounts of chlorate and chlorite ions. It is also a mature and scalable option. Although this solution takes on a more classical approach to water disinfection, it can be easily implemented into both irrigation distribution systems and was reliable making it an excellent solution to lower bacterial contamination in irrigation water applied to Malheur County onions.

11. Acknowledgements

Thank you to professors John Selker and Ganti Murthy, Clint Shock, and Jim Clearwater for their patience and support.

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Appendices A-P

Appendix A: Site Visit Report

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Site Visit Report--Ontario, Oregon
October 11th – 13th, 2013

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Site Visit Highlights
· Fecal matter from unconfined feed lots is infiltrating runoff which ends up in onion fields. This is where the E-coli concentrations stem from. It appears a decentralized system is the only logical approach to the problem due to the fact that each farm receives water from multiple sources· 50% of farms are using drip irrigation and 50% are using furrow

- $3,000/acre/season for current growing practices
- Drip system would need addition of a treatment for coliform bacteria removal
- Chlorine dioxide is an effective method of decontamination within drip systems.
- The experimental sedimentation pond reduced the E-coli concentration by95% at a flow rate of 3.9 gal/h/yd^2. The higher the flow rate, the less effective the decontamination. Polyacrylamide may help increase the flow rate.

Other items to note:

- Onions are on a 5 year crop rotation
- All water at top of hill comes from Owahi Reservoir

The Primary Water Source

All water used for irrigation comes from the Owahi Reservoir and drains into the main canal. This main canal sits on the local highest point in the valley and water is gravity fed to all irrigation networks. Field runoff from cow pastures is infiltrating the water within this main canal, which creates the potential for microbial contamination on the receiving onion fields. Since the water source is extremely hard to identify, all field runoff is mixed with the runoff of the fields in close proximity. It is not an option to try and isolate the contamination.

Furrow System

Currently, a siphon system is used to distribute water from field canals to the crops through furrow irrigation. This system produces 50-55% distribution uniformity due to the difference in water contact time from the top of the field to the bottom. As a result, furrow systems have a high water demand. Currently, furrow irrigation is used by 50% of the farmers in the valley. It is important to note that the labor cost for this system is $80/acre/season.

Drip System

A drip irrigation system is currently used by 50% of the onion farmers in the Treasure Valley. Although upfront costs may seem high, ultimately drip irrigation increases onion yield, decreases water use, decreases soil runoff, allows for excellent water distribution within the field and can provide precise application of herbicides, pesticides and fertilizers. The system consists of the irrigation piping, an apparatus of 4 sand media filters, and a pump. Also, note that the sand media filters do not filter coliform bacteria. Costs for the apparatus are as follows:

$60/acre/season labor costs
$1,100 for hardware
$400 for operation and maintenance annually
$5,000 for any field size for diesel fuel
$15,000 total for all machines (up-front cost)

Chlorine Dioxide Water Treatment

As a treatment technology Chlorine Dioxide gas is a viable option. It is only necessary to use 1-2 ppm of ClO_2 gas for 1-2 miles of drip irrigation tape. The gas is manufactured onsite and is then distributed through the irrigation system. Because of the volatile nature of ClO_2, this treatment will not work for a furrow system. The equipment that creates ClO_2 costs $3,000 initially and can produce enough gas for 100 acres. It has a life span of 5-10 years. Subsequent operation costs are $25/acre/season and include reactants.

Sedimentation Experiment

Dr. Shock is exploring a new gravity fed filtration system that is not yet a mature technology, but has potential to work for water treatment. It uses the soil naturally present in the area as a filter to remove coliform bacteria. Through a catchment pond at the lowest point on the property, it successfully catches significant amounts of runoff and pumps irrigation water back up to the highest elevated field, thus creating a small closed system. The ultimate goal for the catchment pond is to place a piping system underneath, allowing runoff from fields to be filtered and reused. This piping system is not currently in place; however, in a second experiment Dr. Shock quantified the removal of bacterial contaminants through a modified soil column placed in a metal trough. The goal of these experiments is to eventually combine the two and produce clean irrigation water with minimal technology and low cost.



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Appendix B: Team 2 Problem Statement, Criteria, and Constraints

Problem Statement

The Food and Drug Administration is concerned with the quality of irrigation water applied to onions and other farm-to-table crops in the United States. The proposed Food Safety Modernization Act will set new limits for the amount of coliform bacteria present in irrigation water to 126 colony forming units per 100 mL. A water treatment system must be designed to ensure farmers are able to comply with these standards. Field sizes in an area of interest (Malheur County, Oregon) are an average of 40 acres but vary from 10-100 acres. Levels of contamination in irrigation water also vary in the area, within a range of 0-2500 CFU per 100 mL. Irrigation techniques alternate between gravity fed furrow systems to pressurized drip systems. The proposed design must provide farmers with an economically feasible treatment and distribution option that matches or improves upon the current system current distribution system and effectively lowers bacterial coliform contamination levels in irrigated water to the new regulation limit.

Criteria

- Improve water quality, reduce soil erosion, and maintain soil properties over time.
- Minimize harmful by-products of treatment technique for humans, soil, and vegetation.
- Maintain or improve upon current water distribution uniformity.
- Reduce accumulation of algal and mineral growth in current distribution system.
- Appeal to farmers by allowing for easy operation by farmer, including minimal installation, maintenance, and operation training.
- Minimize total cost of treatment apparatus.

Design constraints:

- Treatment must meet all regulations set forth by the Food Safety Modernization Act, most specifically lower coliform bacterial levels to less than 126 CFU/100ml off irrigation water.
- Water use must not exceed current water usage.
- Water quality must be maintained and must meet all EPA, USDA, and NRCS regulations.
- Additional environmental contamination cannot exceed current levels.
- Proposed treatment must maintain profitability of operations.
- Proposed treatment must be mobile and scalable to accommodate different fields and contamination sources.

