CHARACTERIZATION OF WASTEWATER SUBSURFACE DRIP EMITTERS AND DESIGN APPROACHES CONCERNING SYSTEM APPLICATION UNIFORMITY

A Thesis

by

XIAOJING DUAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Biological and Agricultural Engineering

CHARACTERIZATION OF WASTEWATER SUBSURFACE DRIP EMITTERS AND DESIGN APPROACHES CONCERNING SYSTEM APPLICATION UNIFORMITY

A Thesis

by

XIAOJING DUAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Bruce J. Lesikar
Committee Members,	Ann L. Kenimer
	Michael A. Arnold
Head of Department,	Gerald L. Riskowski

August 2006

Major Subject: Biological and Agricultural Engineering

ABSTRACT

Characterization of Wastewater Subsurface Drip Emitters and
Design Approaches Concerning System Application Uniformity. (August 2006)
Xiaojing Duan, B.A., Hebei Institute of Civil Engineering & Architecture, China
Chair of Advisory Committee: Dr. Bruce J. Lesikar

Subsurface drip distribution is an important on-site wastewater treatment technique which is widely used with various soil types and restricted site conditions. It can distribute pretreated wastewater uniformly into soil. Some recent field applications showed low application uniformities, which was reflected in overloading of the field near the supply manifold while low emitter discharge rates occurred at the end of lateral. Designers are seeking appropriate operation pressures and drip zone configurations to improve system application uniformity. This research was conducted to test some popular wastewater drip products in both lab and field-scale experiments.

The first goal of this study was to evaluate the performance of five subsurface drip products under eight operational pressures ranging from 0 to 310 kPa (45 psi). After evaluation of each group of 60 emitters, results showed that Netafim Bioline pressure compensating (PC) emitters exhibited a uniformity coefficient (UC) of 95% with a coefficient of variance (C_v) of 4.9%. The average UC of Geoflow Wasteflow products is 94.4% and C_v value is 6.8%. Flow rate and pressure relationships (Q-H curves) were developed for each drip emitter tested. By analyzing low and normal operational pressure ranges, Q-H curves were fitted to the data and resulted in R^2 values ranging from 1.000 to 0.414. Geoflow pressure compensating products possess the features of non-pressure compensating emitters under low pressure head. Netafim PC products are characterized as pressure compensating over the full range of operational pressures and emit water with nominal uniformity during low pressure range.

To evaluate drip zone configurations with respect to distribution uniformity, a field-scale experiment was set up and three drip tubing products were tested in different dosing and operation schemes. Three factors of wastewater drip system design were tested. System operation pressure (138 kPa/20 psi and 276 kPa/40 psi); different pressure control components (pressure regulator/recirculation valve) and schemes (continuous flushing/intermittent flushing); and supply line length (7.6 m/25 ft, 15.2 m/50 ft, and 30.4 m/100 ft) were evaluated to compare their influence on water application uniformity. It was concluded that, for Geoflow PC and NPC products, among all three factors, system operational pressure has the greatest effect on drip system application uniformity; supply line length has the least influence. For Netafim PC tubing, pressure control scheme has the greatest effect on drip system application uniformity; supply line length has the least influence. The optimal combination of the three factors could save more than 10 minutes of dosing time to meet the required dosing application uniformity. An engineering computation example on system fill time was presented and compared to experimental results to demonstrate the possible gap between typical design processes and real field application.

ACKNOWLEDGMENTS

Many things in the world have not been named, and many things, even named, have never been described. I express sincere gratitude to my Committee Chair, Dr. Bruce Lesikar, for offering me the great opportunity to explore a corner of the unknown and supporting me with encouragement and patience all along. The experience to learn from him was impressive and precious. He deserves my very respect.

I would like to thank Dr. Ann Kenimer for her guidance during my graduate study; her teaching style is excellent. Thanks to Dr. Michael Arnold and Dr. Kenimer for their precious time reviewing my thesis and advising me on writing. Dr. Russell Persyn treated me with timely help. He exemplifies how brilliant a former graduate of our department can be!

I also wish to acknowledge David Carney for the valuable help to set up and improve the experiments. From David I learned a lot more than just skills. I am thankful for the efforts of our student workers; Josh Mosley, Josh Meuth, Justin Mechell, and Heath Voyles. I wish them a promising start on their career.

A big special credit to Sonya; she is so warm-hearted and always supportive to us.

All in all, without the faith and strength from Buddha, I could not have reached where I am. I will follow you and move on.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

According to the U.S. Census Bureau (1999), approximately 25 percent of the estimated 125 million occupied homes in the United States are served by onsite wastewater treatment systems (OWTS), a proportion that has changed little since 1970. More than 60 million people depend on decentralized systems, including the residents of about one-third of new homes and more than half of all mobile homes nationwide (U.S. Census Bureau, 1999). Some communities rely completely on OWTSs.

As a typical technology of OWTS, subsurface drip distribution systems distribute wastewater through tubing with flow regulating emitters installed under the ground. Oron et al. (1993) reported that subsurface drip systems reduced the risk of pollution associated with wastewater to a minimum, because the soil acts as a living filter, cleaning the water. Subsurface drip systems generally consist of four main components: a treatment device, a pump tank, a filtering device, and a drip distribution system. Subsurface wastewater distribution is the most efficient method currently available for application and dispersal of wastewater to the soil. Because of the unique construction of drip distribution systems, they cause less site disruption during installation compared to other technologies and use more of the soil mantle for treatment because of the shallow placement depth (USEPA, 2002). Drip technology is adaptable to irregularly shaped lots in all soil types and is commonly used at sites where conventional drain fields are not appropriate due to site constraints such as shallow soils above a restrictive layer.

This thesis follows the style and format of the *Transactions of the American Society of Agricultural and Biological Engineers*.

However, effective and publicly acceptable land application systems depend on sound design and management of these systems. Several point and line source water distribution systems evaluated in recent years have shown poor performances (Hills, 2000). Results of these evaluations show that pressure head variations and emitter clogging are the main causes for poor water distribution uniformity (Weynand, 2004). Ability to accurately and simply design a drip distribution submain to reach maximum application uniformity, especially when there are a large number of emitters in the unit, is very important to the development and application of wastewater subsurface distribution systems.

Research Objectives

Drip emitters, orientation and operation of the drip system, and method for evaluating and improving application uniformity will be demonstrated in this text. Specific objectives included:

- Evaluate the water emission rates of five types of drip emitters at eight pressures, ranging from 0 to 310.26 kPa (45 psi).
- Evaluate and classify the emitter products according to coefficient of variance C_v and Christiansen’s uniformity coefficient (UC) (ASAE, 1999; ASABE, 2003).
- Characterize the flow-pressure relationship for each emitter model. Classify the emitters as pressure compensating or non-pressure compensating based on exponent coefficient (x) of emitter.
- Test three representative drip tubings with several operating schemes in a field-scale drip system. Characterize the emission volumes of drip emitters along a lateral during zone pressurization stage.

- Use statistical methods to analyze drip zone design and operational schemes with respect to zone pressurization time.
- Use obtained water samples and time records to compute the minimum dose time and dose volume with respect to drip zone design, operational schemes and application uniformity.
- Compute drip zone filling time through traditional engineering design and compare it with experimental data to display the possible variance and consider its impact on system design.

CHAPTER II

WASTEWATER DRIP EMITTER CHARACTERIZATION

INTRODUCTION

Wastewater drip systems utilize water application tubing with emitters, delivering wastewater in small amounts into subsurface soil for treatment. The drip line is normally a 1.27 cm diameter flexible polyethylene tube with emitters attached to the inside wall and equally spaced 0.3 to 0.6 meters apart along its length. There are two emitter types that are primarily used for wastewater dispersal: non-pressure compensating (NPC) and pressure compensating (PC). PC emitters are manufactured to discharge uniformly under varying operating pressures once a minimum pressure is achieved. NPC emitter flow rates increase with increasing pressure. Flow through turbulent-flow emitters, which have a very long labyrinth, reduces the discharge pressure to nearly atmospheric rates. Thus, discharges from NPC emitters are greater at greater pressures (EPA, 2002). Geoflow and Netafim are two known active manufacturers working with wastewater distribution. Geoflow markets both NPC and PC tubing for wastewater application. Netafim markets only PC tubing. Guidelines for design, installation, and management of subsurface wastewater drip systems are generally available from manufacturers and are often specific to the geographic or climatic region.

Drip distribution systems are designed to uniformly distribute water in the field. It is applied in both irrigation and wastewater treatment technology. Irrigation drip systems feature long dosing run times, generally do not operate every day and serve relatively large zones. Wastewater drip systems usually feature multiple even doses per day and relatively short dosing times. These frequent dosings allow uniform effluent distribution while not exceed the soil's biological treatment capacity. Dosing zones are typically smaller than those in irrigation drip systems. The small quantity of effluent emitted during each dosing event means that uniform distribution is extremely critical for subsurface treatment success.

In recent years, research was conducted on application uniformity of subsurface drip systems. Smesrud and Selker (2001) presented a technique for determining design criteria for application uniformity of micro-irrigation system. This study considered both water conservation and environmental protection.

A measurement system was developed by Stone et al. (2005) to evaluate the water delivery rates of a site-specific center pivot irrigation system. The comparison between measured water deliveries from each segment of the site-specific irrigation system to the design parameters showed that the irrigation system was delivering water to the control areas at rates approximately as it was designed. Several studies have used these concepts to determine efficiency and uniformity of irrigation systems used in urban and agricultural settings. In Utah, a model for estimating turf water requirements was developed (Aurasteh, 1984). The Florida Mobile Irrigation Labs were used to evaluate irrigation system in both agricultural and urban areas by conducting a series of tests over 2 hour periods, measuring pump flow rates, sprinkler pressures and flow rates, and application uniformities (Micker, 1996). In assessments of irrigation sprinkler system performance in California, Pitts et al. (1996) found a mean distribution uniformity (DU) (Equation 2.6) of 0.64 in all systems tested. The average DU for nonagricultural turfgrass sprinklers was 0.49. More than 40% of the tested systems had a DU of less than 0.4. Baum et al. (2005) evaluated residential irrigation system uniformity in the South Central Florida ridge and determined typical residential equipment uniformity under ideal conditions. It was proved that sprinkler brand and pressure affected the uniformity values. All implications emphasized the need for proper design of residential irrigation systems to achieve higher irrigation uniformity distribution.

Application uniformity is difficult to measure, because emitters are buried and can not be readily observed. Emitters must be excavated to measure flow rates. Sadler et al. (1995) determined the effect of excavating subsurface emitters on emitter discharge rate and uniformity measurement, and discussed errors in these determinations when soil-limiting flow caused a vertical water column between the emitter and the soil surface. Upward free water movement was observed from buried emitters on other soils.

Ravina et al. (1992) found that different types of emitters had different susceptibilities to clogging, but for any particular type of emitter, clogging sensitivity was inversely proportional to the discharge of the emitter. He advised that when effluent is used in micro-irrigation it is important to maintain turbulent flow in the laterals to prevent sedimentation. Smajstrla and Clark (1992) studied hydraulic characteristics of five commercial drip tapes and found that they vary widely as a function of emitter design. Camp et al. (1997) evaluated surface and subsurface drip systems after eight years of use, reporting more reduction in uniformity for subsurface systems than for surface systems, which was primarily caused by soil entry into the tubing. Hills et al. (2000) studied four management schemes for lessening chemical precipitation and observed that pH reduction to 6.8 was most effective for reducing clogging in drip tapes. Hills et al. (2000) assessed the performance of four different types of manufactured drip tapes with secondary effluent from an activated sludge wastewater treatment plant. They also evaluated a chlorination and filtration procedure for drip tape systems used in wastewater effluent. The study results indicated that drip tape technology has significantly improved in recent years.

Of all the factors that affect application uniformity, emitter manufacturer’s variation, emitter clogging, slope variation, and pressure variation are the most important. In lab conditions, statistical and distribution uniformity of emitter flow rate was determined as a function of emitter variation, operating pressure, and length of run (Bralts et al. 1982). Geoflow design and installation manual (Geoflow, 2004) stated a nominal flow variation of 5% under recommended operating pressures (68.95-310.26 kPa/10-45 psi). The manufacturer's coefficient of variation is 0.03 or lower for Bioline PC tubing (Netafim, 2004). Over a pressure range of 0 to 379 kPa (55 psi), the flow rate of any individual emitter may not vary more than 10% from the nominal discharge rate (Netafim, 2004).

Parameters to Evaluate Wastewater Subsurface Drip Products

There are many parameters for evaluating wastewater subsurface drip systems. The water distribution can actually be measured by using a sampling and estimation procedure based on statistical analysis for each zone. Listed below are some statistical parameters that are most frequently used in micro-irrigation systems evaluation. Computations follow the methodology proposed by Keller and Bliesner (1990) and Kang and Nishiyama (1996).

The following performance indicators were calculated:

The average emitter discharge rate, q_a (m^3/s):

$$q_a = \frac{1}{n}\sum_{i=1}^{n} q_i \qquad 2.1$$

where,

q_i , is the flow rate of the emitter i (m^3/s),

n, is the total number of emitters.

The standard deviation of emitter flow rate, S_q, (ASAE, 1999):

$$S_q = \left\{ \frac{1}{n-1} \left[\sum_{i=1}^{n} q_i^{\,2} - \frac{1}{n} \left(\sum_{i=1}^{n} q_i \right) \right]^2 \right\}^{1/2} \qquad 2.2$$

The variation coefficient of emitter flow, C_v (ASAE, 1999), is a statistical term which evaluates the standard deviation. Manufacturers usually publish the coefficient of variation for each of their products, and the system designer must consider this source of variability:

$$C_v = \frac{S_q}{q_a} \tag{2.3}$$

Uniformity of water application is a major design factor requiring close attention. Christiansen's uniformity coefficient (UC) was developed to measure the uniformity of sprinkler systems, and it has occasionally been applied to other forms of irrigation. The Christiansen's UC (%) evaluates the mean deviation, which is represented in ASABE standards.

$$UC = 100\left(1 - \frac{1}{nq_a}\sum_{i=1}^{n}\left|q_i - q_a\right|\right) \tag{2.4}$$

UC and C_v are two most commonly used uniformity expressions. Individual emitter flow non-uniformity is caused primarily by manufacturing variation and emitter plugging and wear.

Other frequently used uniformity measures in irrigation systems are the emission uniformity EU (%) and low quarter distribution uniformity DU (%).

The measure of emission uniformity EU (ASABE, 2003) is used in trickle irrigation while it was applied to sprinkler situations under the name of Pattern Efficiency:

$$EU = [1.0 - \frac{1.27C_v}{\sqrt{n}}] * (\frac{q_n}{q_a}) * 100\% \tag{2.5}$$

where,

q_n , is minimum flow rate of the emitters sampling group.

Low quarter distribution uniformity (DU) (Marriam and Keller, 1978) has been applied to all types of irrigation systems:

$$DU = 100(\frac{q_m}{q_a}) \tag{2.6}$$

where,

q_m, is average flow rate of the emitters in the lowest quartile.

The average variation coefficient of flow rates for each emitter through three times of sampling is named C_{ve}:

$$C_{ve} = \frac{S_{qe}}{q_{ae}} = \frac{\left\{ \frac{1}{n-1} \left[\sum_{i=1}^{n} q_{ie}{}^{2} - \frac{1}{n} \left(\sum_{i=1}^{n} q_{ie} \right) \right]^{2} \right\}^{1/2}}{q_{ae}} \qquad 2.7$$

A micro-irrigation system uniformity classification was developed to characterize the emitters based on UC and C_v and summarized. (Tables 2-1, 2-2)

Table 2-1 Micro-irrigation system uniformity classifications based on manufacturer variance coefficient *

Emitter type	C_v range	Classification
Point-source	<0.05	Excellent
	0.05 – 0.07	Average
	0.07 – 0.11	Marginal
	0.11 – 0.15	Poor
	>0.15	Unacceptable
Line-source	<0.10	Good
	0.10 – 0.20	Average
	>0.20	Marginal to Unacceptable

* Adopted from ASABE Standards EP405.1, (2003)

Table 2-2 Micro-irrigation system uniformity classifications based on emitter discharge uniformity *

Uniformity Coefficient, UC (%)	Classification
above 90%	Excellent
90%-80%	Good
80%-70%	Fair
70% -60%	Poor
below 60%	Unacceptable

* Adopted from ASAE Standards EP 458 (1999)

The uniformity classifications were developed for irrigation. In wastewater drip systems, a small volume of wastewater is dosed to the soil at predetermined time intervals throughout the day. However, due to different objectives and operation methods, irrigation processes do not typically require as many daily dosings as wastewater drip systems. The volume of applied effluent is limited by soil characteristics and system loading rate. The differences should be considered when using the classifications above.

Emitter Flow Rate and Pressure Head Relationship

A numerical method to measure the desirability of pressure flow characteristics for a given emitter device is based on a flow rate vs. pressure curve (Q-H) fitted to an equation of the following form:

$$Q = CH^{x} \tag{2.8}$$

where,

Q, emitter flow rate, m^3/s.

C, emitter coefficient that accounts for real discharge effects and makes the units correct, 1/second.

H, pressure head in the lateral at the location of emitters, meters.

x, the exponent characteristic of the emitter, unitless.

The exponent x indicates the flow regime and emitter type. It is a measure of how sensitive the flow rate is to pressure changes. The value of x will typically range between 0.0 and 1.0. A higher value for x indicates a higher sensitivity of the flow rate to pressure changes. For pressure compensating emitters, the ideal discharge exponents should be less than 0.1 and approach 0. The discharge exponent should approach 0.5 for non-pressure compensating emitters (Cuenca, 1989). The emitter exponent values for various flow regimes and emitter classification were listed in Table 2-3 (IA, 2002). As shown in Table 2-3, emitters with exponents less than 0.5 are entitled to be called pressure compensating, to different extents (CIT, 2002).

Table 2-3 Emitter exponent values for various flow regimes and emitters (Adapted from IA, 2002)

Flow regime	Exponent x	Emitter type
Variable flow path	0.0	Fully pressure compensating ⇕ Partially pressure compensating
	0.1	
	0.2	
	0.3	
Vortical flow	0.4	
Fully turbulent flow	0.5	Non-pressure compensating ⇕ Fully non-pressure compensating
Mostly turbulent flow	0.6	
	0.7	
Mostly laminar flow	0.8	
	0.9	
Fully laminar flow	1.0	

As shown in Figure 2-1, most manufacturers specified the flow rate versus pressure parameters within the pressure range of 68.95 kPa (10 psi) to 310.26 kPa (45 psi) for their drip emitters (U.S.EPA, 2002). According to observation during some field experiments, water starts dripping from emitters upon initiating the dosing event (0 pressure) and continues while the system reaches the desired operation pressure (68.95-310.26 kPa/10-45 psi) (Persyn, 2000). Therefore, it is necessary to investigate an emitter’s performance and distribution uniformity considering the specific low pressure range of 0 to 68.95 kPa (10 psi).

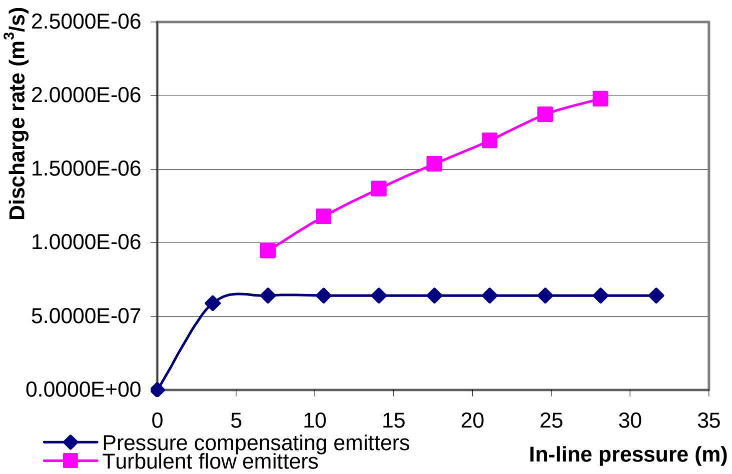

Figure 2-1 NPC and PC emitter discharge rates versus in-line pressures (Adopted from U.S. EPA, 2002)

Until now there have not been any experiment-based publications on the duration of the pressurization stage and water volume that is discharged during that stage. The reason could be that the pressurization stage varies greatly among different products and field conditions and it is hard to issue general design criteria.

The objectives of the first component of this study are listed below:

1. Evaluate water emission rates of five types of drip emitters at eight pressures, ranging from 0 to 310.26 kPa (45 psi).

2. Evaluate and classify the emitter products according to coefficient of variation C_v and Christiansen's uniformity coefficient (UC) (ASAE, 1999; ASABE, 2003).

3. Characterize the flow-pressure relationship for each emitter model. Classify the emitters as pressure compensating or non-pressure compensating based on exponent coefficient (x) of emitter.

METHODOLOGY

Emitter and Tubing Models

Five drip products with different characteristics were examined in this study (Table 2-4). These products are specifically marketed for use with wastewater and were selected to provide a range of discharge rates and emitter models of common usage.

Table 2-4 Manufacturer parameters of selected drip tubing (Netafim, 2004; Geoflow, 2004) *

	Tubing model	Type	Inside diameter	Emitter spacing	Nominal discharge rate	Suggested normal operation pressure
1	Geoflow WFCL 164-24-500	NPC	14 mm (0.55 inch)	0.61 m (2 feet)	3.90 liter/hr@137.9 kPa (1.03 GPH@20 psi)	68.9-310.3 kPa (10-45 psi)
2	Geoflow WFPC 162-24-500	PC	14 mm (0.55 inch)	0.61 m (2 feet)	2.00 liter/hr@137.9 kPa (0.53 GPH@20 psi)	68.9-310.3 kPa (10-45 psi)
3	Geoflow WFPC 164-24-500	PC	14 mm (0.55 inch)	0.61 m (2 feet)	4.00 liter/hr@137.9 kPa (1.06 GPH@20 psi)	68.9-310.3 kPa (10-45 psi)
4	Netafim Bioline 08WRAM 0.6-24V	PC	14.5 mm (0.57 inch)	0.61 m (2 feet)	2.27 liter/hr@137.9 Kpa (0.6 GPH@20 psi)	48.3-413.7 Kpa (7-60 psi)
5	Netafim Bioline 08WRAM 1.0-12500	PC	14.5 mm (0.57 inch)	0.305 m (1 foot)	3.79 liter/hr@137.9 Kpa (1.0 GPH@ 20 psi)	48.3-413.7 Kpa (7-60 psi)

* NPC = non-pressure compensating; PC = pressure compensating

Testing Apparatus

This study used a laboratory-scale apparatus fitted with 10 lines of wastewater drip tubing, each 3.04 m in length. The apparatus used in this research to determine emitter flow rates and lateral end pressures in the laboratory was previously described by Persyn (2000) and Weynand (2004). Some modifications were performed to the testing apparatus. Each lateral was attached between a supply and return manifold system. Laterals are isolated using ball valves located before each lateral so that the same pressure gauge could be linked to each single line to measure operating pressure. A sketch of the testing apparatus used in this research is shown in Figure 2-2.

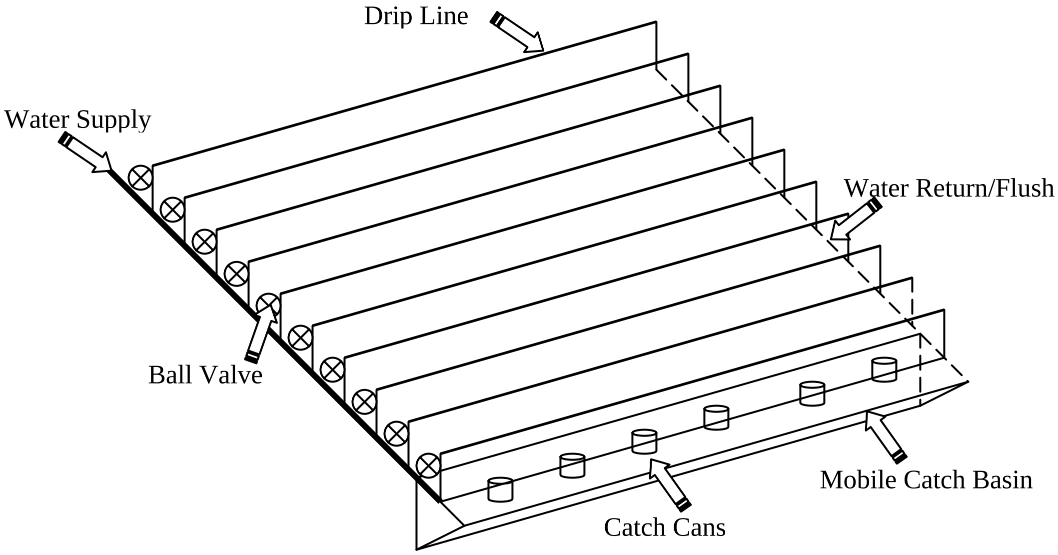

Figure 2-2 Layout of the test apparatus for emitter evaluation

Tap water was used in the experiment to reduce the effects of biological growth or variances in water quality. Water was supplied to the laterals from a 0.85 m^3 (225 gallon) tank using a 373-watt (½ horse power), high head pump. The system pump (AERMOTOR S series) is a 4” submersible pump which features ½ HP, 4.543 m^3/hour (20 GPM), 6 STG. The pump performance curve was published in the user manual and listed as Figure 2-3.

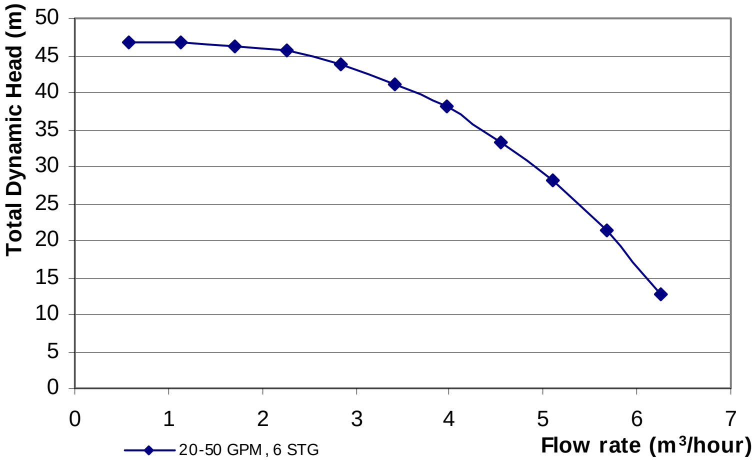

Figure 2-3 Pump characteristics curve (Adapted from AERMOTOR S Series Owner's manual, 2005)

A glass thermometer with a measuring range of -20 ~ +80°C was suspended in the middle of tank to monitor water temperature. Water temperature was maintained at +23°C (±2°C) by adding hot/cold water as needed.

To quantify the uniformity of this drip system, the catch-can method of uniformity testing was as described by both the American Society for Agricultural Engineers (ASAE) and the National Resources Conservation Service (NRCS) (ASAE, 1999). Small pieces of cotton string were attached to individual emitters to direct discharged water down into the catch cans located in a mobile catch basin. The strings were saturated before each sampling event. The water samples collected in containers were weighed on an electric balance with measurement accuracy of ±0.01 gram and converted to volume. A pressure gauge was installed on the supply manifold to allow a periodic check of the operating pressure.

Sampling Protocol

Sampling Time

In this study, a sampling event was conducted by connecting 10 individual 3.05 m lengths of tubing to the testing apparatus. Each lateral had six emitters. This allowed a grouping of approximately 60 emitters to be evaluated at one time. New tubings were allowed to drip 3 hours for conditioning before any sampling. In previous research on filtration and management considerations for subsurface drip irrigation (T. P. Trooien, 2000), the flow amount to each zone was measured and dripped for approximately 30 minutes to test the flow rates of the drip lines after the system was filled. Clark (2005) let the system runs for 5 minutes prior to sampling water. As Persyn (2000) suggested, the pump was turned on and emitters were allowed to drip for approximately 2 minutes to allow air to escape from the pipe. The system was only sampled when no air was exiting from the emitters and only during the fully pressurized dosing stage. Due to limited time and the weighing device’s range, the water collection period was set at 4 minutes (water volume ranges from 100 to 400ml) to minimize error associated with starting and stopping of individual runs. For each type of emitter/tubing under each specific pressure, the sampling event on each lateral was repeated 3 times consecutively. All weighed containers were emptied and wiped dry with a paper towel between sampling events.

Operating Pressures on Emitters

The sampling events were conducted under eight specified pressures listed as 13.79 kPa/2 psi/1.41 m, 27.58 kPa/4 psi/2.81 m, 41.37 kPa/6 psi/4.22 m, 55.16 kPa/8 psi/5.62 m, 68.95 kPa/10 psi/7.03 m, 103.42 kPa/15 psi/10.54 m, 137.90 kPa/20 psi/14.20 m and 310.26 kPa/45 psi/31.63 m. During each dosing trial, the pressures at the inlet and at the end of the 10 laterals were measured by pressure gauges.

A standard test on the emitter discharge rate in response to pressure (ASABE, 2003) was conducted to develop sample data and for comparison with manufacturer-provided performance data. In this research, the emitter exponent x and constant value C (Equation 2.8) were derived from polynomial regression (exponential) in Microsoft EXCEL. The reported figures were compared with data offered by the manufacturers as a reference.

RESULTS AND DISCUSSION

Evaluation of Emitters

The average variation coefficient C_{ve} for all emitters through 3 repetitions of sampling was computed to check experiment error caused by manually operation (Table 2-5). The C_{ve} value was around 1%, which indicated that statistical results were not greatly influenced by experiment operation and can represent emitter's real conditions.

The emitter should have a C_v of 0.03 or lower in order for a waste dispersal system to operate with an EU of 95% (Netafim, 2004). The nominal variance coefficient for Geoflow products is 5% (Geoflow, 2004). The experiment results showed that the average application uniformity coefficient (UC) of Netafim products is 96.4%; average coefficient variance (C_v) is 4.9% (Table 2-5). The average UC of Geoflow Wasteflow products is 94.4%, and the C_v value is 6.8%.

Table 2-5. Summary of statistical analysis on tested emitters *

Tubing Model	Type**	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
Geoflow WFCL 164-24-500	NPC	95.83	0.0528	86.95	93.32	0.0069
Geoflow WFPC 162-24-500	PC	94.92	0.0670	81.41	91.49	0.0102
Geoflow WFPC 164-24-500	PC	92.57	0.0873	77.98	87.79	0.0109
Netafim Bioline 08WRAM 0.6-24V	PC	95.79	0.0577	90.02	94.61	0.0122
Netafim Bioline 08WRAM 1.0-12500	PC	96.98	0.0394	92.2	95.73	0.0148

* Note: Mean values under eight pressures between 0 and 31.65 m (45 psi)
** NPC = non-pressure compensating; PC = pressure compensating

An evaluation of the five drip tubings is shown in Table 2-6. It is a comparison of the observed results to the recommended classifications for micro-irrigation systems (Tables 2-1, 2-2). Five types of drip tubing were classified to excellent performance based on uniformity coefficient. The classification based on coefficient variation ranged from marginal to excellent.

Table 2-6. Micro-irrigation system classifications of tested emitters based on uniformity coefficient (UC) * and manufacturer's coefficient of variation (C_v) **

Classification Factors and Results	Geoflow WFCL 164-24-500	Geoflow WFPC 162-24-500	Geoflow WFPC 164-24-500	Netafim Bioline 08WRAM0.6-24V	Netafim Bioline 08WRAM1.0-12500
UC (%)	95.83	94.92	92.57	95.79	96.98
Classification	Excellent	Excellent	Excellent	Excellent	Excellent
C_v	0.0528	0.0670	0.0873	0.0394	0.0577
Classification	Average	Average	Marginal	Excellent	Average

* Adopted from ASAE Standards EP 458 (1999).
** Adopted from ASABE Standards EP405.1 (2003).

Emitter Flow Rate and Pressure Head Relationship

Development of the flow rate and pressure relationship in the form of a curve is an important step in the process of defining emitter characteristics. It serves as the basis of emitter type selection and system design. As mentioned in the introduction, the emitter exponent x and constant value C were derived using polynomial regression in Microsoft EXCEL.

As stated in the Drip-In PC manual (Drip-In, 2004), at low pressure ranges of 68.95-103.42 kPa (7.03-10.54 m)/(0-15 psi), PC emitters behave like a turbulent-flow emitter (NPC emitter); from 103.42 to 413.69 kPa (10.54-42.61 m)/(15-60 psi), the emitters are fully pressure compensating (Drip-In, 2004). To test the assumption's general applicability on PC emitters and to optimally simulate emitter's characteristics under various pressures, the flow-pressure (Q-H) curve was studied separately in two ranges: low pressure and normal operation pressure. As noted in Table 2-4, for Geoflow products, the low pressure range is from 0 to 68.95 kPa (7.03 m/10 psi); the suggested normal pressure range is 68.95-310.26 kPa (7.03-31.63 m/10-45 psi). For Netafim products, the low pressure range is from 0 to 48.26 kPa (4.92 m/7 psi); the suggested normal pressure range is 48.26-413.69 kPa (4.92-42.61 m)/(7-60 psi).

Geoflow WFCL 164-24-500

The Geoflow NPC emitter had an emission rate range of 3.88×10^{-7} m^3/s to 1.81×10^{-6} m^3/s for a pressure range of 1.4 m to 31.6 m, respectively (Table 2-7).

As shown in Table 2-8 and Figure 2-4, flow rates given in the GEOFLOW user's manual (Geoflow, 2004) for WFCL 164-24-500 average 1.27×10^{-7} m^3/s greater than the experimental results. A possible reason for this phenomenon was the tubing tested had 'Drip-In Classic' emitters with a nominal flow rate 3.785 liters/hour@6.89 kPa (1 GPH@15 psi) (EPRI, 2004). This supposition was confirmed after a piece of tubing was cut open and the emitter inside observed to be a green color. In fact, the experimental data and "Drip-In" user manual data (Drip-In, 2004) fit very closely, the average difference between the data points was less than 1% of the sample average value (Figure 2-4).