Appendix C: Evaluation Matrices for Decision of Final Design

	Technical Alternative		Test case	Sediment Filter	Chlorine dioxide	Ozone	UV	Do nothin g
Regulatory	Weight							
Meets all regulations	1	1	1	1	1	1	0	
Compatibility	1	1	1	1	1	1	1	
Technical								
Mature	8	5	3	4	3	3	5	
Scalable	8	5	5	5	5	5	2	
Mobility	8	5	2	5	5	5	5	
Operation and maintenance	6	5	3	3	1	3	5	
Overall Technical score		30	20	13	17	14	16	17
Environmental								
Soil impact	5	5	3	3	3	3	3	
Crop impact	5	5	3	3	3	3	3	
Run off impact	5	5	3	3	3	3	3	
Overall Environmental Score	15	75	45	45	45	45	45	
Social								
Grower acceptance	5	5	3	3	2	3	5	
Community acceptance	5	5	4	2	2	4	5	
Overall Social score		10	50	35	25	20	35	50
Economic								
Annual cost/acre	45	5	3	5	2	1	5	
Overall Economic Score		45	225	135	225	90	45	225
Overall Score								
		100	370	228	312	169	141	0
Scores Normalized to 100	100	100. 0	61.6	84.3	45.7	38.1	0.0	

The ranking system consists of five categories of concern: regulations, technical, social, environmental, and economical. There are pass/fail criteria for regulations and economics, because we chose these as the two most important deciding factors for farmers. The scale was reduced from a ten point scale to a five point ranking scale to reduce objectivity. The technology will receive a score of “zero” if it does not meet regulations or if it costs more than $150 per acre. As score of 0 indicates failure, one is poor, two is below the acceptable level, three is acceptable, four is above the acceptable, and five is excellent. Economic regulations are weighted at 45% because economics is the driving factor in the grower/ client decision. Technical considerations are weighted 30% because they are key in making a feasible engineering design.

Scale	Description	Economic	Maturity	Scalable	Mobility	Operation and maintenance	Environmental	Grower acceptance	community acceptance
0	Fail	>900		Cannot work for irrigation	Cannot move water				
1	Poor	>300	Not used for disinfection	Can only work for either small fields (<10 or large farms >80 acres)	Can move/ distribute water with extreme modifications and high expense	Costly, regular, labor intensive, or hazardous operation	net negative	Never used in irrigation, can damage crops, or hazardous to operator	Dangerous
2	Below acceptable level	300-160	Used for disinfection but not commonly and not necessarily for irrigation	Will only work for 40 acre fields	Can move/distribute water with many modifications and expense	Regular, labor intensive, training intensive, or hazardous operation	slight net negative	Potentially damaging to crops, potentially dangerous to operator, and not commonly used	Potentially dangerous
3	Acceptable	140-160	Used commonly for disinfection but not necessarily for irrigation	Can be used for 20-60 acre fields	Can distribute water with modifications	Yearly or less maintenance requirements and simple operation which can be preformed by grower or laborer with simple training or few potential hazards	No net effect	Not potentially damaging to crops or grower, is used but not a common practice in farming	Not dangerous and limited environmental impacts
4	Above Acceptable Level	100-140	Used for disinfection and experimentally in irrigation	10-80 acre fields	Can move/disabuse water without modifications	Yearly or less than yearly maintenance simple operation with minimal training not hazardous	net positive	Is used in farming practices	Not dangerous no negative environmental impact
5	Excellent	<100	common practice in disinfection and irrigation	Can be scaled to any sized field	Can move/distribute water without modifications	Less than yearly maintenance, no addition operation training, no hazards	very positive	Saves water, soil, increases yield, or is economically beneficial in another way, is a common practice in farming	Not dangerous with positive environmental impact

Appendix D: Area for a Sediment Filter

This is the calculation for the size of a sediment filter based on Shock et al. (2013) design. Darcy's law is used to solve for area of 10, 40, and 60 acre fields using the flow rate of irrigation water and the experimental K_{sat} value. This K_{sat} is used because this is the anticipated soil conditions on the fields.

$$A = \frac{QL}{K_{sat}\Delta H}$$

Filter area for furrow irrigated fields

Field size [ac]	Flow rate of water (Q) [gal/min]	Flow Path (L) [in]	Pressure head ΔH [ft]	Area of Filter [ac]
10	250	4	3	0.6
40	1000	4	3	2.5
60	1500	4	3	3.8

Filter area for drip irrigated fields

Field size [ac]	Flow rate of water (Q) [gal/min]	Flow Path (L) [in]	Pressure head ΔH [ft]	Area of Filter [ac] for 5 ft head
10	121	4	3	0.3
40	484	4	3	1.2
80	968	4	3	1.8

Then to check the calculations, experimental velocity is used to determine the area of the filtration tank. Area of the filtration tank is equal to the flow rate for irrigation (Q) divided by the velocity of water through soil. The velocity of water through soil is determined from information from Ross. As expected these values are equal providing confidence in the input of the equations in excel.

$$v_s = \frac{Q_{exp}}{A_{exp}} = 0.0012 \qquad A = \frac{Q}{v_s}$$

Experimental velocity used to determine filter size for furrow irrigated onions

Field size (A) [ac]	Velocity of water through soil [ft/min]	Irrigation flow rate (Q) [gal/min]	Area of filter [ac]
10	0.0012	250	0.6
40	0.0012	1000	2.5
60	0.0012	1500	3.8

Experimental velocity used to determine filter size for drip irrigated onions

Field size (A) [ac]	Velocity of water through soil [ft/min]	Irrigation flow rate (Q) [gal/min]	Area of filter [ac]
10	0.0012	120	0.3
40	0.0012	480	1.2
60	0.0012	970	1.8

Appendix E: Sediment Filtration Costs

Cost factors considered include: cost of construction, cost of land occupied by filter, cost of gravel and sand, operation and maintenance, net costs, contingency, and mobilization.