Table 2-7 Emitter characterization of Geoflow WFCL 164-24-500 (T=20~25°C) *

Pressure (m)	q_a (m^3/s)	S_q (m^3/s)	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
1.41	3.88E-07	1.99E-08	95.89	0.0514	85.94	93.06	0.0031
2.81	5.47E-07	2.93E-08	95.83	0.0535	86.87	93.13	0.0042
4.22	6.74E-07	3.48E-08	95.94	0.0516	88.99	94.75	0.0033
5.63	7.76E-07	3.88E-08	96.02	0.0500	87.13	93.39	0.0095
7.03	8.65E-07	4.21E-08	96.15	0.0487	87.04	93.53	0.0080
10.5	1.06E-06	5.49E-08	95.83	0.0520	86.96	93.21	0.0060
14.1	1.22E-06	6.26E-08	95.6	0.0514	87.1	93.28	0.0085
31.6	1.81E-06	1.16E-07	95.38	0.0640	85.54	92.24	0.0089
Average			95.83	0.0528	86.95	93.32	0.0069

* q_a, average emitter discharge rate; S_q, standard deviation of emitter flow rate; UC, Christiansen's uniformity coefficient; C_{ve}, variation coefficient of emitter flow rate; EU, emission uniformity; DU, low quarter distribution uniformity; C_{ve}, average variation coefficient among sampling events

Table 2-8 Flow rate vs. pressure of Geoflow WFCL 164-24-500

Q-H	Total pressure range (0-31.63 m/45 psi)							
	$Q = 3.292 \times 10^{-7} H^{0.4939}$							
H(m)	1.41	2.81	4.22	5.62	7.03	10.54	14.20	31.63
Q(m^3/s)	3.88E-07	5.47E-07	6.74E-07	7.76E-07	8.65E-07	1.06E-06	1.22E-06	1.81E-06

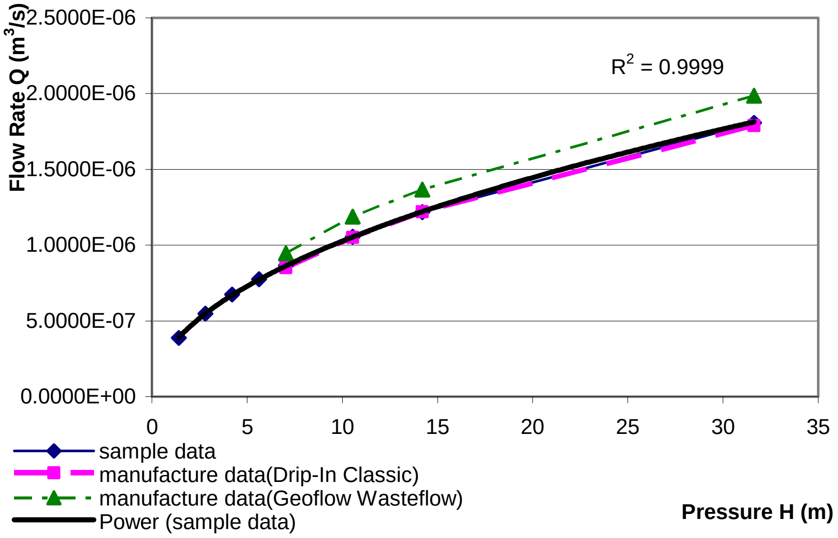

Figure 2-4 Q-H curve of Geoflow WFCL 164-24-500 (0-31.63 m/45 psi)

After evaluating another set of data generated on a second roll of tubing with model 'GEOFLOW WFCL 164-24-500', the author obtained similar experimental results.

An R^2 value of 0.999 means the Q-H equation described the flow-pressure relationship precisely. The emitter exponent x is 0.4939, which conforms to the conclusion of exponent value 0.5 for NPC emitters (IA, 2002).

Geoflow WFPC 162-24-500

The Geoflow PC two liter/hour emitter was evaluated to determine the emission rate with pressure characteristics (Tables 2-9, 2-10 and Figures 2-5, 2-6, 2-7).

The emission rate increased rapidly with respect to pressure until 7.03 m pressure and then exhibited a relatively constant but slightly decreased emission rate (Table 2-9, Figure 2-5).

Table 2-9 Emitter characterization of Geoflow WFPC 162-24-500 (T=20~25°C)

Pressure (m)	q_a (m^3/s)	S_q (m^3/s)	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
1.41	2.69E-07	1.69E-08	95.49	0.0628	85.4	92.51	0.0115
2.81	3.80E-07	1.96E-08	96.3	0.0515	86.23	93.33	0.0111
4.22	4.68E-07	2.39E-08	96.39	0.0510	85.79	93.4	0.0059
5.63	5.41E-07	2.77E-08	96.4	0.0511	85.41	93.36	0.0055
7.03	5.90E-07	3.51E-08	95.71	0.0595	80.11	91.93	0.0058
10.5	5.90E-07	4.40E-08	94.18	0.0746	75.23	89.93	0.0106
14.1	5.67E-07	4.16E-08	94.11	0.0734	77.82	90.87	0.0093
31.6	5.71E-07	6.39E-08	90.79	0.1120	75.28	86.62	0.0218
Average			94.92	0.0670	81.41	91.49	0.0102

* q_a, average emitter discharge rate; S_q, standard deviation of emitter flow rate; UC, Christiansen's uniformity coefficient; C_v, variation coefficient of emitter flow rate; EU, emission uniformity; DU, low quarter distribution uniformity; C_{ve}, average variation coefficient among sampling events

Table 2-10 Flow rate vs. pressure equations of Geoflow WFPC 162-24-500

<table>
<tr><td rowspan="2">Q-H</td><td colspan="8">Total pressure range (0-31.63 m/45 psi)</td></tr>
<tr><td colspan="8">$Q = 3.0673 \times 10^{-7} H^{0.2418}$</td></tr>
<tr><td></td><td colspan="4">Low pressure range (0-8 psi)</td><td colspan="4">Normal pressure (10-45 psi)</td></tr>
<tr><td>H(m)</td><td>1.41</td><td>2.81</td><td>4.22</td><td>5.62</td><td>7.03</td><td>10.54</td><td>14.20</td><td>31.63</td></tr>
<tr><td>Q(m^3/s)</td><td>2.69E-07</td><td>3.80E-07</td><td>4.68E-07</td><td>5.41E-07</td><td>5.90E-07</td><td>5.90E-07</td><td>5.67E-07</td><td>5.71E-07</td></tr>
<tr><td></td><td colspan="4">$Q = 2.2592 \times 10^{-7} H^{0.5054}$</td><td colspan="4">$Q = 5.5846 \times 10^{-7} H^{0.0095}$</td></tr>
</table>

Considering the whole pressure range, the obtained flow rate vs. pressure equation is not ideal for a PC emitter. The emitter exponent x is 0.2418 (Table 2-10), which was classified as partially pressure compensating (Table 2-3) (IA, 2002). For the purpose of describing the PC emitter's characteristics more precisely, the Q-H relationship was divided into two pressure ranges.

The Q-H equation for the whole pressure range exhibited an R^2 value of 0.7037 (Figure 2-5).

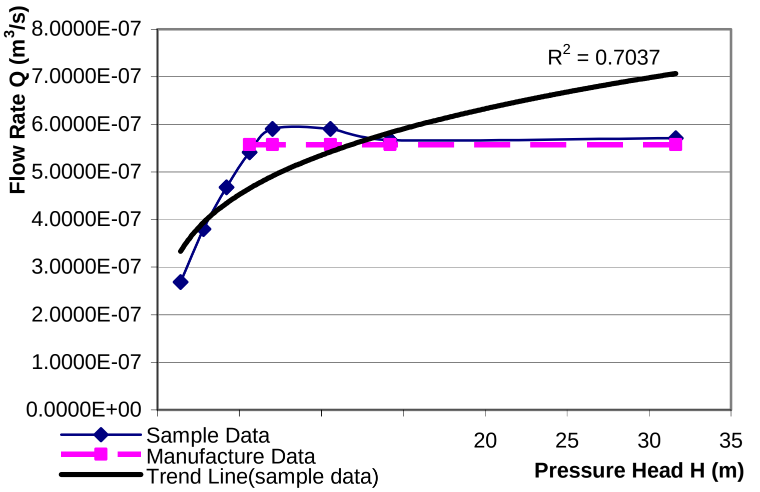

Figure 2-5 Q-H curve of Geoflow WFPC 162-24-500 (0-31.63 m/45 psi)

In low pressure range, R^2 value of 1.000 indicates the Q-H equation described the flow-pressure relationship precisely (Figure 2-6). The emitter exponent x is 0.5054, which conforms to the conclusion of exponent value 0.5 for NPC emitters (IA, 2002), proved emitters characterizing performance as NPC in low pressure range. There is no reference data from the manufacturer for the flow rate-pressure below 68.95 kPa (7.03 m/10 psi).

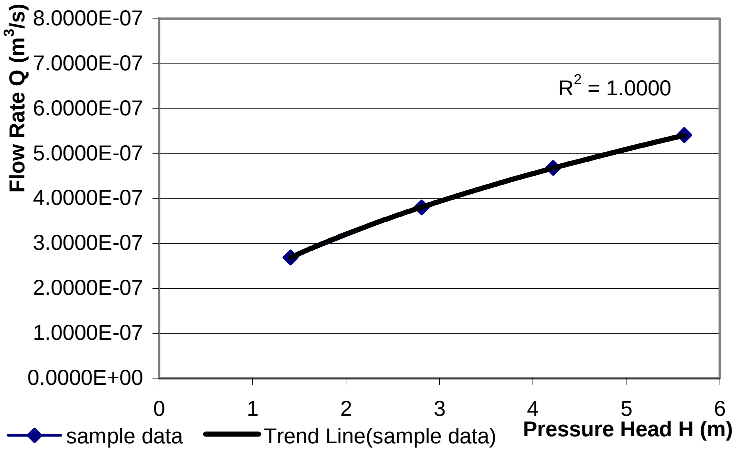

Figure 2-6 Q-H curve of Geoflow WFPC 162-24-500 (Low Pressure)

In the suggested normal operation pressure range, emitter exponent x is 0.0095, which conforms to the conclusion of the exponent value less than 0.1 for PC emitters (IA, 2002), proving emitter performance as pressure compensating. In this pressure range, the average difference value between manufacturer-published data and sampled data in the normal pressure range (7.03-31.63 m) is 2.22×10^{-8} m^3/s, about 4% of average sampled flow rate. In the normal operation pressure range, R^2 value of 0.05521 represents a fair representation of flow-pressure relationship (Figure 2-7). This result may be attributed to a slight reduction in the emitter flow rate at greater pressure.

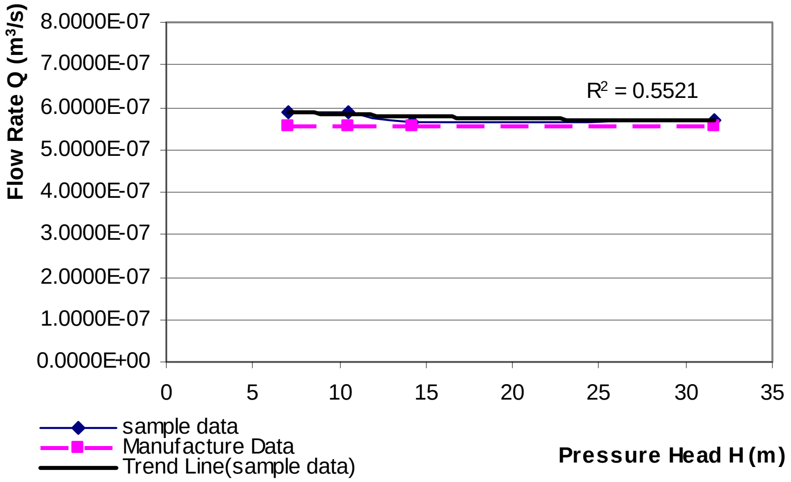

Figure 2-7 Q-H curve of Geoflow WFPC 162-24-500 (Normal Pressure)

Geoflow WFPC 164-24-500

The Geoflow PC four liter/hour emitter was evaluated to determine emission rates with pressure characteristics (Tables 2-11, 2-12 and Figures 2-8, 2-9, 2-10).

Emission rate increased rapidly with respect to pressure until 7 m pressure and then exhibited a relatively constant emission rate (Table 2-11, Figure 2-8).

Table 2-11 Emitter characterization of Geoflow WFPC 164-24-500 (T=20~25°C)

Pressure (m)	q_a (m^3/s)	S_q (m^3/s)	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
1.41	3.78E-07	3.44E-08	92.09	0.0911	78.17	87.06	0.0110
2.81	5.43E-07	4.82E-08	92.36	0.0889	77.02	87.44	0.0110
4.22	6.71E-07	5.88E-08	92.5	0.0876	76.49	87.41	0.0074
5.63	7.79E-07	6.63E-08	92.69	0.0851	78.41	87.98	0.0084
7.03	8.75E-07	7.40E-08	92.79	0.0846	78.54	88.16	0.0117
10.5	9.71E-07	8.54E-08	92.6	0.0880	79.23	87.95	0.0082
14.1	9.65E-07	8.01E-08	93.1	0.0830	79.84	88.42	0.0096
31.6	9.85E-07	8.87E-08	92.44	0.0900	76.11	87.89	0.0195
Average			92.57	0.0873	77.98	87.79	0.0109

* q_a, average emitter discharge rate; S_q, standard deviation of emitter flow rate; UC, Christiansen's uniformity coefficient; C_v, variation coefficient of emitter flow rate; EU, emission uniformity; DU, low quarter distribution uniformity; C_{ve}, average variation coefficient among sampling events.

Table 2-12 Flow rate vs. pressure equations of Geoflow WFPC 164-24-500

Q-H	Total pressure range (0-31.63 m/45 psi)							
	$Q = 4.035 \times 10^{-7} H^{0.322}$							
	Low Pressure Range (0-8 psi)				Normal Pressure (10-45 psi)			
H(m)	1.41	2.81	4.22	5.62	7.03	10.54	14.20	31.63
Q(m^3/s)	3.78E-07	5.43E-07	6.71E-07	7.79E-07	8.75E-07	9.71E-07	9.65E-07	9.85E-07
	$Q = 3.1631 \times 10^{-7} H^{0.5224}$				$Q = 7.985 \times 10^{-7} H^{0.0659}$			

Considering the whole pressure range, the obtained flow rate vs. pressure equation is not ideal for a PC emitter. The emitter exponent x is 0.322 (Table 2-12), which was classified as partially pressure compensating (Table 2-3) (IA, 2002). For the purpose of describing the PC emitter's characteristics more precisely, the Q-H relationship was divided into two pressure ranges.

The Q-H equation for the whole pressure range exhibited an R^2 value of 0.8418 (Figure 2-8).

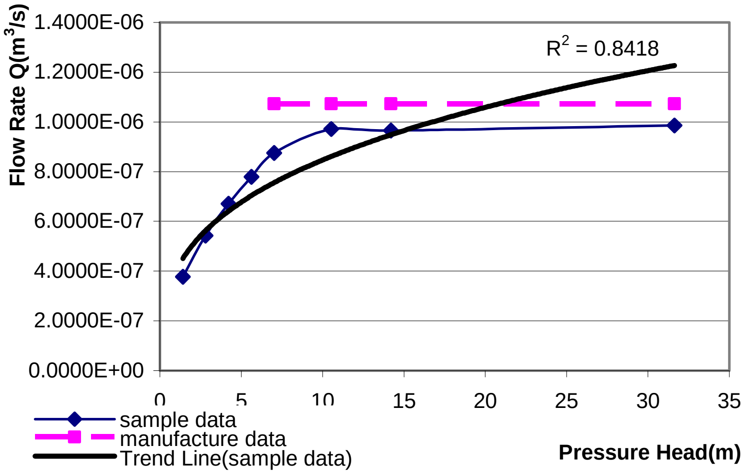

Figure 2-8 Q-H curve of Geoflow WFPC 164-24-500 (0-31.63 m/45 psi)

In low pressure ranges, R^2 value of 0.9991 indicates the Q-H equation described the flow-pressure relationship precisely (Figure 2-9). The emitter exponent x is 0.5224, which conforms to the conclusion of an exponent value of 0.5 for NPC emitters (IA, 2002), proved emitters characterizing performance as NPC in low pressure range. There is no reference data from the manufacturer for the flow rate-pressure below 68.95 kPa (7.03 m/10 psi).