Cost estimate for sediment filter construction					
Construction	Total cost per growing acre [$/ac]				
Filter size [ac]	Cost per filter area [$/ac]	Total cost [$]	Cost per field acre [$/ac]		
2.5	1100	2750	68.75		68.75
Loss from occupied land					
Fields size [ac]	Filter size [ac]	% of land taken by filter [%]	Net profit of onions [$/ac]	Loss [$]	
40	2.5	6.25	30000	1875	46.9
Gravel and sand					
Filter Layer	Height [in]	Volume [yd^3]	Cost [$\$/yd^3$]	Cost [$]	
Sand	4	1300	3.3	4477	1007
Gravel	8	2700	13.3	35816	

Silt	4	1300	0	0	
Operation and maintenance					
Field size [ac]	Annual Cost [$]				
40	150				3.75
Cost [$/ac]	1123				
Contingency	10%	112			
Mobilization	5%	56			
Total cost per acre [$/ac]	1127				
Annual costs					
Loan Amount [$]	Years of payment [yrs.]	Rate [%]	Annual payment [$/ac]		
1127.161063	10	3%	130		130

Appendix F: Chlorine Dioxide Does and Feed Rate Calculations

Problem Statement

What is the required dose of Chlorine dioxide needed for a log inactivation of 2?

Assumptions

- Required retention time = 1 minute

Equations used

$$-\log\left(\frac{N}{N_0}\right) = kCt$$

C = Chlorine dioxide dose = 2.5 mg/L

$$-\log\left(\frac{N}{N_0}\right) = \log \text{inactivation} = 2$$

t = retention time = 1.2 minute
N = Desired final E. coli population = 126 cfu
N_0 = initial E. coli population = 2500 cfu

Solution

$$\mathrm{k} = \frac{-\log\left(\frac{N}{N_0}\right)}{\mathrm{Ct}}$$

$$\mathrm{k} = \frac{2}{(2.5\frac{\mathrm{mg}}{\mathrm{L}})(1\mathrm{min})} = 0.8$$

Solving for C using calculated k *value*

$$\mathrm{C} = \frac{-\log\frac{\mathrm{N_0}}{\mathrm{N}}}{\mathrm{kt}} = \frac{-\log\left(\frac{126\ \mathrm{cfu}}{2500\ \mathrm{cfu}}\right)}{(0.8)(1.2\mathrm{min})}$$

$$\mathrm{C} = \mathbf{1.6}\ \frac{\mathbf{mg\ ClO_2}}{\mathbf{L}}$$

Conclusion

A dose of **1.6 mg/L ClO_2** is required for the desired final *E. coli* concentration

Appendix G: Chlorine Dioxide Mass per Season

Problem Statement

How much ClO_2 is necessary for a 1.6 mg/L (1.6 ppm) treatment of the contaminated water in Malheur County for both furrow and drip irrigation systems?

Assumptions

Furrow:

- 75 sets in one season
- 12 hours in one set
- Water Flow Rate = 1000 gal/min

Drip:

- 50 sets in one season
- 8 hours in one set
- Water Flow Rate = 500 gal/min

Equations

There are no equations used in these calculations because they are solved using dimensional analysis.

Solution

Furrow

$$1.6\frac{mgClO_2}{L}\left(\frac{3.7L}{gal}\right)\left(\frac{1{,}000gal}{\min}\right)\left(\frac{60\min}{1hr}\right)\left(\frac{1g}{1{,}000mg}\right)\left(\frac{12hr}{set}\right)\left(\frac{75sets}{season}\right)\left(\frac{1kg}{1{,}000g}\right)=320\frac{kgClO_2}{season}$$

320 kg ClO_2/season

Drip:

$$1.6\frac{mgClO_2}{L}\left(\frac{3.7L}{gal}\right)\left(\frac{500gal}{\min}\right)\left(\frac{60\min}{1hr}\right)\left(\frac{1g}{1{,}000mg}\right)\left(\frac{8hr}{1set}\right)\left(\frac{50sets}{season}\right)\left(\frac{1kg}{1{,}000g}\right)=71\frac{kgClO_2}{season}$$

71 kg ClO_2/season

Conclusion

The amount of chlorine dioxide needed per season is much higher for furrow irrigation systems. This makes sense because there are more sets in the furrow irrigation system with more time devoted to each set.

Appendix H: Cost Analysis of Filtration Furrow Design

Problem

What is the cost of creating a pre-chlorine dioxide treatment filtration system for furrow distribution?

Known

	Furrow with Filtration System	Furrow with Plug Flow Reactor System
ClO_2 Generation System (Dollars)	3,000	3,000
Diesel for Generator (dollars/acre/season)	25	25
Pump (Dollars)	9,000	9,000
Gas for Pump (Dollars/acre/season)	148	148
Chemical Costs (Dollars/acre/season)	55	55
Filtration System (Dollars)	17,650	N/A
Sand Media (Dollars/acre/season)	13	N/A
Piping and Cement Slab (Dollars)	910	910
Holding Tank (Dollars)	1,050	1,640
Total Initial costs (Dollars)	31,610	14,550
Total Costs (Initial and Recurring with 5%, 10 year annualized loan) (Dollars/acre/season)	345	$275

Solution

Furrow irrigation costs to implement a chlorine dioxide treatment are estimated below. It should be noted that these are variable costs and many are quotes from specific companies from surrounding areas in the Northwest. The sand and gravel estimates are from Ohio because no local costs could be found.