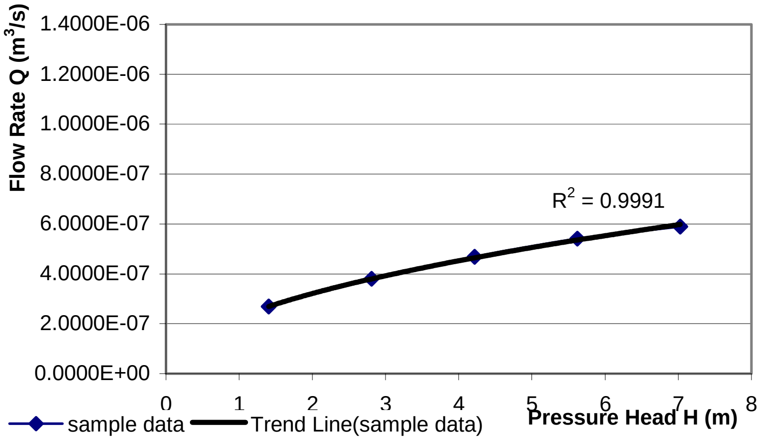

Figure 2-9 Q-H curve of Geoflow WFPC 164-24-500 (Low Pressure)

In the suggested normal operation pressure range, the emitter exponent x is 0.0659, which conforms to the conclusion of exponent value less than 0.1 for PC emitters (IA, 2002), proving emitter performance as pressure compensating. In this pressure range, the average difference between manufacturer-published data and sampled data in the normal pressure range (7.03-31.63 m) is 1.58×10^{-7} m^3/s, about 17% of average sampled flow rate (Figure 2-10).

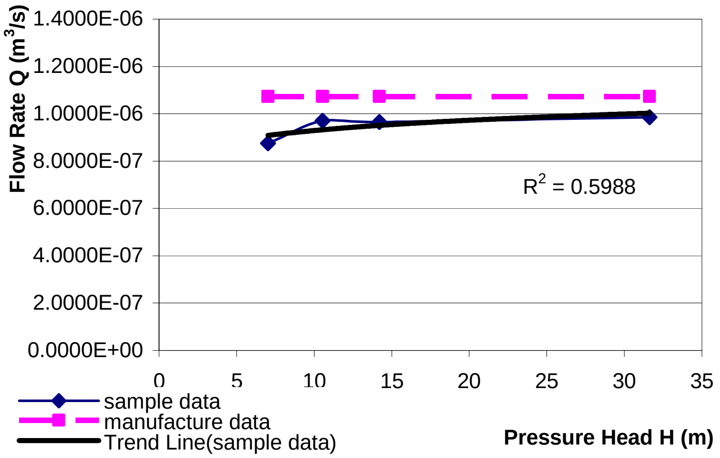

Figure 2-10 Q-H curve of Geoflow WFPC 164-24-500 (Normal Pressure)

The study showed that Geoflow PC emitters demonstrated the properties of NPC emitter under a relatively low operation pressure range between 0 and 68.95 kPa (7.03 m/10 psi). In addition, these PC emitters discharge a relatively uniform flow rate Q over a pressure range from 68.95 kPa (7.03 m/10 psi) to 310.26 kPa (31.63 m/45 psi).

Netafim Bioline 08WRAM0.6-24V

The Netafim PC 2.27 liter/hour emitter was evaluated to determine emission rate with pressure characteristics (Tables 2-13, 2-14 and Figures 2-11, 2-12, 2-13).

The emission rate increased rapidly with respect to pressure until 4 m pressure and then decreased about 10%; after that the emitter exhibited a relatively constant flow rate in the pressure range from 10.54 m to 31.63 m (Table 2-13, Figure 2-11).

Table 2-13 Emitter characterization of Netafim Bioline 08WRAM0.6-24V (T=20~25°C)

Pressure (m)	q_a (m^3/s)	S_q (m^3/s)	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
1.41	5.17E-07	5.78E-08	92.84	0.1120	83.92	91.37	0.0256
2.81	6.67E-07	5.39E-08	93.94	0.0808	86.81	91.96	0.0087
4.22	7.15E-07	3.17E-08	96.44	0.0444	92.65	95.47	0.0065
5.63	7.14E-07	3.36E-08	96.34	0.0471	92.14	95.66	0.0082
7.03	7.03E-07	3.36E-08	96.37	0.0477	91.97	95.54	0.0057
10.5	6.87E-07	3.12E-08	96.53	0.0454	91.74	95.56	0.0108
14.1	6.76E-07	2.82E-08	96.86	0.0417	93.07	95.87	0.0114
31.6	6.73E-07	2.83E-08	97.04	0.0420	87.85	95.48	0.0206
Average			95.79	0.0577	90.02	94.61	0.0122

* q_a, average emitter discharge rate; S_q, standard deviation of emitter flow rate; UC, Christiansen's uniformity coefficient; C_v, variation coefficient of emitter flow rate; EU, emission uniformity; DU, low quarter distribution uniformity; C_{ve}, average variation coefficient among sampling events.

Table 2-14 Flow rate vs. pressure equations of Netafim Bioline 08WRAM0.6-24V

Q-H	Total pressure range (0-31.63 m/45 psi)							
	$Q = 5.9535 \times 10^{-7} H^{0.0599}$							
	Low Pressure Range (0-6 psi)			Normal Pressure (8-45 psi)				
H(m)	1.41	2.81	4.22	5.62	7.03	10.54	14.20	31.63
Q(m^3/s)	5.17E-07	6.67E-07	7.15E-07	7.14E-07	7.03E-07	6.87E-07	6.76E-07	6.73E-07
	$Q = 4.7153 \times 10^{-7} H^{0.3033}$			$Q = 7.985 \times 10^{-7} H^{0.0659}$				

Considering the whole pressure range, the obtained flow rate vs. pressure equation is ideal for a PC emitter. The emitter exponent x is 0.0599 (Table 2-14), which was classified as pressure compensating (Table 2-3) (IA, 2002). The Q-H equation for the whole pressure range exhibited an R^2 value of 0.414 (Figure 2-11). For the purpose of describing the PC emitter's characteristics more precisely, the Q-H relationship was divided into two pressure ranges.

In the whole pressure range from 0 to 310.26 kPa (31.63 m/45 psi), the difference between flow rates given by manufacturer and sample data averaged 2.58×10^{-8} m^3/s, which is about 4% of average sample flow rate.

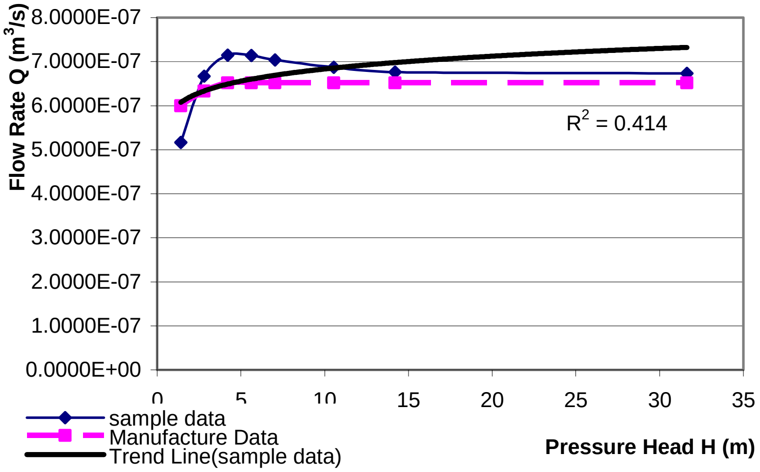

Figure 2-11 Q-H curve of Netafim Bioline 08WRAM0.6-24V (0-31.63 m/45 psi)

In the low pressure range (Figure 2-12), R^2 value of 0.9714 indicates the Q-H equation described the flow rate-pressure relationship precisely. The emitter exponent x is 0.3033, which was classified as partially pressure compensating (IA, 2002).

In the suggested normal operation pressure range, the emitter exponent x is 0.0659, which conforms to the conclusion of exponent value less than 0.1 for PC emitters (IA, 2002), proving emitter performance as pressure compensating. The Q-H equation for the normal pressure range exhibited an R^2 value of 0.8352 (Figure 2-13).

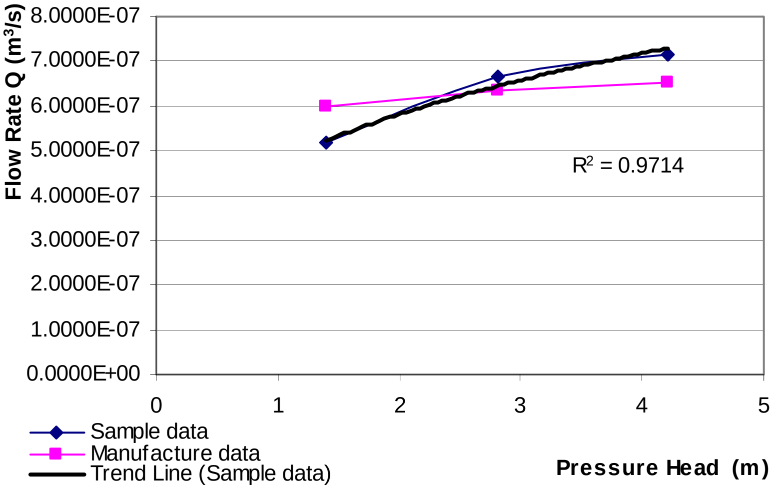

Figure 2-12 Q-H curve of Netafim Bioline 08WRAM0.6-24V (Low Pressure)

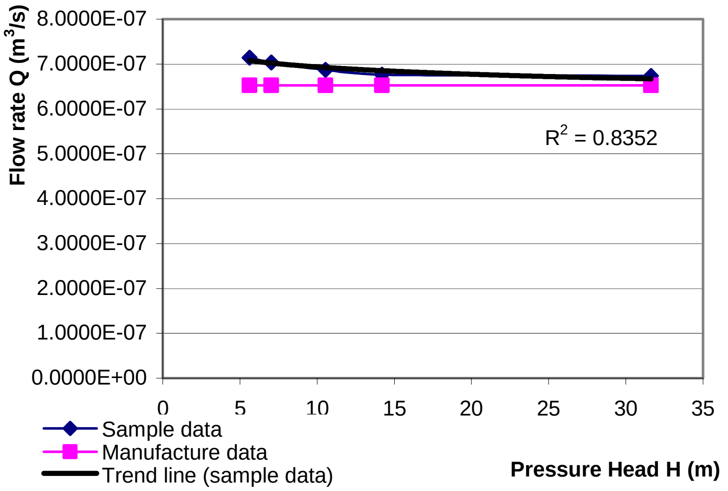

Figure 2-13 Q-H curve of Geoflow WFPC 164-24-500 (Normal Pressure)

Netafim Bioline 08WRAM1.0-12500

The Netafim PC 3.79 liter/hour emitter was evaluated to determine emission rate with pressure characteristics (Tables 2-15, 2-16 and Figures 2-14, 2-15, 2-16).

The emission rate increased rapidly with respect to pressure until 4 m pressure and then decreased about 5%; after that the emitter exhibited a relatively constant flow rate in the pressure range from 7.03 m to 31.63 m (Table 2-15, Figure 2-14).

Table 2-15 Emitter characterization of Netafim Bioline 08WRAM1.0-12500 (T=20~25°C)

Pressure (m)	q_a (m^3/s)	S_q (m^3/s)	UC (%)	C_v	EU (%)	DU (%)	C_{ve}
1.41	7.45E-07	4.71E-08	95.32	0.0632	89.56	94.04	0.0302
2.81	9.56E-07	3.43E-08	97.15	0.0359	94.4	96.01	0.0101
4.22	1.01E-06	2.92E-08	97.75	0.0290	94.43	96.81	0.0064
5.63	9.97E-07	2.89E-08	97.79	0.0290	93.36	96.83	0.0078
7.03	9.88E-07	2.87E-08	97.86	0.0291	92.91	96.74	0.0079
10.5	9.61E-07	3.20E-08	97.56	0.0333	92.16	96.4	0.0156
14.1	9.57E-07	3.91E-08	96.88	0.0408	91.54	95.47	0.0195
31.6	1.01E-06	5.56E-08	95.55	0.0552	89.28	93.51	0.0207
Average			96.98	0.0394	92.2	95.73	0.0148

* q_a, average emitter discharge rate; S_q, standard deviation of emitter flow rate; UC, Christiansen's uniformity coefficient; C_v, variation coefficient of emitter flow rate; EU, emission uniformity; DU, low quarter distribution uniformity; C_{ve}, average variation coefficient among sampling events.

Considering the whole pressure range, the obtained flow rate versus pressure equation is ideal for a PC emitter. The emitter exponent x is 0.067 (Table 2-16), which was classified as pressure compensating (Table 2-3) (IA, 2002). The Q-H equation for the whole pressure range exhibited an R^2 value of 0.4245 (Figure 2-11). For the purpose of describing the PC emitter's characteristics more precisely, the Q-H relationship was divided into two pressure ranges.

In the whole pressure range from 0 to 310.26 kPa (31.63 m/45 psi), the difference between flow rates given by manufacturer and sample data averaged 7.58×10^{-8} m^3/s, which is about 8% of average sample flow rate.

Table 2-16 Flow rate vs. pressure equations of Netafim Bioline 08WRAM1.0-12500

Q-H	Total pressure range (0-31.63 m/45 psi)							
	$Q = 8.3687\times10^{-7} H^{0.0670}$							
	Low Pressure Range (0-6 psi)			Normal Pressure (8-45 psi)				
H(m)	1.41	2.81	4.22	5.62	7.03	10.54	14.20	31.63
Q(m^3/s)	7.45E-07	9.56E-07	1.01E-06	9.97E-07	9.88E-07	9.61E-07	9.57E-07	1.01E-06
	$Q = 6.8646\times10^{-7} H^{0.2831}$			$Q = 9.6975\times10^{-7} H^{0.0052}$				

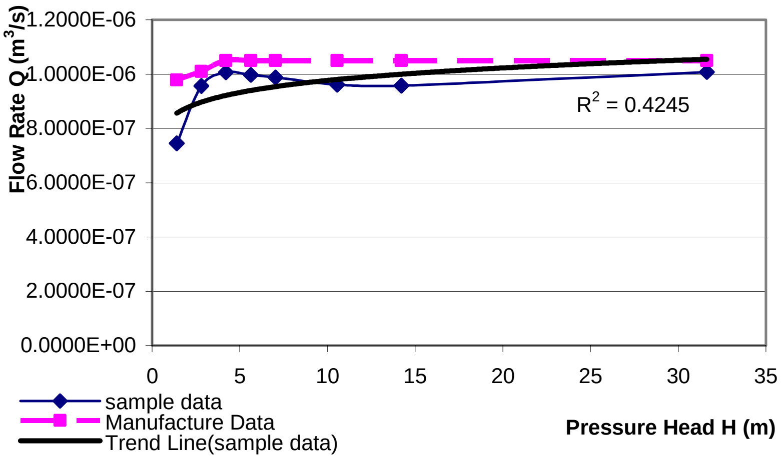

Figure 2-14 Q-H curve of Netafim Bioline 08WRAM1.0-12500 (0-31.63 m/45 psi)

In the low pressure range (Figure 2-15), R^2 value of 0.9562 indicates the Q-H equation described the flow-pressure relationship precisely. The emitter exponent x is 0.2831, which was classified as partially pressure compensating (IA, 2002).

In the suggested normal operation pressure range, the emitter exponent x is 0.0052, which conforms to the conclusion of exponent value less than 0.1 for PC emitters (IA, 2002), proving emitter performance as pressure compensating. The Q-H equation for the normal pressure range exhibited an R^2 value of 0.735 (Figure 2-16).

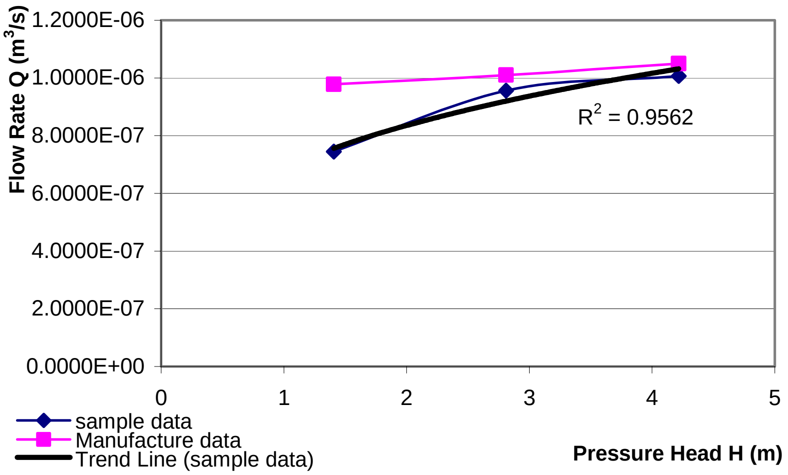

Figure 2-15 Q-H curve of Netafim Bioline 08WRAM1.0-12500 (Low Pressure)

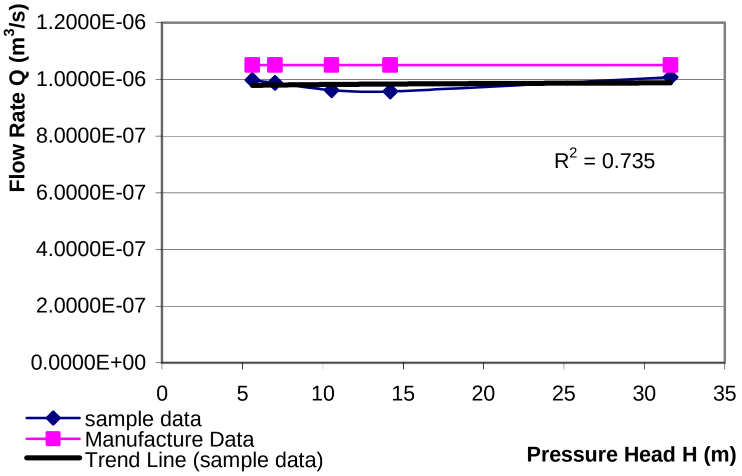

Figure 2-16 Q-H curve of Netafim Bioline 08WRAM1.0-12500 (Normal Pressure)

Displayed in the flow rate-pressure equations of two types of Netafim tubings, emitter exponents are both smaller than 0.1 in the pressure range of 0 to 310.26 kPa/45 psi, which conforms to the IA's definition of PC emitter (IA, 2002). Those two types of Netafim emitters both showed the highest discharge rates under the pressure range of 13.79 kPa (2 psi) to 68.95 kPa (10 psi). It can be concluded that Netafim PC emitters function properly under low operation pressures with an acceptable uniformity coefficient around 95%.