Conclusion

In Figure 19, the pretreatment filtration design is shown. The main advantage of a filter system is the increased consistency in the reduction of the amount organic material, providing a higher confidence in the efficacy of the disinfection dosage. The proposed system would employ a pump to pull water out of the field's head canal and pump it through pipes to a four-pod sand media filtration system. After it exits the sand media filters, it would be injected with a dose of 1.6 mg/L chlorine dioxide gas from the chlorine dioxide generation system. Then, the water would move to a large holding tank where it would be held for a retention time of 1.2 minutes. The holding tank would have a volume of 1,200 gallons, to ensure the retention time of 1.2 minutes is reached and a flow rate of 1,000 gal/min is maintained (Appendix I). The holding tank would be made of polyethylene due to its resistance to chlorine dioxide's corrosive properties (Bergman, 2000). Lastly, the water would be released from the holding tank and fed back to the head canal so it could be siphoned and applied via furrows to the field. The entire system would be not be mobile and a flatbed semi-truck would need to be rented for a season to move the filtration system to the field.

If a filtration system is chosen, a filter system has an initial cost of $17,654 (Fresno Castings and Valves, 2013). Crushed silica sand costs $10.00 for a 10 pound bag. Gravel costs $4.00 for a ton ("Price List", 2010). With a sand requirement of 5,200 pounds, the cost is $520 per season. With a gravel requirement of 2,240 pounds, the cost is about $4.50 per season. The total cost for filter media is about $525 per season, which is a total additional $13 an acre. The sand must be replaced every year or two, but if garnet is used in place of sand, it can last up to 4 years (Jim Klauzer, 2014). Unfortunately, garnet can cost about three times as much as sand.

The chlorine dioxide generator used for either system has an initial cost of $3,000 (Saunders, 2013). This generator uses diesel which yields fuel costs of about $25 an acre/season (Appendix N). The chemical cost for this generator is about $55 per acre (Appendix K). The costs associated with maintenance for this system is $100 per season, which is about $2.50 per acre (Saunders, 2013).

Using the sand media filtration system, a 130 cubic foot holding tank made of polyethylene has an initial cost of approximately $1,050 ("Vertical Liquid Storage Tanks", 2013).

Adding all of these costs together, the sand media filtration system would cost $70 more per acre per season than using a plug flow reactor system.

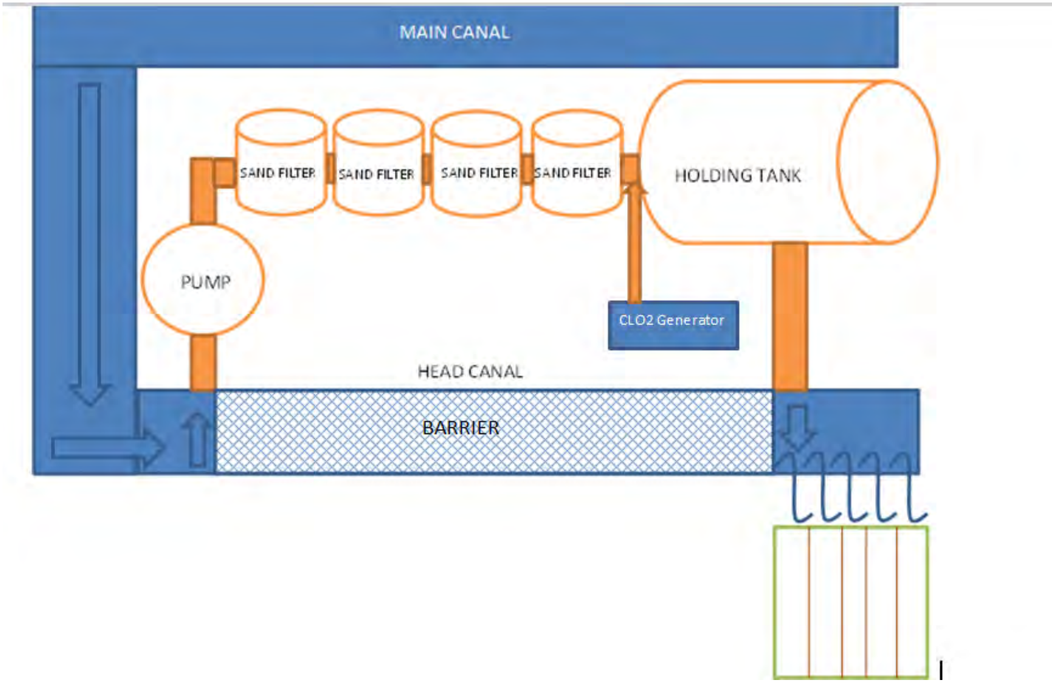


Figure 19: A chlorine dioxide treatment system with a sand media filtration system implemented in a furrow irrigation field.

Appendix I: Holding Tank Volume

Problem Statement

What would the volume of each of the four individual holding tanks be if the contact time necessary is 1.2 minutes and the flow rate is 1000 gal/min?

Assumptions

$\mathrm{Q} = 1{,}000\ \frac{\mathrm{gal}}{\mathrm{min}}$
$\mathrm{t} = 1.2\ \mathrm{min}$
Tanks = 4

Equations

$\mathrm{V} = \mathrm{Q} * \mathrm{t}$

Solution

$$\mathrm{V} = \mathrm{Q} * \mathrm{t} = 1{,}000\ \frac{\mathrm{gal}}{\mathrm{min}} * 1.2\ \mathrm{min}$$

$$\mathrm{V} = 1{,}200\ \mathrm{gal}$$

$$1{,}200\ gal\frac{0.1336\ ft^3}{1gal} \cong 160ft^3\ \text{Total Volume}$$

$$\frac{160ft^3}{4\ tanks} = \mathbf{40ft^3\ per\ holding\ tank}$$

Conclusion

Each of the four holding tanks would need to have a volume of $\mathbf{40ft^3}$ to satisfy both the flow rate and contact time for the dosage rate.

Appendix J: Head Loss Due to Junctions for Furrow Irrigation System

Problem Statement

What is the head loss in the piping for the furrow disinfection system?