Summary

Emitter's flow rate vs. pressure curves and exponents were listed in table 2-17 for the reference of drip products selection and drip zone design:

Table 2-17 Emitter exponents classification in different pressure ranges *

	Classification factors and results	Geoflow WFCL 164-24-500	Geoflow WFPC 162-24-500	Geoflow WFPC 164-24-500	Netafim Bioline 08WRAM 0.6-24V	Netafim Bioline 08WRAM 1.0-12500
Low pressure	Exponent x	---	0.5054	0.5224	0.3033	0.2831
	Classification	---	NPC	NPC	Partially PC	Partially PC
Normal pressure	Exponent x	---	0.0095	0.0659	0.0659	0.052
	Classification	---	PC	PC	PC	PC
Whole pressure range	Exponent x	0.4939	0.2418	0.322	0.0599	0.067
	Classification	NPC	Partially PC	Partially PC	PC	PC

* NPC = non-pressure compensating, PC= pressure compensating.

According to the classification, four PC products perform according to the definition of pressure compensating in nominal operational pressure ranges suggested by manufacturers. In low pressure ranges, PC products can not be regarded as pressure compensating; the classifications vary from partially to non-pressure compensating.

CONCLUSIONS

The first part of this research was conducted to examine and characterize five types of PC and NPC tubings from the manufacturers GEOFLOW and NETAFIM. All the tests were conducted on new products:

1. This part of study evaluated water distribution of five types of emitters from manufacturers Geoflow and Netafim under 8 pressures between 0 and 310.26 kPa (45 psi). The average application uniformity coefficient (UC) of Netafim products is 96.4%; average variance coefficient (C_v) is 4.9%. The average UC of Geoflow Wasteflow product is 94.4% and C_v value is 6.8%.

2. According to micro-irrigation drip system classifications (ASAE, 1999; ASABE, 2003), five emitter types were all evaluated as excellent performance based on UC. The classification results of five emitter models based on C_v range from marginal to excellent.

3. The generally accepted model used to describe the emitter's discharge and pressure relationship (Q-H) is in the form of an exponent equation. After the flow-pressure (Q-H) curves or each emitter model was generated, according to the optimal match between simulated Q-H curves and experiment data was achieved. Considering the whole pressure range from 0 to 310.26 kPa (45 psi), Netafim products are pressure compensating; Geoflow products distribute wastewater as partially pressure compensating (IA, 2002).

4. In order to better simulate the performance of PC emitters under different pressures, the Q-H curves were divided into two ranges: low pressure and normal pressure. Within the low pressure ranges (0-68.95 kPa for Geoflow, 0-48.26 kPa for Netafim), four emitter models all have exponent values greater than 0.1. In the low pressure range, Geoflow PC emitters showed the characteristics of NPC emitters and Netafim products were partially pressure compensating.

Considering the manufacturers' suggested normal pressure ranges (68.95-310.26 kPa for Geoflow, 48.26-310.26 kPa for Netafim), the four PC emitters all have exponent values less than 0.1, which agree with the definition of pressure compensating emitter. However, there exist gaps between nominal flow rates and sample data.

CHAPTER III

SYSTEM APPLICATION UNIFORMITY IN DRIP ZONE DESIGN

INTRODUCTION

After the characterization of emitters described in Chapter II, three types of drip tubing with tested emitters were applied in a field scale wastewater drip system to facilitate research on drip zone design.

Figure 3-1 illustrates a wastewater drip distribution system. The components of a typical drip distribution system installation include: pump and pump tanks, filters, pressure regulators, drip zone, controllers, flush valves, air relief valve, etc.

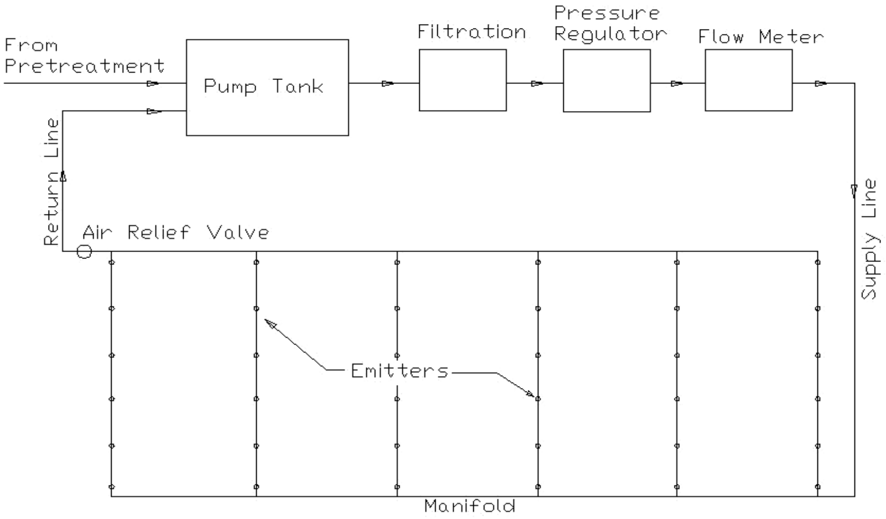

Figure 3-1 Typical wastewater drip system composition

The pump tank is an important component of a wastewater distribution system. Figure 3-2 shows a typical pump tank equipped with a high head submersible pump. Pumps provide the hydraulic energy needed for distributing wastewater to the drip field, periodically flushing the drip system, and filtering the wastewater before it enters the drip field. Pressure pumps that produce 45.4-75.7 liter/min (12-20 GPM) and utilize 110 volts with a ½ horse power motor will generally be the most cost effective strategy for domestic size drip fields (Netafim, 2002). A filter can dramatically minimize the chance of system failure and add years to the life of the drip field by preventing clogging of lateral orifices and drip emitters (Netafim, 2002).

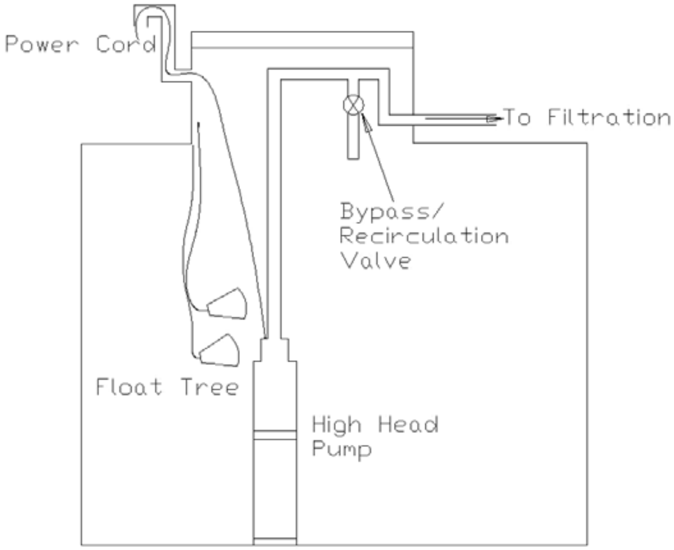

Figure 3-2 Typical pump tank components

The drip zone can be viewed as an independent part of the system. It is composed of a supply line, zone control valves, supply manifold, drip laterals, drip emitters, return manifold, return line, check valves, and air/vacuum relief valves (Figure 3-1). Pressure regulators help to maintain constant and stable water pressure for any irrigation/drip system thereby protecting piping and other components. The supply line and manifold provide wastewater to the inlet of the drip laterals. Drip emitters located along the laterals emit wastewater into the soil at design discharge rates under specific field operation pressures. Air/vacuum relief valves are installed at the points of high elevation within the system to keep soil from being sucked into the emitters due to back siphoning or back pressure. This protection is an absolute necessity with subsurface drip distribution systems. The return manifold and return line facilitate lateral flushing for cleaning and allow wastewater to return to the pretreatment device.

Approaches to sizing wastewater subsurface drip distribution systems require special considerations. The ability to accurately and simply design a drip zone, especially when there are a large number of emitters, is very important to the operation and evaluation of a high-performing drip distribution system. Designers of wastewater drip systems need to know how specific drip products will perform under field conditions. Designers aim to develop a system that will have a hydraulic balance such that any zone within the system has a known and uniform emitter discharge. Because substantial variations in operating pressure can occur in a field system due to elevation changes and friction loss, design concerns should focus on the operating pressure/emitter discharge relationships of the emitters (Clark, 2005). Manufacturer recommended hydraulic loading rates are expressed as an areal loading rate in gallons per day per square foot of drip distribution footprint area. Layout of the drip distribution network must be considered carefully. Two important consequences of network layout are the impacts on pump size necessary to achieve adequate flushing flows and the extent of localized overloading due to internal drip lateral drainage. Typically, the zone flow rates are based on a 0.6 m (2 ft) emitter and drip line spacing. Therefore, each emitter would serve 0.36 m^2 (4 ft^2) of footprint area.

For a site that is not limited by its configuration, lateral lengths depend on hydraulic considerations for the system. Long lateral lengths can be used along with a smaller number of laterals for each zone to reduce the overall pump flow rates needed for periodically flushing the laterals, but this approach increases the total dynamic pressure head for the system. For this configuration, the first design criterion that needs to be considered is the maximum allowable pressure loss for the lateral.

Some designers effectively construct a drip lateral by connecting parallel runs of tubing using flexible PVC pipe, or elbows, and drip line tubing at the end of each run to form a U-shaped loop. In this condition, drip laterals consist of several runs (usually 2, 3, or 4 runs per lateral). There are several potential advantages to using loops to increase the length of individual drip laterals. Loops allow the number of laterals within the drip field or zone to be minimized while maintaining runs along the contour and fitting the available area. It also reduces the pump flow rate needed to flush the laterals within a given zone. This significantly increases flexibility for design layout and pump selection. Loops are also used to place the supply and return manifolds in the same trench, reducing construction costs and consolidating the system layout. Disadvantages to increasing the length of each lateral using loops is the increased friction loss that has to be accommodated.

Measurements of system pressure and flow rates are useful in evaluating system performance. Weynand (2004) tested emitters from two different wastewater drip fields that had been previously operated for several years to analyze slope effects on emitter plugging. Application uniformity of three different laterals within each field was evaluated. He recorded the operating pressure during evaluation. The operation pressures in the two laterals were 49.62 kPa (7.2 psi) and 64.83 kPa (9.4 psi), far below the recommended operation pressure of 172.34 kPa (25 psi) to 275.80 kPa (40 psi) (Netafim, 2002). Sites which were operated below the recommended pressure showed the lowest application uniformity (less than 50%) and the most emitter plugging. Talozi and Hill's (2001) model of drip distribution systems showed similar results. Unacceptable uniformity was attributed to lack of normal operating pressures in the drip laterals. Low operating pressures, in turn, might be attributable to design and/or installation problems (Weynand, 2004).

Distribution systems usually complete a pump dosing cycle that includes four components: pressurization stage, pressurized stage, depressurization stage and resting. The pressurization flow is the flow entering the system from the point of initiating the dosing event until the system reaches the desired operation pressure (Weynand, 2004). From that point, the system operates fully pressurized, which is regarded as the pressurized stage. After the pump is turned off, the system is in the depressurization stage until it stops dripping water. From that time, the system is in the resting stage until the next dosing event begins. Among the four stages, only the pressurized stage is regarded as uniform distribution that accomplishes the main objective of using drip emitters. But wastewater distributed during the pressurization stage impacts the distribution uniformity of any single dosing cycle. According to engineering experience, the water discharged during the four stages is assumed to be: pressurization (more than 1 pipe volume), pressurized stage (2~3 pipe volume), and depressurization (1 pipe volume) and resting stage (no discharge). Thus designers strive to minimize the relative volume of effluent distributed during the pressurization and depressurization periods and maximize the effluent volume during the pressurized stage. The North Carolina Department of Environment and Natural Resources (EPRI, 2004) prefers to use at least five-pipe volumes while dosing (six volumes are needed to have 80% of the dose delivered under full pressurization). Sometimes, the dosing time results in less than four pipe volumes delivered to the field, which some designers and regulators believe is too small to assure uniform distribution. To date, design guidelines for dosing volume and dosing time are mainly based on experience and consider only one stage of the whole dosing cycle.

Several control methods/system components are adopted for use in the residential, single family application of subsurface wastewater treatment techniques. These drip zone operational pressure control schemes, which focus on balancing field pressure and flow requirements with a limited pump selection, are summarized below.

- Gate/globe valves are used in the supply line to control zone operation pressure by increasing the friction loss in the system. Gate/globe valve restrict liquid flow and increase back pressure.
- Pressure regulators are installed in the supply line. The function of pressure regulators is to maintain constant and stable liquid pressure for the drip system. Pressure regulators allow limited flow restriction until desired system pressure is reached.
- A recirculation valve in the pump discharge assembly facilitates by-pass flow. It is used to control operation pressure in the field by re-circulating flow within the pump tank.
- The drip zone is constructed with a gate/globe valve in the return line to restrict the return flow to maintain the operating pressure. When the drip lateral is flushed, a greater volume of effluent passes through the lateral resulting in substantial pressure drops between the supply and return manifolds, increasing the flow variance between the emitters at the inlet versus those at the return end. This greater emitter flow rate variability needs to be accounted for in the design of drip fields consisting of both PC and NPC drip emitters. The flow rate variance is also more difficult to predict for NPC systems.

The obtained emitter flow rate versus pressure curves from Chapter II will be used in this part of the research. The objectives of the research include:

- Test three representative drip tubings with several operating schemes in a field-scale drip system. Characterize the emission volumes of drip emitters along a lateral during zone pressurization stage.
- Use statistical methods to analyze drip zone design and operational schemes with respect to zone pressurization time.

- Use obtained water samples and time records to compute the minimum dose time and dose volume with respect to drip zone design, operational schemes and application uniformity.
- Compute drip zone filling time through traditional engineering design and compare it with experimental data to display the possible variance and consider its impact on system design.

METHODS

Field-scale Experiment Setup

This study examined a hypothetical field design chosen to represent a generally-used mid-size wastewater treatment system. Three types of drip tubing were applied in this field-scale experiment which included both PC and NPC emitters (Table 3-1). The analytical example with system parameters and field conditions is shown in Figures 3-3, 3-4 and is summarized in Table 3-2.

Table 3-1 Manufacturer' parameters of selected emitter and driplines (Netafim, 2004) (Geoflow, 2004) *

Tubing model	Type	Inside diameter	Emitter spacing	Nominal discharge rate	Suggested operation pressure
Geoflow WFCL 164-24-500	NPC	14 mm (0.55 inch)	0.61 m (24 inch)	3.90 liter/hr 1.03 gph@ 20 psi	68.9-310.3 kPa (10-45 psi)
Geoflow WFPC 162-24-500	PC	14 mm (0.55 inch)	0.61 m (24 inch)	2.00 liter/hr 0.53 gph@ 20 psi	68.9-310.3 kPa (10-45 psi)
Netafim Bioline 08WRAM 0.6-24V	PC	14.5 mm (0.57 inch)	0.61 m (24 inch)	2.27 liter/hr 0.6gph@ 20 psi	48.3-413.7 kPa (7-60 psi)

* NPC = non-pressure compensating, PC= pressure compensating

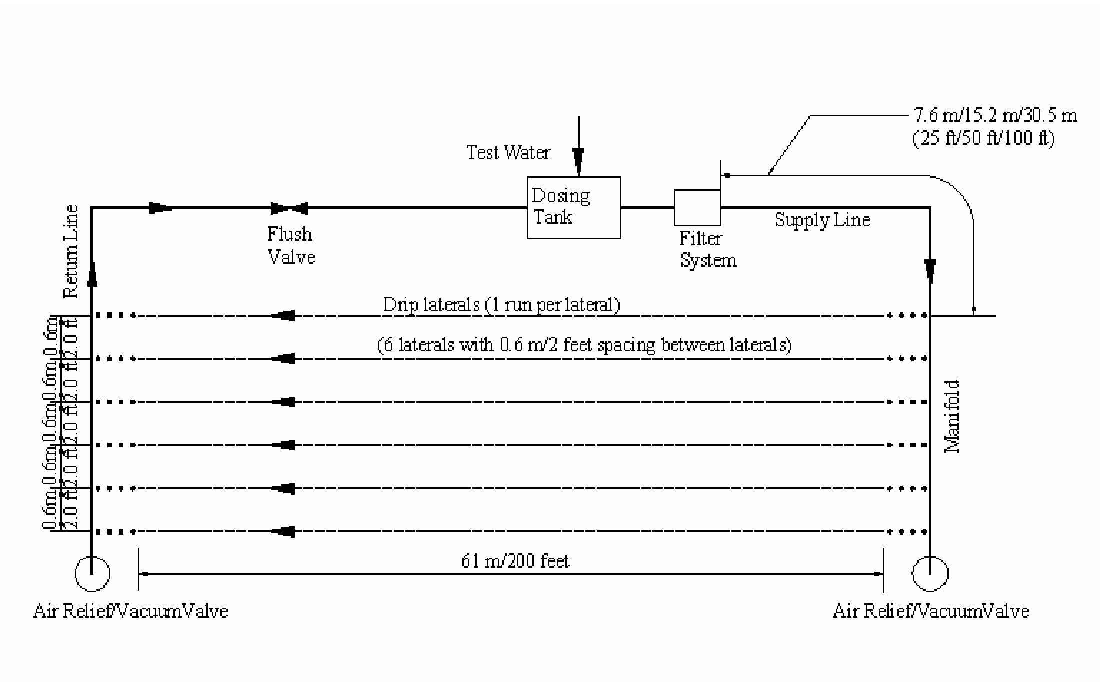

Figure 3-3 Field scale test apparatus for non-pressure compensating tubing and emitters

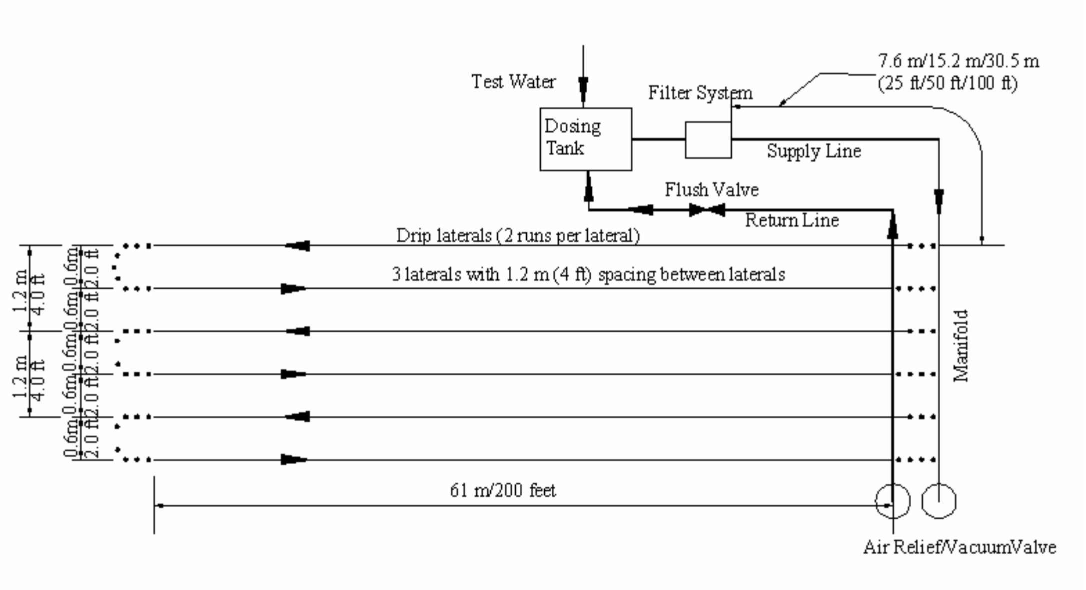

Figure 3-4 Field scale test apparatus for pressure compensating tubing and emitters

Sampling Protocol

For a 95% confidence level, to accurately determine wastewater application uniformity, as few as 18 flow measurements per zone can provide a reasonable estimate of actual water flow in a drip system (Tyson and Curtis, 1998). Measurements must be taken only after the system has reached its normal operating pressure and flow rate. These measurements should be scattered uniformly over the testing zone to accurately represent conditions throughout the entire zone. A suggested sampling pattern is to take measurements at the inlet, 1/5, 2/5, 3/5, 4/5 along the lateral, and at the far end of the equally-spaced laterals (Tyson and Curtis, 1998) (Figure 3-5).

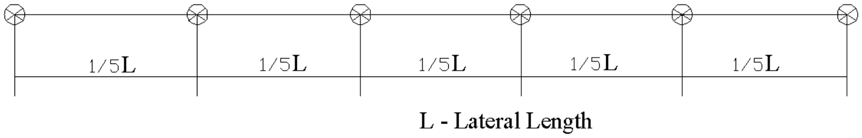

Figure 3-5 Suggested emitter sample distribution along a lateral

In this study, six emitters evenly distributed along each lateral were chosen and marked for sampling (Figure 3-5). For better support and to keep the system horizontal, laterals were tied together and attached to a pre-stressed steel wire. At each emitter sampling position, the laterals were separated and fixed on planks for the convenience of water collection. The catch-can method of uniformity testing was used to collect water (ASAE, 2000).

Before any sampling event new tubing was dripped 3 hours for conditioning to normal use status. A flow meter was installed at the beginning of the supply line and was used to record the pump's performance every 15 seconds. As suggested by Kang (1996), pressures at the inlet and far end of each lateral were recorded for flow rate measurements (Kang, 1996). Therefore, three pressure gauges were installed at the pump, in the supply line and on the return manifold to detect pressure variation in the system. The pressure gauge on the return manifold was used to determine the time required to pressurize the drip zone. Water samples were collected from pump initiation until the pressure reading reached expected lateral end pressures. Figures were generated in Microsoft Excel to plot the emitted sample volumes and the corresponding emitters' location along a lateral (Appendix B, Figures B.1 ~ B.32).

Before each test run, the whole system was blown out with compressed air for 5 minutes to remove water inside the laterals and supply line. The catch cans were removed from below the emitters by co-workers immediately after the pump was turned off so that water emitted during the depressurization stage would not enter the cans or influence the experiment's accuracy. The cans were then collected for weighing.

Table 3-2 Experimental drip system parameters and components

System pump	AERMOTOR S series, 4” submersible pump features with ½ HP, 20 GPM, 6 STG		
Field slope toward the submain and lateral	0		
Filter	Netafim Model DF100-140 (Disc filter with 140 mesh and 0.0984 m^3/min (26 GPM))		
Supply line length	7.6 m/15.2 m/30.5 m (25 ft/50 ft/100 ft)		
Supply line diameter	0.0262 m(1.033 inch)		
Manifold length	3.6 m (12 ft)		
Manifold diameter	0.0262 m (1.033 inch)		
Manifold element length from inlet to first lateral	0.6 m (2 feet)		
Lateral inlet orifice discharge-pressure equation	$q = 21.4 * D^2 * H^{1/2}$ (International unit) *		
Inner diameter of lateral inlet orifice	D = 0.0085 m		
Lateral element length from inlet to the first emitter	0.3 m (1 ft)		
Emitter spacing	0.6 m (2 ft)		
Pressure regulator	Netafim PRV075HF20V2K(137.9 kPa/20 psi) & Netafim PRV075HF45V2K (275.8 kPa/45 psi)		
Emitter model	Geoflow WFCL 164-24-500	Geoflow WFPC 162-24-500	Netafim Bioline 08WRAM0.6-24V
Number of laterals on manifold	6	3	3
Lateral diameter	0.014 m (0.55 inch)	0.014 m (0.55 inch)	0.0145 m (0.57 inch)
Lateral spacing	0.6 m (2 ft)	1.2 m (4 ft)	1.2 m (4 ft)
Number of laterals	6	3	3
Number of emitters along each lateral	100	200	200
Emission equation (normal pressure stages)	$Q = 3.292 \times 10^{-7} H^{0.4939}$	$Q = 5.5846 \times 10^{-7} H^{0.0095}$	$Q = 7.9852 \times 10^{-7} H^{0.0659}$

* (Adapted from U.S. EPA, 2002)

Table 3-3 Specific testing scenarios investigated in field-scale experiments *

Scenario index	Pressure control scheme and pressure	Geoflow WFCL 164-24-500	Geoflow WFPC 162-24-500	Netafim Bioline 08WRAM0.6-24V
1	Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure	Y	------	Y
2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	Y	Y	Y
3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	Y	Y	Y
4	Flow restriction (gate valve on return line) & continuous flushing & 137.9 kPa (20 psi) end pressure	Y	------	------
5	Flow restriction (gate valve on supply line) & intermittent flushing & 275.8 kPa (40 psi) end pressure	------	------	Y
6	Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure	------	Y	Y
7	Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure	------	Y	Y
8	310.26 kPa (45 psi) pressure regulator & intermittent flushing	------	Y	Y

* Y= this scenario was applied on the tubing model.

Design Scenarios Evaluated

Three factors related to drip zone design were evaluated during the field-scale experiment. Variables included:

- Supply line length: 7.6 m or 15.2 m or 30.5 m (25 ft, 50 ft, 100 ft).
- System operational pressure groups: 14.1 m (137.8 kPa/20 psi) or 28.1 m (275.8 kPa/40 psi).
- Operational pressure control schemes, including:
  1) bypass flow at the pump discharge assembly; intermittent flushing.
  2) pressure regulator on the supply line; intermittent flushing.
  3) flow restriction (gate valve on the supply line); intermittent flushing.
  4) flow restriction (gate valve on the return line); continuous flushing.

As presented in Table 3-3, several combinations of the three factors above were tested on both PC and NPC drip products for comparison of the influence on drip zone operation time and wastewater application uniformities.

Statistical Analysis of Drip Zone Pressurization Time

This section aims to compare and analyze the time needed to pressurize the drip system for each pair of scenarios and supply line lengths. Three influential design factors were examined including:

- Supply line length: 7.6 m or 15.2 m or 30.5 m (25 ft/50 ft/100 ft).
- System operational pressure groups: 14.1 m (137.8 kPa/20 psi) or 28.1 m (275.8 kPa/40 psi).

- Operational pressure control schemes.

It may not be possible to directly link this dose time section to certain field design criteria; however, it would benefit design professionals if trends in system pressurization time due to differing fitting and control practices could be better defined. This would facilitate interpretation of design guidance as well as improve service to the industry. The general objective is to shorten the duration of the pressurization stage.

This study assumed the whole drip zone is pressurized when the pressure at the end of the lateral reaches the operational pressures (137.9 kPa/20 psi or 275.8 kPa/40 psi). All tests and comparisons are based on the same system configurations which were summarized in Tables 3-1 and 3-2. Statistical analyses consisted of description of data values; two independent-sample T test, one-way ANOVA and Tukey HSD test.

The hypotheses for this study were as follows:

$H_0 : \beta_1 = \beta_2 = ... = \beta_n$ (Null Hypothesis: a uniform time was needed in all scenarios/ practices to fill and pressurize the drip zone).

$H_a : \beta_i \neq \beta_j ;\ i, j \in (1, n)$ (Research Hypothesis: the drip zone pressurization times are not equal in all scenarios).

The one-way ANOVA test was used to detect significant differences of drip zone pressurization time in all scenarios. As an important indicator of ANOVA tests, the F statistic is the ratio of the two estimates of variance. A large value of the F ratio provides evidence against the null hypothesis that the variances of between-scenarios value and within-scenarios value are equal. A two independent-sample T test was used on PC tubings to determine the level of significant differences between the 137.89 kPa (20 psi) and 275.82 kPa (40 psi) operational pressure groups. Significance probabilities were determined at the 0.05 level. If the significance value was less than 0.05, we concluded there was strong evidence to reject the null hypothesis.

Therefore the pressurization times for all scenarios are not equal. Tukey HSD was used to sequence the dose time factor and identify which pairs of means were not significantly different from each other after multiple comparison procedures. Statistical analysis was performed using SPSS version 13.0 (SPSS, 2004).

Drip Zone Dose Time Calculation

EPRI (2004) encourages designers to establish dosing time based on a minimum number of drip tubing volumes (after pressurization). This approach ensures sufficient time to achieve uniform distribution of wastewater (EPRI, 2004). In this study, several scenarios were applied in a field-scale experiment. Scenarios were a combination of three drip zone design factors: supply line length, drip zone operational pressure, and operational pressure control scheme. The dosing time required to satisfy specific application uniformities in each scenario was computed based on the emitter's Q-H relationship equation as described in Chapter II as well as experiment results in this chapter.

To compute drip zone dose the emission volumes of drip emitters along a lateral during zone pressurization stage was characterized. Then water samples and time records were used to compute the minimum dose time (Equations 3.1~3.5). The drip zone dose time was specifically determined to meet a pre-determined drip zone application uniformity (AU). The required drip zone dose times in all applied scenarios were computed and reported for expected AUs of 85%, 90%, and 95%. All calculations assumed that emitters do not drip during the depressurization and resting stages. Dose time was composed of two parts (the pressurization stage and the pressurized stages):

1. Pressurization stage T_1 (initiation of flow with a lateral end pressure of 0 to an objective

end pressure): 137.9 kPa (20 psi) was applied as the objective pressure on NPC emitters, while both 137.9 kPa (20 psi) and 275.8 kPa (40 psi) were applied to PC emitters. Pressurization time, T_1, was recorded for this stage. Experimental results were used to plot emission volume versus emitter position to develop a linear trend line. The r^2 value of the linear trend line was checked to make sure the value is greater than 0.9000. The difference in emission volume on each run of a lateral, ΔV_1, was determined as the difference between the emission volume of emitters at the beginning (V_{inlet1}) and at the end of each run (V_{end1}) during this stage (Equation 3.1).

2. Pressurized stage T_2: After the end pressure of the lateral reached the operational pressure, the system was assumed to be totally pressurized and stable. Pressures at emitters along the lateral were calculated using the measured lateral inlet and end pressures (assume the value drops linearly from the inlet to the end). The maximum flow rate difference, ΔQ_2, was derived using the relevant emitter Q-H equation obtained in Chapter II and the calculated pressures at each run's beginning and end (Equation 3.2). Where a time, T_2, in this stage is required for a specific scenario/scheme, ΔV_2 is determined based on T_2 (Equation 3.3). Application uniformity, X%, is obtained from Equation 3.4. The value of T_2 was iterated until X% was within $\pm 1\%$ of a target AU value.

After rounding up, the total dose time for each dosing event is the sum of times for the pressurization and pressurized stages (Equation 3.5).

The computation process is listed below:

$$\Delta V_1 = V_{inlet1} - V_{end1} \qquad 3.1$$

$$\Delta Q_2 = Q_{inlet2} - Q_{end2} \qquad 3.2$$

$$\Delta V_2 = \Delta Q_2 * T_2 \qquad 3.3$$

$$1 - \frac{(\Delta V_1 + \Delta V_2)}{V_{avg}} = X\% \qquad 3.4$$

$$T = T_1 + T_2 \qquad 3.5$$

where,

V_{inlet1} and V_{end1}, discharges of sample emitters at the beginning and end of each run during the pressurization stage.

ΔV_1, the maximum discharge difference along each run obtained in the pressurization stage (Equation 3.1).

Q_{inlet2} and Q_{end2}, flow rates of sample emitters at the beginning and end of each run in the pressurized stage.

ΔV_2, the maximum discharge difference along each run obtained in the pressurized stage (Equation 3.2).

V_{avg}, the emitters' average dose volume along each run.

X%, computed application uniformity (Equation 3.4).

T_1, system discharge time in the field-scale experiment, also regarded as pressurization time, time from initiation of flow until the to the lateral end pressure reaches operational pressure.

T_2, duration of the pressurized stage, wherein the emitters drip under designed operational pressure and perform the function of uniform distribution.

T, dose time, supposing the drain down volume of depressurization is ignored (Equation 3.5).

Since areal hydraulic loading rates were expressed in terms of gallons per day per square foot of drip distribution footprint area, the application uniformity could possibly be increased by decreasing each lateral's length or increasing the number of runs per lateral. The former method reduces friction loss and thus decreases emitter flow rate variance along the tubing; the latter compensates the emitters' flow rate variance by considering several emitters' discharge in an average small distribution footprint area (calculate average application rate over greater area rather than single emitter).

Normally, emission volume from a single emitter is divided by the application area (lateral spacing × emitter spacing) to determine an areal application rate. This proposed method for calculating areal loading would consider several emitters on parallel laterals to obtain dose volume and then divide by their total associated application area (runs per lateral × lateral spacing × emitter spacing).

In this research, drip zone dose time was computed under four lateral layouts: single run, 2 runs, 3 runs, and 4 runs per lateral. Lateral lengths used are summarized in Table 3-2. Figure 3-6 illustrates different lateral layouts.