Assumptions

- Small radius (r_s) =0.5ft
- Large radius (r_b) =3ft
- Friction coefficient for polyethylene is negligible (*Ecological Fluid Mechanics*)
- Assume $K_e = 0.5$ for abrupt outlets (*Ecological Fluid Mechanics*)

Equations

Please note: all equations and conversions taken from *Ecological Fluid Mechanics*

$$Velocity\ in\ Small\ Pipes\ \ Q\frac{ft^3}{s} * \left(\frac{1}{(r_s ft)^2 \pi}\right) = v\frac{ft}{s}$$

Q= flow rate
r_1= small radius

$$Velocity\ in\ Small\ Pipes\ \ Q\frac{ft^3}{s} * \left(\frac{1}{(r_s ft)^2 \pi}\right) = v\frac{ft}{s}$$

Q= flow rate
r_2= small radius

$$Head\ loss\ (h_L) = K_e \frac{V_1^2}{2g}$$

$h_L = head\ loss$
$K_e = coefficient\ of\ friction$
$V_1 = velocity\ in\ pipe\ with\ r_s$
$g = graviety$

Ratio to get friction coefficient for junction loss $\frac{D_1}{D_2}$

$D_1 = diameter\ of\ big\ pipe$
$D_2 = diameter\ of\ big\ pipe$

$$Total\ head\ loss = \sum H_L\ (\#tanks)$$

$H_L =\ \ head\ loss$

Solution

Velocity:

$$Velocity\ in\ Small\ Pipes\ \ 2.23\frac{ft^3}{s}*\left(\frac{1}{(0.5ft)^2\pi}\right)=2.84\frac{ft}{s}$$

$$Velocity\ in\ Big\ Pipes\ \ 2.23\frac{ft^3}{s}*\left(\frac{1}{(3ft)^2\pi}\right)=0.0789\frac{ft}{s}$$

Head loss: in polyethylene layflat pipes:

$$h_L=K_e\frac{V_1^2}{2g}$$

$$\frac{0.5(2.84\frac{ft}{s})^2}{2(32.2\frac{ft}{s^2})}=\ \mathbf{0.057}\boldsymbol{ft\ loss}$$

Head loss in aluminum pipes:

$\frac{D_1}{D_2}\sim 0.2$ therefore $K_e=0.87$ (*Ecological Fluid Mechanics)*

$$\frac{0.87(2.84\frac{ft}{s})^2}{2(32.2\frac{ft}{s^2})}=\mathbf{0.11}\boldsymbol{ft\ loss}$$

$$Total\ head\ loss=\sum H_L\ (\#tanks)$$

Total head loss from junctions:

0.11(4)+0.057(4) = 0.663 ft. of loss
=8 inches of loss

Total head loss from junctions:

1 psi = 27.68 in H_2O

$$\frac{1\ psi}{27.68\text{ in }H_2O}=\frac{x\ psi}{8\text{ in }H_2O}$$

x = 0.29 psi in loss due to junctions

Conclusion

The pressure loss in the junctions is not high enough to be a problem. Therefore the pressure head initially does not have to be increased.

Appendix K: Chemistry and Cost for the Generation of Chlorine Dioxide

Problem Statement

What is the chemical cost for disinfection using Chlorine Dioxide in furrow and drip systems?

Assumptions

- HCl is sold in 80% solution

Equations used

$$5NaClO_2 + 4HCl \leftrightarrow 4ClO_2 + 5NaCl + H_2O$$

Solution

Furrow Irrigation

$$\frac{320 \text{ kg } ClO_2}{\text{season}} * \frac{1000 \text{ g}}{1 \text{ kg}} * \frac{1 \text{ mol}}{67.45 \text{ g } ClO_2} = \frac{4744 \text{ mol } ClO_2}{\text{season}}$$

1 * (X mol HCl) * 0.8 solution = 4744 mol ClO_2 = 5930 mol HCl

1.25 * (X mol $NaClO_2$) = 4744 mol ClO_2 = 3795 mol $NaClO_2$

$$5930 \text{ mol HCl } * \frac{36.45 \text{ g HCl}}{1 \text{ mol HCl}} = 216148.5 \text{ g HCl} \cong 216 \text{ kg HCl}$$

$216 \text{ kg HCl} = 0.35 * \text{solution weight}$ → solution weight = 617 kg HCl

$$617 \text{ kg HCl} * \frac{1\text{lb}}{0.453592} = 1360 \text{ lbs HCl}$$

$$1360 \text{ lbs HCl} * \frac{\$327}{500 \text{ lbs}} = \$890 \text{ per 40 acre field}$$

$$= \$\mathbf{22 \text{ for HCl per acre per season}}$$

$$3795 \text{ mol } NaClO_2 * \frac{90.45 \text{ g}}{1 \text{ mol}} = 343258 \text{ g } NaClO_2 \cong 343 \text{ kg } NaClO_2$$

$$343 \text{ kg } NaClO_2 * \frac{\$46}{12 \text{ kg}} = \$1316 \text{ per 40 acre field}$$

$$= \$\mathbf{33 \text{ for } NaClO_2 \text{ per acre per season}}$$

Drip Irrigation

$$\frac{71 \text{ kg } ClO_2}{\text{season}} * \frac{1000 \text{ g}}{1 \text{ kg}} * \frac{1 \text{ mol}}{67.45ClO_2} = \frac{1053 \text{ mol } ClO_2}{\text{season}}$$