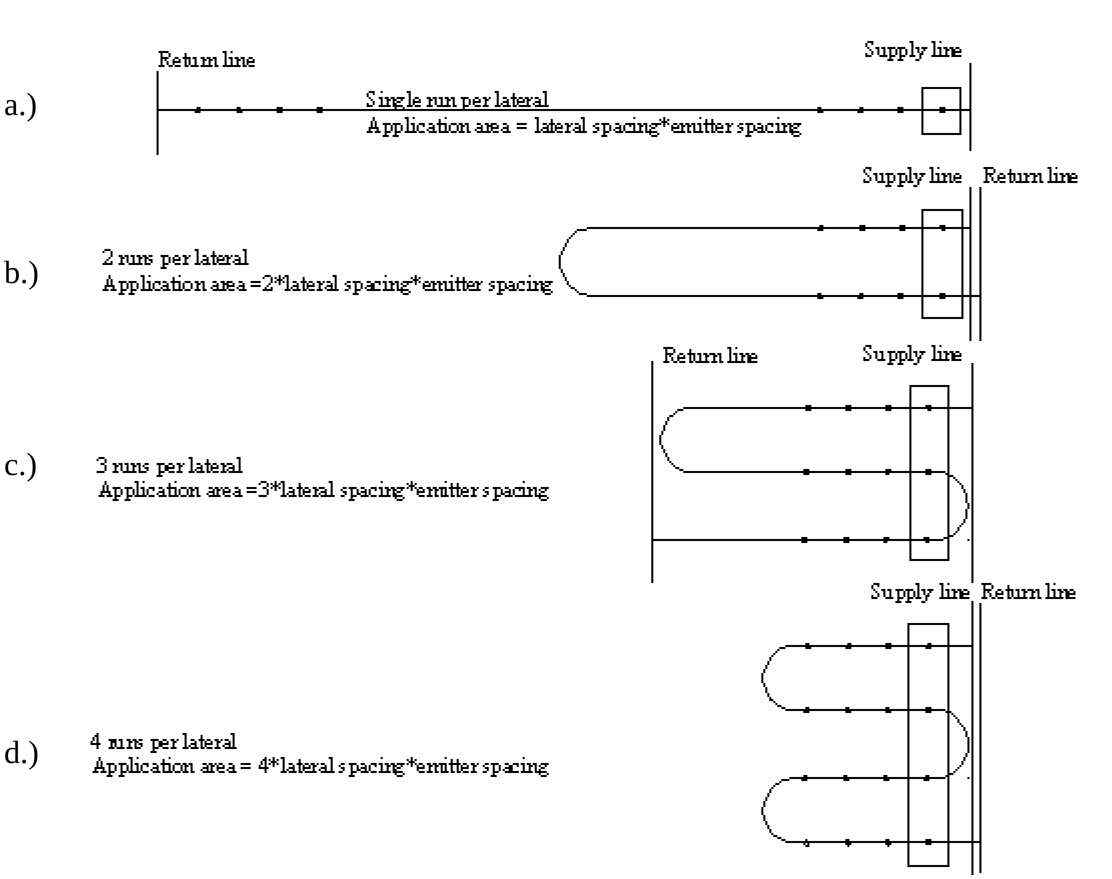

Figure 3-6 Application area demonstration for calculation of application uniformity: a) single run, b) two runs, c) three runs, d) four runs per lateral

Drip Zone Fill Time Computation and Evaluation

In field wastewater drip projects, dosing time is generally decided by maximum wastewater flow, loading rates of different soil types, and drip tubing properties. System design should incorporate acceptable emitter discharge variations associated with pressure variations due to friction and elevation changes. Thus designers need to balance several factors like characteristics of the field, pump output, system/subunit uniformity, and pressure distribution.

As a part of the pressurization stage, the sequence in which sections of the system fill with water can have a substantial effect on discharge uniformity; hence associated corrections of the system operation scheme may be necessary. The objective of this section is to compare a subsurface drip system’s fill time estimated using engineering design to that observed through field-scale experiments. In addition, this study aims to point out the variance that might exist between design and observed durations for consideration during the design processes. Estimation of system fill time is based on the assumption that system components are fully filled in sequence: first the supply line, second the manifold and last the laterals. With water flowing into each part, the friction loss adds up and influences the pump’s flow rate and working efficiency.

The computation process of drip system fill time consisted of two steps: total dynamic head (TDH) calculations and fill time computation for each component of the system. Related methods and formulae are displayed in Appendix D.

However, the computation method used in this study was only an approximation because pump rates will be greater than design estimates during the filling phase and pressures will be much lower, causing a higher pump flow rate. This tends to speed up the filling process. However, this will be at least partially offset by emitters dripping during pressurization.

RESULTS AND DISCUSSION

Experiment Data Compilation

For each selected emitter model, the dose volume and emission time during the pressurization stage for each scenario (the combination of three drip zone design factors: supply line length; drip zone operational pressures; operational pressure control schemes) are listed in Appendix B (Figures B.1 ~ B.32 and Tables B.1 ~ B.48).

In every scenario, lateral inlet and end pressures as well as the pressurization times are listed. Emission volumes at individual sampling positions along the laterals were averaged based on the three supply line lengths, and the data curves were drawn in Microsoft EXCEL. For scenarios in which data for the three supply lines were very close, an average data curve was generated and the related linear trend line drawn to simulate experimental data along the lateral length. The sample volume at the beginning of each run was found to be the greatest, while the volume at the end of each run was the least. When the curves for the three supply lines were scattered, the linear trend line was added to each curve separately. The r^2 values of the linear trend lines ranged from 0.95 to 0.91 and the slopes were negative, which indicated that sample volumes decreased with increasing distance from the run’s inlet and that this relationship between them was linear.

Statistical Analysis on Drip Zone Pressurization Time

Geoflow WFCL 164-24-500

Time required to pressurize the drip zone using Geoflow NPC emitters is presented in Tables 3-4 and 3-5. The pressurization times for the continuous flushing and pressure regulator scenarios were close (Table 3-4) (subset a); and they are on average 23 seconds shorter than the other two scenarios (subset b).

Table 3-4 Descriptive and Tukey HSD test on drip zone pressurization time for Geoflow WFCL 164-24-500 (seconds) *

Different scenarios **	N	Mean pressurization time (s)	Std. deviation	95% Confidence interval for mean	
				Lower bound	Upper bound
Scenario 1 b	9	89.56	17.60	76.04	103.10
Scenario 2 a	9	67.56	6.29	62.72	72.39
Scenario 3 b	9	87.33	7.42	81.63	93.03
Scenario 4 a	9	63.44	5.66	59.09	67.79
	36	76.97	15.40	71.76	82.19

* Means for groups in homogeneous subsets (a, b) are displayed. Mean difference significance is 0.05.
** Scenario index is available in Table 3-3.

Table 3-5 ANOVA of Geoflow WFCL 164-24-500 pressurization time (seconds) *

	Sum of squares	df	Mean square	F	Sig.
Between scenarios	4836.31	3	1612.10	14.80	0.000
Within scenarios, Between different supply lines	3484.67	32	108.90		
Total	8320.97	35			

* Time to pressurize the drip zone

For Geoflow WFCL 164-24-500, the F value was 14.80. Therefore, it was concluded that scenarios/pressure control schemes had a more crucial influence on pressurization time than did different supply line lengths. Because the residential system supply line lengths chosen for this experiment were relatively short (7.6 m/25 ft, 15.2 m/50 ft, 30.5 m /100 ft), the influence of supply line length was insignificant relative to pressurization time when compared to other zone design parameters.

Geoflow WFPC 162-24-500

The pressurization time for Geoflow PC emitters is presented in Tables 3-6, 3-7 and 3-8.

Table 3-6 Descriptive and Tukey HSD test on drip zone pressurization time of Geoflow WFPC 162-24-500 (seconds) *

Different scenarios **	N	Mean pressurization time (s)	Std. deviation	95% Confidence interval for mean	
				Lower bound	Upper bound
Scenario 2 c	9	178.56	3.13	176.15	180.96
Scenario 3 d	9	197.89	9.31	190.74	205.04
Scenario 6 c	9	180.56	9.28	173.43	187.69
Scenario 7 a	9	125.78	6.36	120.89	130.67
Scenario 8 b	9	144.00	7.26	138.42	149.58
	45	165.36	27.60	157.06	173.66

* Means for groups in homogeneous subsets (a, b, c, d) were displayed. Mean difference significance is 0.05.

* Scenario index is available in Table 3-3.

A one way ANOVA test was conducted across the five scenarios and three supply line lengths. Results are shown in Table 3-7.

Table 3-7 ANOVA of Geoflow WFPC 162-24-500 pressurization time (seconds)

	Sum of squares	df	Mean square	F	Sig.
Between scenarios	31375.42	4	7843.86	142.30	0.000
Within scenarios, Between different supply lines	2204.89	40	55.12		
Total	33580.31	44			

* Time to pressurize the drip zone.

The F ratio value of 142.30 provides evidence against the null hypothesis that the variances of between-scenario value and within-scenario value are equal. Thus, the pressurization times for the five scenarios are not equal.

The Tukey HSD (post-hoc test) multiple comparison procedure shows all possible comparisons between the three treatment groups (Table 3-6). By multiple comparisons, the five scenarios were grouped into four subsets; each comprised scenarios with statistically similar mean values (Table 3-6). The pressurization times for scenario 2 (137.89 kPa/20 psi pressure regulator) and scenario 6 (recirculation valve and 275.8 kPa/40 psi inlet pressure) were regarded as similar (subset c). The pressurization time for scenario 7 (flow restriction on return line and 275.8 kPa/40 psi end pressure) was significantly less than other pressurization times. Scenario 3 (recirculation valve and 137.9 kPa/20 psi inlet pressure) exhibited the greatest mean time to pressurize the drip zone. The time difference between scenario 3 and 7 was 72 seconds.

A two independent-sample T test was applied on Geoflow PC tubing to check different system pressures' influence on pressurization time (Table 3-8).

Table 3-8 Two independent-sample T-test on drip zone operation pressures of Geoflow WFPC 162-24-500 (seconds) *

T-test for equality of means					
t	Sig. (2-tailed)	Mean difference of pressurization time (s)	Std. error difference	95% Confidence interval of the difference	
6.140	0.001	38.11	6.21	25.59	50.63

* Time to pressurize the drip zone

According to the T-test result, the observed significance value was 0.001; thus the hypothesis that average values under two pressure groups are equal was rejected. Using higher pressure such as 275.79 kPa (40 psi) in the system could save on average 38 seconds in the pressurization stage. Therefore among the three drip zone design factors, system operational pressure and pressure control schemes had the greatest influence on pressurization time.

Netafim Bioline 08WRAM0.6-24V

The evaluation of pressurization time for Netafim PC emitters is presented in Tables 3-9, 3-10 and 3-11.

Table 3-9 Descriptive and Tukey HSD test on drip zone pressurization time of Netafim Bioline 08WRAM0.6-24V (seconds) *

Different scenarios **	N	Mean pressurization time (s)	Std. deviation	95% Confidence interval for mean	
				Lower bound	Upper bound
Scenario 1 c	9	618.56	32.30	593.75	643.36
Scenario 2 a	9	137.00	4.64	133.44	140.56
Scenario 3 a	9	181.89	4.26	178.62	185.16
Scenario 5 c	9	692.44	528.00	286.83	1098.10
Scenario 6 a	9	153.44	13.40	143.12	163.77
Scenario 7 a	9	120.78	3.87	117.81	123.75
Scenario 8 b	9	275.89	90.30	206.49	345.29
	63	311.43	296.00	236.78	386.07

* Means for groups in homogeneous subsets (a, b, c) were displayed. Mean difference significance is 0.05.
** Scenario index is available in Table 3-3.

A one way ANOVA test was conducted to compare among the seven scenarios and three supply line lengths (Table 3-10).

Table 3-10 ANOVA of Netafim Bioline 08WRAM0.6-24V pressurization time (seconds) *

	Sum of squares	df	Mean square	F	Sig.
Between scenarios	3143481.43	6	523913.57	12.74	0.000
Within scenarios, between different supply lines	2303038.00	56	41125.68		
Total	5446519.43	62			

* Time to pressurize the drip zone

The F-ratio value of 12.74 provides evidence against the null hypothesis. Pressurization times for the seven scenarios are not equal. The significance is less than 0.05, further supporting rejection of the null hypothesis.

The Tukey HSD multiple comparison procedure shows all possible comparisons between the three treatment groups. By multiple comparison, the 7 scenarios were grouped into three subsets; each comprising scenarios with statistically similar mean values. The two scenarios with flow restriction (a gate valve on supply line) and intermittent flushing exhibited the longest pressurization time, which suggests this pressure control method is not suitable for use in field settings. All other scenarios' pressurization time were classified into one subset. Except scenarios 1 and 5, scenario 7 (flow restriction, gate valve on return line and continuous flushing and 275.8 kPa/40 psi end pressure) had the shortest pressurization time and Scenario 8 (310.26 kPa/45 psi pressure regulator and intermittent flushing) had the greatest. The pressurization times of scenarios 7 and 8 had a difference of 2.5 minutes.

A two independent-sample T-test was applied on Netafim PC tubing to check the different system pressures' influence on pressurization time (Table 3-11).

Table 3-11 Two independent-samples T-test on drip zone operation pressures of Netafim Bioline 08WRAM0.6-24V (seconds) *

T-test for equality of means					
t	Sig. (2-tailed)	Mean difference of pressurization time (s)	Std. error difference	95% Confidence interval of the difference	
0.024	0.981	1.84	76.07	-150.27	153.96

* Time to pressurize the drip zone.

According to the T test, the observed significance value was 0.981, much greater than 0.05; consequently we could not reject the null hypothesis that average values under the two pressure groups are equal. The mean difference in pressurization time using 28.2 m (275.8 kPa/40 psi) and 14.1 m (137.9 kPa/20 psi) was only 1.84 seconds. Therefore, for Netafim Bioline 08WRAM0.6-24V, that operational system pressure does not appear to have a crucial influence on pressurization time. The three drip zone design factors can be sequenced by pressurization time as (from the greatest to least): operational pressure control schemes, system operational pressure, supply line length.

Drip Zone Dose Time Calculation and Summative Discussion

Dosing times for field-scale experiments were computed and listed in Tables 3-12, 3-13, 3-14. During the dosing cycle, the minimum inlet pressure for the drip field is determined based on the length of the longest drip lateral and the minimum operating pressure required at the distal end to assure uniform drip rates from the emitters. For NPC tubing, the drip rate from each emitter must also be considered. For Geoflow Wasteflow Classic with 0.6 m (24 inch) emitter spacing, the corresponding maximum lateral length is 64 m (210 ft) (Geoflow, 2004).

This study showed that, for NPC tubing, the adoption of lateral lengths up to 61 m (200 ft) cause a significant pressure along the lateral with subsequent pressure differences on emitters. The published friction loss for Geoflow NPC tubing is 33.20 kPa (3.38 m/4.8 psi) for a lateral length of 61 m (200 ft) and a flow rate of 0.0067 m^3/min (1.76 GPM) (Geoflow, 2004), which agrees with the pressure observed during the experiment. This friction loss interferes with meeting required dosing application uniformity. The maximum application uniformity that could be realized with this lateral length was 86%, with an excessively long dosing time (Table 3-12). Based on all tested factors, the length for each run should be decreased to far less than 64 m (210 ft) to keep the maximum dosing volume variation within 10%.

In the scenarios with a gate valve in the supply line and intermittent flushing, pump failure (caused by high friction loss in the system) led to very long pressurization times for tubing to reach an operation pressure of 137.9 kPa (20 psi) at the end of laterals. The results indicated gate valves in the supply line are not an appropriate option in field settings and should be avoided. Therefore evaluation of this control component/method was abandoned for Geoflow PC tubing.

Results indicated pressure regulators could be an appropriate approach to shorten dosing time and improve pressure distribution in system. This management strategy is widely applied in the field. But it is relatively hard to reach application uniformity as high as 95% with long runs of lateral because of excessive pressure loss.

Judging from single lateral computations, for NPC emitters, it is hard to reach ideal application uniformity in a short dosing time. For PC emitters, dosing times are also longer than expected and not very practical in field. Therefore computation was conducted on looped laterals with 2, 3, and 4 runs, respectively. The results are listed in Tables 3-12, 3-13, 3-14.

In Table 3-12, the scheme of 2 runs instead of a single run using NPC tubing shortened the required dose time from around 50 minutes to only a few minutes. Looping laterals also had a beneficial effect for PC tubing. By using the looped laterals, designers can greatly improve water distribution uniformity in an average footprint area with a comparatively short dose time.

Table 3-12 Drip zone dosing time for Geoflow WFCL 164-24-500 (minutes) *

Lateral layout		Single run lateral			Looped lateral (2 runs)			Looped lateral (3 runs)			Looped lateral (4 runs)		
Expected application uniformity (AU)		85%	90%	95%	85%	90%	95%	85%	90%	95%	85%	90%	95%
Scenario 1	Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure	52	------	------	2	2	2 98.4%	2 86.4%	2	3	2	2	2 100%
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	53	------	------	2	2	2 98.3%	2	2	3	2	2	2 100%
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	52	------	------	2	2	2 97.3%	2	2	3	2	2	2 100%
Scenario 4	Flow restriction (gate valve on return line) & continuous flushing & 137.9 kPa (20 psi) end pressure	55	------	------	2	2	2 99.0%	1	2	4	2	2	2 100%

* Percentage values under computed dose times represent the minimum application uniformity in this scenario/configuration of the drip zone.