1 * (X mol HCl) * 0.8 solution = 1053 mol ClO_2 = 1316 mol HCl

1.25 * (X mol $NaClO_2$) = 1053 mol ClO_2 = 842 mol $NaClO_2$

$$1316 \text{ mol HCl} * \frac{36.45 \text{ g HCl}}{1 \text{ mol HCl}} = 47968 \text{ g HCl} \cong 48 \text{ kg HCl}$$

$$48 \text{ kg HCl} = 0.35 * \text{solution weight} \longrightarrow \text{solution weight} = 137 \text{ kg HCl}$$

$$137 \text{ kg HCl} * \frac{1 \text{ lb}}{0.453592 \text{ kg}} = 302 \text{ lbs HCl}$$

$$302 \text{ lbs HCl} * \frac{\$327}{500 \text{ lbs}} = \$198 \text{ per 40 acre field} = \$\mathbf{5 \text{ for HCl per acre per season}}$$

$$842 \text{ mol } NaClO_2 * \frac{90.45 \text{ g}}{1 \text{ mol}} = 76159 \text{ g } NaClO_2 \cong 76 \text{ kg } NaClO_2$$

$$76 \text{ kg } NaClO_2 * \frac{\$46}{12 \text{ kg}} = \$291 \text{ per 40 acre field}$$

$$= \$\mathbf{7 \text{ for } NaClO_2 \text{ per acre per season}}$$

Conclusion

Total chemical cost for furrow systems are **$55 per acre per season**.
Total chemical cost for drip systems are **$12 per acre per season**.

Appendix L: Chlorine Dioxide System Costs (Year 1 vs. Annual)

Drip Irrigation

Year 1 Costs

Chlorine Dioxide Generation System: $3,000/40 acres= $75/acre

Chemicals: $480/40 acres= $12/acre

Maintenance for ClO2 Generation System: $100/40 acres= $2.50/acre

Total: $90/acre

Annual Costs

Chemicals: $12/acre

Maintenance for ClO2 Generation System: $100/40 acres= $2.50/acre

Total: $15/acre

Furrow Irrigation

Initial Costs (On an annualized loan--No year 1 costs)

Chlorine Dioxide Generation System: $3,000

Pump: $9,000

Holding Tanks: $1,640

Layflat: $50

PVC: $45

Aluminum Pipes: $375

Cement Slab: $440

Maintenance for ClO2 Generation System: $100

Total: $14,650 on a 5%, 10 year, annualized loan= $1,900

Total per acre: $1,900/40 acres= $45/acre

Annual Costs

Chemicals: $2,205

Fuel for pump: $5,940

Fuel for generator: $1,000

Total: $9,145/40 acres

Total per acre: $230/acre

Appendix M: Net Present Value of ClO_2 Water Treatment System in Drip and Furrow Irrigation Systems

Problem Statement

What is the difference in net present value of a drip and furrow irrigation system if a chlorine dioxide water treatment system is implemented?

Assumptions

Drip:

- 50 sets in one season
- 8 hours in one set
- Average Field Size = 40 acres
- Minimum acceptable rate of return (MARR) is 10%
- Lifetime of the system is 10 years

Furrow:

- 75 sets in one season
- 12 hours in one set
- Average Field Size = 40 acres
- Minimum acceptable rate of return (MARR) is 10%
- Lifetime of the system is 10 years

Equations and Tables

Consulted Dr. John Shea for equations and methods.

$$NPV_{10} = -IC + A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$$

Drip Irrigation Expenses without ClO2		Drip Irrigation Income		Drip Irrigation Initial Costs without ClO2	
Seed	$16,300	Onion Yield	$218,000	Irrigation Machinery	$48,000
Fertilizer	$5,700			Tape Installer	$8,000
Pesticide	$20,200			Tape Lifter	$10,000
Custom & Consultants	$15,100			Tape Winder	$15,000
Irrigation	$2,000				
Other	$3,300				
Storage	$12,600				
Labor	$7,000				
Drip Tape	$16,000				
Interest	$2,900				
Sand Media	$50				
Fuel	$3,200				
Total	$104,350		$218,000		$81,000

Drip Irrigation Expenses with ClO2		Drip Irrigation Income		Drip Irrigation Initial Costs with ClO2	
Seed	$16,300	Onion Yield	$218,000	Irrigation Machinery	$48,000
Fertilizer	$5,700			Tape Installer	$8,000
Pesticide	$20,200			Tape Lifter	$10,000
Chemical	$480			Tape Winder	$15,000
Custom & Consultants	$15,100			ClO2 Generation System	$3,000
Irrigation	$2,000				
Other	$3,300				
Storage	$12,600				
Labor	$7,000				
Drip Tape	$16,000				
Interest	$2,900				
Sand Media	$50				
Fuel	$3,200				
Total	$104,830		$218,000		$84,000

Furrow Irrigation Expenses without ClO2	Furrow Irrigation Income	Furrow Irrigation Initial Costs without ClO2

Seed	$16,300	Onion Yield	$181,900	Irrigation Machinery	$8,900
Fertilizer	$11,300				
Pesticide	$25,300				
Custom & Consultants	$15,100				
Irrigation	$2,000				
Other	$3,300				
Storage	$12,600				
Labor	$9,300				
Interest	$2,900				
Total	$98,100		$181,900		$8,900

Furrow Irrigation Expenses with ClO2		**Furrow Irrigation Income**		**Furrow Irrigation Initial Costs with ClO2**	
Seed	$16,300	Onion Yield	$181,900	Irrigation Machinery	$8,900
Fertilizer	$11,300			ClO2 Generation System	$3,000
Pesticide	$25,300			Pump	$9,000
Chemical	$2,205			Holding Tanks	$1,640
Custom & Consultants	$15,100			Layflat	$50
Irrigation	$2,000			PVC	$45
Other	$3,300			Aluminum Pipes	$375
Storage	$12,600			Cement Slab	$440
Labor	$9,300				
Interest	$2,900				
Fuel	$6,940				
Total	$107,245		$181,900		$23,450

Solution

Drip Irrigation *without* Chlorine Dioxide System

A= Annual Profit (Income – Expenses) = \$218,000-\$104,350=\$113,650

IC=Initial cost = \$81,000

i = MARR = 10% = 0.1

N = Number of years = 10 yrs

$$NPV_{10} = -81{,}000 + 113{,}650(6.144567)$$

$$\boldsymbol{NPV_{10} = \$617,330}$$

Drip Irrigation with Chlorine Dioxide System

A= Annual Profit (Income – Expenses) = \$218,000-\$104,830 = \$113,170

IC=Initial cost = \$84,000

i = MARR = 10% = 0.1

N = Number of years = 10 yrs

$$NPV_{10} = -84{,}000 + 113{,}170(6.144567)$$

$$\boldsymbol{NPV_{10} = \$611,380}$$

Drip Irrigation Change in Net Present Value from Implementing a Chlorine Dioxide Water Treatment System

$$611{,}380 - 617{,}330 = \boldsymbol{-\$5,950}$$

Furrow Irrigation *without* Chlorine Dioxide System

A= Annual Profit (Income – Expenses) = \$181,900-\$98,100=\$83,800

IC=Initial cost = \$8,900

i = MARR = 10% = 0.1

N = Number of years = 10 yrs

$$NPV_{10} = -8{,}900 + 83{,}800(6.144567)$$

$$\boldsymbol{NPV_{10} = \$506{,}015}$$

Furrow Irrigation with Chlorine Dioxide System

A= Annual Profit (Income – Expenses) = \$181,900-\$107,245= \$74,655

IC=Initial cost = \$23,450

i = MARR = 10% = 0.1

N = Number of years = 10 yrs

$$NPV_{10} = -23{,}450 + 74{,}655(6.144567)$$

$$\boldsymbol{NPV_{10} = \$435{,}270}$$

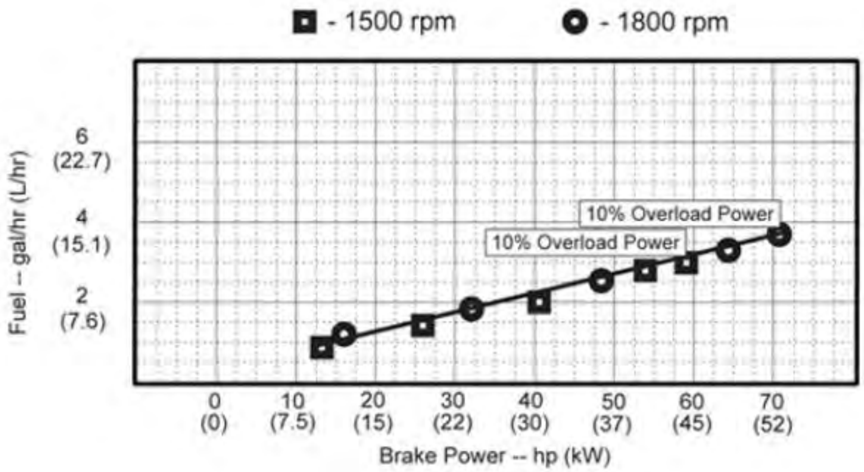
Furrow Irrigation Change in Net Present Value from Implementing a Chlorine Dioxide Water Treatment System

$$\$435{,}270 - \$506{,}015 = -\,\boldsymbol{\$70{,}745}$$

<u>Conclusion</u>

Implementing a chlorine dioxide water treatment system reduces the net present value of a drip irrigation system by about \$6,000. Implementing a chlorine dioxide system reduces the net present value of a furrow irrigation system by about \$70,000. It is almost ten times more expensive to implement a chlorine dioxide water treatment system into a furrow irrigated field than into a drip irrigated field.

Fuel Efficiency Curve for 50hp Generator Used in Net Present Value for Drip Irrigation



This curve was used to justify the 2 gallons/hour fuel consumption rate for the 50 horsepower generator used in drip irrigation. Jim Klauzer told Team 2 that the generator was a "John Deere, 50 hp generator". This information helps to produce the fuel costs used for drip irrigation in the net present value analysis.

Appendix N: Chlorine Dioxide Generator Power Cost

Problem Statement

What is the cost associated with running the chlorine dioxide generator using diesel fuel on a per season basis for furrow irrigation?

Assumptions

Furrow:

- Fuel Consumption of Generator = 0.28 gallons/hour
- 75 sets in one season
- 12 hours in one set
- Price of Diesel Fuel = $4.00/gal
- Average Field Size = 40 acres

Equations

There are no equations used in this calculation because it is solved using dimensional analysis.

Solution

Furrow:

$$0.28\frac{gal}{hr}\left(\frac{12hr}{1set}\right)\left(\frac{75sets}{1season}\right)\left(\frac{\$4.00}{gal}\right)=\frac{\$1,008}{season}$$

$$\frac{\frac{\$1,008}{season}}{40acres}=\$25.20/acre/season$$

$25.20/acre/season

Conclusion

The cost to power the chlorine dioxide generator using diesel fuel is approximately $25 per acre per season.

Appendix O: Furrow Irrigation Pump Power Requirements

Problem statement

What are the power requirements for the pump for the furrow irrigation disinfection system?

Assumptions

- Bed of the truck is a maximum of 6.5 feet above the head canal
- No frictional losses
- The pump runs with 100% efficiency
  (Williams et al., 2013)

Equations used:

$P = \rho * g * h * Q$

Where:
P= power required for the pump (Watts)
ρ= density of water (1,000 kg/m^3)
g= gravity constant (9.8 m/s^2)
h= 2 meters (assumed)
Q= 1,000 gpm or 63 liters/s

Solution:

$$\text{Power} = 1{,}234{,}800\ \frac{(\text{kg} * \text{liters})}{(\text{s}^3 * \text{m})} * \frac{1\ Watt}{1{,}000\,\frac{(\text{kg} * \text{liters})}{(\text{s}^3 * \text{m})}} = 1{,}234.8\ \text{Watts}$$

$$1{,}234.8\ \text{Watts} * \frac{1\ hp}{745\ Watts} = \mathbf{1.66\ \mathit{hp}}$$

Conclusion

The minimum power for this pump is 1.66 horsepower. After research on various pump flow rates, types of pumps, and a two pump option, the most economical and feasible option was a 24 horsepower trash pump running on gasoline that can accommodate a 1,000 gallon per minute flow and costs about $9,000. This horsepower is about 15 times more powerful than necessary. A 24 horsepower pump is the pump that is used in industry because it can accommodate such a high flow rate. Its dimensions are 8 feet long by 4 feet wide by 4 feet high and it weighs 1,125 pounds ("IPT Pumps, 2013). A corresponding pump curve efficiency of a 24 horse power pump meets 1,000 gallons per minute at about 10 feet of head (Koshinamerica.com). This pump is heavy, but it is trailer mounted, so it should be able to be transported with relative ease. Although diesel is commonly used for agricultural pumps, the gasoline pumps researched use the same amount of fuel per hour as the diesel and gasoline is less expensive than diesel. The only problem with this pump is that it consumes 2 gallons of gasoline per hour and only can hold 12 gallons of gasoline. The irrigation set time for furrows is 12 hours, as previously mentioned, so the gasoline would need to be replenished half way through the irrigation set.

Appendix P: Life cycle analysis for furrow and drip disinfection systems

Problem Statement:

What is the life time economic, greenhouse gas, and energy impacts of the proposed disinfection systems?

Assumptions:

The EIO LCA website is contains current numbers

Solution:

The values in the table were determined using EIO LCA values for cost or economic impact in U.S. dollars, greenhouse gasses measured in C02e and energy in trillion Joules. These values were converted from million units to one unit and then multiplied by the amount of the material that was used in the design. The results are displayed in the tables below.

DRIP

				Values from EIOLCA								
Pipes	Length (ft)	Price ($)/ft	Total Price	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
PVC	50	9	450	2350000	4.49	1060	0.00106	17.6	0.0000176	225	0.48	0.0079
Layflat	50	3.2	160	2350000	4.49	1060	0.00106	17.6	0.0000176	225	0.17	0.0028
Drip tape	522720	2	1045000	2350000	4.49	1060	0.00106	17.6	0.0000176	2300000	1108	18.4
ClO2 Tanks	6	20	120	2350000	4.49	1060	0.00106	17.6	0.0000176	27	0.1272	0.002
Total	522826		1045610	N/A	N/A	N/A	N/A	N/A	N/A	2347489	1108	18.4

Fuel	Gal/Hr Req'd	$/gal/hr	$/hr	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Diesel (pump)	0.34	4	1.36	1273000	8532	540	0.00054	8.5	0.000008	51000	64.6	0.67
Diesel (generator)	0.1	4	0.4	1273000	8532	540	0.00054	8.5	0.000008	51000	65	0.7
Total	0.1	4	0.4	N/A	N/A	N/A	N/A	N/A	N/A	51000	65	0.7

Metals	ft^2	$/ft^2	$	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Stainless Steel	132	included	included	1273000	8532.1716	539.8	0.00054	8.5	0.0000085	100000	154	1.8
Total	132	0	0	N/A	N/A	N/A	N/A	N/A	N/A	100000	154	1.8

OVERALL total	Economic ($)	GHG (CO2e)	Energy (TJ)
	2498488.7	1327	20.8567

FURROW

				Values from EIOLCA								
Pipes	Length (ft)	Price ($)/ft	Total Price	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Layflat	15	3.2	48	2350000	4.49	1060	0.0011	17.6	0.000018	67	0.05	0.00
PVC	5	9	45	2350000	4.49	1060	0.0011	17.6	0.000018	22	0.05	0.001
Tanks	17.6	19.9	350	2350000	4.49	1060	0.0011	17.6	0.000018	79	0.37	0.006
Total	38	32.09	443	N/A	N/A	N/A	N/A	N/A	N/A	169	0.47	0.008

Fuel	Gal/Hr Req'd	$/gal/hr	$/hr	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Gas (pump)	2	3.3	6.6	1273000	8532	540	0.00054	8.5	0.0000085	51000	65	0.67
Diesel (generator)	0.28	4	0.4	1273000	8532	540	0.00054	8.5	0.0000085	51000	65	0.67
Total	2.28	7.3	7	N/A	N/A	N/A	N/A	N/A	N/A	102000	129	1.3

Metals	ft	$/ft	$	**Cost ($)**	**Cost ($)/ft**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Aluminum	15	25	375	1273000	8532	540	0.00054	8.472	0.0000085	1020000	192	4.67
Total	15	25	375	N/A	N/A	N/A	N/A	N/A	N/A	1020000	192	4.67

Concrete	Area (ft^2)	Price ($)/ft^2	Total Price	**Cost ($)**	**Cost ($)/ft^2**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
Slab	87.5	5	438	1920000	21943	1470	0.0015	60.5	0.000061	0.00023	0.643	0.026
Total	87.5	5	438	N/A	N/A	N/A	N/A	N/A	N/A	0.00023	0.643	0.026

Pump	Total Price($)	Length (ft)	Width (ft)	**Cost ($)**	**Cost ($)/unit**	**CO2/ $ Million**	**CO2/$1**	**TJ/ $ Million**	**TJ/ $1**	Economic ($)	GHG (CO2e)	Energy (TJ)
24 Hp ITP Pump	9,000	8	4	2120000	236	530	0.00053	7.97	0.000008	0.0042	4.77	0.072
Generator	3,000	2	1.16									
Total	12,000	8	4	N/A	N/A	N/A	N/A	N/A	N/A	0.0042	4.77	0.072

OVERALL total	Economic ($)	GHG (CO2e)	Energy (TJ)
	1122169	327	6.1