Table 3-13 Drip zone dosing time for Geoflow WFPC 162-24-500 (minutes) *

Lateral layout		Single run lateral			Looped lateral (2 runs)			Looped lateral (3 runs)			Looped lateral (4 runs)		
Expected application uniformity (AU)		85%	90%	95%	85%	90%	95%	85%	90%	95%	85%	90%	95%
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	22	33	70	3	3	3 100%	4	5	8	3	3	3 100%
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	28	36	76	4	4	4 100%	4	6	9	4	4	4 100%
Scenario 6	Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure	13	19	38	3	3	3 100%	3 86.9%	4	5	3	3	3 100%
Scenario 7	Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure	16	20	47	3	3	3 100%	2 88.2%	3	5	3	3	3 100%
Scenario 8	310.26 kPa (45 psi) pressure regulator & intermittent flushing	13	19	38	3	3	3 100%	3 88.2%	3	5	3	3	3 100%

* Percentage values under computed dose times represent the minimum application uniformity in this scenario/configuration of the drip zone.

Table 3-14 Drip zone dosing time for Netafim Bioline 08WRAM0.6-24V (minutes) *

Lateral layout		Single run lateral			Looped lateral (2 runs)			Looped lateral (3 runs)			Looped lateral (4 runs)		
Expected application uniformity (AU)		85%	90%	95%	85%	90%	95%	85%	90%	95%	85%	90%	95%
Scenario 1	Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure	23	35	80	10	10	10 100%	10	10	10 95.6%	10	10	10 100%
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	14	22	50	3	3	3 100%	3	3	5	3	3	3 100%
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	17	27	78	4	4	4 100%	4	4	6	4	4	4 100%
Scenario 5	Flow restriction (gate valve on supply line) & intermittent flushing & 275.8 kPa (40 psi) end pressure	15	22	42	11	11	11 100%	11	11	11 97.9%	11	11	11 100%
Scenario 6	Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure	13	18	36	3	3	3 100%	3	3	6	3	3	3 100%
Scenario 7	Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure	9	13	26	4	4	4 100%	4	4	5	4	4	4 100%
Scenario 8	310.26 kPa (45 psi) pressure regulator & intermittent flushing	8	12	22	5	5	5 100%	5	5	5 97.4%	5	5	5 100%

* Percentage values under computed dose times represent the minimum application uniformity in this scenario/configuration of the drip zone.

Drip Zone Fill Time Computation and Evaluation

Dosing is usually the last critical step in the wastewater drip system design process. Using the model described in Appendix D, engineering computations of dose time were completed, and the results compared to drip zone filling times observed in field experiments. Results are listed in Tables 3-15, 3-16:

Table 3-15 Total dynamic head (TDH) calculation results for design examples (m)

Component		Geoflow WFPC 162-24-500			Netafim Bioline 08WRAM0.6-24V		
Supply line head loss (m)	D=0.124 m	L=7.6 m	L=15.2 m	L=30.5 m	L=7.6 m	L=15.2 m	L=30.5 m
		2.68	5.39	10.79	2.71	5.39	10.79
Manifold head loss (m)	D=0.124 m L=3.05 m	1.08			1.10		
Drip lateral friction loss (m/100 m)		5.5			5.75		
Fitting friction loss (m)	PVC tees& elbows, Orifice, valves	1.46~1.62			1.49~1.62		
	Filter	2.44			2.44		
	Pressure regulator	4.02			3.84		
	Flow meter	3.51			3.51		
Elevation Head (m)		3.05			3.05		
Zone pressure (m)		1.40			1.40		
Velocity head (m)		0.06			0.04		
Total Dynamic Head (m)		90.11	99	116.7	88.5	96.3	100.8

Table 3-16 Calculated and experimental filling times for design examples (seconds)

	Geoflow WFPC 162-24-500			Netafim Bioline 08WRAM 0.6-24V		
	Supply line length (m)			Supply line length (m)		
1. T_1	7.6	15.2	30.5	7.6	15.2	30.5
Time to fill the supply line (s)	3	6	11	2	4	10
2. T_2	Manifold length = 3.05 m			Manifold length = 3.05 m		
Time to fill the manifold (s)	2			2		
3. T_3						
Time to fill a lateral (s)	120			123		
Total fill time $T = T_1 + T_2 + T_3$ (Engineering computation) (s)	124	127	134	127	129	135
Fill time from experimental drip zone (s)	159	161	165	122	123	129

Comparing estimated fill times to those observed during experimentation, it took an average 35 seconds longer to fill the drip zone with Geoflow product than estimated. For Netafim products the estimation was close to experimental results.

Results stress the need to know basic hydraulic and materials properties for appropriate engineering design and the need to understand variance between design outcomes and actual field operation conditions. The difference between engineering computations and experimental results need to be verified. Errors in calculated values in this study were attributed to five possible sources:

- A pressure loss of 41.37 kPa (6.0 psi) was observed in this field-scale experiment while the published Netafim (2004) friction loss is 28.96 kPa (4.2 psi) for a Bioline length of 121.92 m (400 ft).
- The engineering calculation is based on the assumption that drip zone is not completely full until the lateral end pressure reaches 13.79 kPa (2 psi). In the field, systems may be filled at lower end pressures.
- It was assumed that filling of drip laterals is controlled by the inlet orifice. Further, it was assumed that water does not enter the drip lateral until it fills both the supply line and

manifold. In reality, water may enter the laterals before the manifold and supply line are fully filled.

- When the orifice equation was applied, the pressure was assumed to increase evenly from 0 to 13.79 kPa (2 psi), which may not agree with real conditions.
- It was assumed water did not exit the emitters until the drip zone is absolutely full. However observation in the field-scale experiment, indicated a small amount of water was emitted during the filling stage. This phenomenon led to a pump flow rate greater than estimated through the design process.

CONCLUSIONS

After the evaluation of drip zone pressurization time and dose time computation for several system operational scenarios, the following conclusions can be drawn:

1. The pressurization stage significantly influences the application uniformity of a dosing event. If the variance of emitted water volume is significant during pressurization, it will lead to poor distribution uniformity. Because the subsequent pressurized stage also has emission variability due to pressure difference along the lateral, the sum of two emission variances may lead to an excessive dose time for desired application uniformity.

2. According to both the experimental results and engineering computations, increase of system pressure has more effect on improving wastewater application uniformity than other management variables. In those field applications where pressure control components are used , the priority sequence of other components to improve application uniformity is: including a pressure regulator, continuous flushing, and recirculation at the pump. The residential supply

line and manifold lengths do not severely affect dose time and dose volume. The critical factors are friction loss within drip tubing and the corresponding pump performance.

3. Three operating factors were discussed in this chapter: drip zone operational pressures (137.9 kPa/20 psi or 275.8 kPa/40 psi); different drip zone pressure control schemes; and supply line length [7.6 m (25 ft), 15.2 m (50 ft), 30.5 m (100 ft)]. Among these factors, for Geoflow PC and NPC products, system operational pressure has the greatest effect on drip system application uniformity and supply line length has the least influence. For Netafim PC tubing, among all three factors, the pressure control scheme had the greatest effect on drip system application uniformity and supply line length had the least influence. The most beneficial combination of the three factors could save more than 10 minutes of dosing time to meet the required application uniformity.

4. For application of maximum lateral lengths in drip zone design, looped laterals with several runs is a valuable method to improve water application uniformity and to shorten the required dose time. For Geoflow NPC tubing, a layout using two runs per lateral requires only two minutes to obtain application uniformity above 95%, however this uniformity can not be reached when using a single run lateral. For Geoflow and Netafim PC tubing, two runs or more per lateral greatly shortened dose time.

5. As demonstrated in the design examples, gaps exist between engineering computations of pressurization time and observed during experimentation. Five possible causes based on assumptions made in the engineering calculations were attributed to this gap. However further study is needed to verify error sources and suggest changes in design methodology.

CHAPTER IV

SUMMARY

The first component of this research characterized five wastewater drip emitters within the pressure range from 0 to 310.26 kPa (45 psi). The flow rates of emitters were determined through a lab-scale experiment. Seven statistical parameters were used to evaluate the emitter's performance. The relationship of emitter's discharge rate and pressure were defined in both low pressure and normal operation pressure ranges. Exponent of each emitter model was classified based on the definitions of pressure compensating or non-pressure compensating. The results indicated that the emitters performance based on the uniformity coefficient are excellent. However the tested flow rates of four emitter models have discrepancies to the nominal discharge rates.

The second goal of this research focused on statistical evaluation of drip zone dosing cycle for the assistance of better system design. Three drip zone design factors were tested: the supply line length, operation pressure and pressure control scheme. Statistical analysis on the pressurization time indicated that for a residential family-sized wastewater drip system, among the three factors, supply line length has the least influence on the dose time required considering zone application uniformity. Computation of drip zone dose time was conducted under specific application uniformity of 85%, 90% and 95%. It was proved that using multiple runs per lateral in the field could greatly shorten drip zone dose time. There is strong correlation between dose times and dosing zone characteristics (emitter model, lateral length, lateral layout, and zone components), system pressure and pump performance. The design process should balance these factors and decrease the gap between engineering computations and field application for better treatment of wastewater.

CHAPTER V

RECOMMENDATIONS

This research provided new information on drip emitter characteristics. Data was limited to usage of new tubing and tap water. Further studies in this area should consider the wastewater quality and its influence on emitter performance. As for the design approaches of dose time and drip zone configuration to achieve specific application uniformities, there is also a need to apply the test methodology to larger scale field apparatus, not just residential, single-family size wastewater treatment system. And if possible, further research should be conducted to quantify the difference between design and field application, and to make it readily available for designers' reference.

REFERENCES

AERMOTOR S Series Owner’s manual. 2005. Aermotor. Available at www.aeromotor.com. Accessed at August, 2005.

ASAE Standards. 46th Ed. 1999. EP458. Field evaluation of microirrigation systems. St. Joseph, Mich.: ASAE.

ASAE Standards. 48th Ed. 2001. S553. Collapsible emitting hose (drip tape)-specifications and performance testing. St. Joseph, Mich.: ASAE.

ASABE Standards. 50th Ed. 2003. EP405.1. Design and installation of microirrigation systems. St. Joseph, Mich.: ASABE.

Aurasteh, M. R., M. Jafari and L. S. Willardson. 1984. Residential lawn irrigation management. *Trans. ASAE* 27(2):470-472.

Baum, M. C., M. D. Dukes and G. L. Miller. 2005. Analysis of residential irrigation distribution uniformity. *Trans. ASCE*. 131(4):336-341.

Bralts, V.F., I.P. Wu and H.M. Gitlin. 1981. Manufacturing variation and drip irrigation uniformity. *Trans. ASAE*. 24(1):113-119.

Camp, C.R. 1998. Subsurface drip irrigation: A review. *Trans. ASAE* 41(5):1353-1367.

Center for Irrigation Technology. 1998. *Irrigation system design*. CATI Publication No. 025230

Center for Irrigation Technology. 2002. *Irrigation performance report*. CATI Publication No. 020102

Clark, G.A., F.R. Lamm and D.H. Rogers. 2005. Sensitivity of thin-walled drip tape emitter discharge to water temperature. *Applied Engineering in Agriculture*. 21(5): 855-863

Cuenca, R.H. 1989. *Irrigation Systems Design: An Engineering Approach*, Englewood Cliffs, N.J. Prentice-Hall: 317-350

Drip-in Irrigation Inc. 2005. *Turbulent flow drip line*. Available at www.dripin.com/ProductFiles/pdf/DripIn_Cl_Brc.pdf. Accessed at August, 2005.

Electric Power Research Institute. 2004. *Wastewater Subsurface Drip Distribution: Peer Review Guidelines for Design, Operation, and Maintenance*, Palo Alto, Calif. and Tennessee Valley Authority, Chattanooga, Tenn:5-23

Geoflow USA, 2004. Geoflow Wastewater Design, Installation and Maintenance Guidelines, *subsurface Drip for On-site Wastewater Reuse and Disposal*. Charlotte, NC: Geoflow, Inc.:18-25.

Hills, D. J. and M. J. Brenes. 2000. Microirrigation of wastewater effluent using drip tape. *Appl. Eng. Agric*., 17(3):303-308.

Irrigation Association Water Management Committee (IA). 2002, *Drip Design in the Landscape*. Falls Church, Va.

Keller, J. and R. D. Bliesner. 1990. *Sprinkle and Trickle Irrigation*. New York: Van Nostrand Reinhold.

Kang, Y. and S. Nishiyama. 1996. Analysis of microirrigation systems using a lateral discharge equation. *Trans. ASAE* 39(3): 921-929.

Marriam, J. L. and J. Keller. 1978. *Farm Irrigation System Evaluation: A Guide for Management*. Utah State Univ., Logan, Utah: Dept. of Agricultural and Irrigation Engineering.

Netafim Irrigation, Inc. 2004. *Bioline Design Guide*. Fresno, Calif.

Persyn, R. A., 2004, Uniformity of Wastewater Dispersal Using Subsurface Drip Emitters, Master’s thesis, Texas A&M University, Dept. of Biological and Agricultural Engineering.

Pitts, D., K. Peterson, G. Gilbert and R. Fastenau. 1996. Field assessment of irrigation system performance. *Appl. Eng. Agric*., 12(3):307-313.

Ravina, I., E. Paz et al. 1992. Control of clogging in drip irrigation with stored municipal sewage effluent. Agric. Water Mgnt. 33(2):127-137.

Sadler, E. J., C. R. Camp and W. J. Busscher. 1995. Emitter flow rate changes caused by excavating subsurface microirrigation tubing. In *Proc. 5th Int'l Microirrigation Congress*, 764-767. St Joseph, Mich.: ASAE

Smajstrla, A. G. and G. A. Clark. 1992. Hydraulic performance of microirrigation drip tape emitters. ASAE paper No 92-2057. St. Joseph, Mich.:ASAE

Smesrud, J. K. and J. S. Selker. 2001. Analytical Solution for Normal Irrigation Distribution Parameters. *Trans. ASAE* 43(5):1154.

SPSS. 2004. *SigmaPlot for Windows*. Ver. 3.2. Chicago, Ill.: SPSS, Inc.

Stone, K. C., E. J. Sadler and J. A. Millen. 2005. Water flow rates from a site-specific irrigation system. *Appl. Eng. Agric*., 12(3):307-313

Trooien, T. P., A. Mahbub and F. R. Lamm. 2000. Filtration and maintenance consideration for SDI systems. Kansas State University Agricultural Experiment Station, Manhattan, KS.

Talozi, S. A. and D. J. Hills. 2001. Simulating emitter clogging in a microirrigation subunit. *Trans. ASAE* 44(6): 1503-1509.

Tyson, T. W. and L. M. Curtis. 1998. Evaluating water distribution uniformity. *Alabama Cooperative Extension System*. ANR-468.

U.S. Bureau of the Census. 2000. *1999 Census of Housing*. Washington, DC: U.S. Dept. of Commerce.

U.S. Environmental Protection Agency (EPA). 1997. *Response to Congress on Use of Decentralized Wastewater Treatment Systems*. Office of Water. EPA 832-R-97-001b.

U.S. Environmental Protection Agency (EPA), 2002. *Onsite Wastewater Treatment Systems Manual*. Office of Water. EPA 625-R-00-008.

Weynand, V. L. 2004. Evaluation of The Application Uniformity of Subsurface Drip Distribution System, Master's thesis, Texas A&M University, Department of Biological and Agricultural Engineering.

APPENDIX A

Appendix A includes the locations and flow rates data of sampling emitters under different pressures applied in Chapter II.

Table A.1 Flow rates of Geoflow WFCL 164-24-500 (ml/min)

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
Pressure= 13.79 kPa/2 psi/1.41 m										
1	23.71	23.92	23.34	23.34	23.11	25.14	25.08	20.17	23.65	23.36
2	24.18	23.22	24.21	23.52	25.07	25.15	22.93	24.37	22	23.72
3	23.96	22.79	22.99	22.64	22.46	24.53	24.34	24.81	24.35	20.86
4	23.39	24.34	23.55	23.75	22.43	21.81	23.81	22.77	21.57	23.81
5	21.36	23.25	24.32	21.24	22.77	21.2	21.89	22.2	22.23	22.41
6	24.29	25.3	23.8	22.62	23.35	21.05	23.19	25.04	22.56	24.16
Pressure= 27.58 kPa/4 psi/2.81 m										
1	30.98	37.1	35.18	33.6	29.28	31.74	36.14	30.52	32.59	32.03
2	31.07	35.7	35.91	34.6	33.91	32.29	32.06	34.31	30.64	33.82
3	34.7	31.05	35.19	34.67	35.67	35.66	30.89	32.74	32.48	34.62
4	30.95	31.17	31.02	32.5	35.92	36.65	34.58	30.38	35.73	36.42
5	32.24	33.76	29.59	35.27	30.95	36.37	37.49	33.81	32.56	30.2
6	35.07	34.55	31.82	33.66	35.14	38.02	33.53	33.9	35.11	30.68
Pressure= 41.37 kPa/6 psi/4.22 m										
1	37.97	45.7	43.12	41.36	36.18	38.76	43.82	37.59	39.44	39.27
2	38.42	43.77	44.03	42.7	41.85	39.43	39.08	42.23	37.32	41.43
3	42.5	38.12	43.1	42.52	43.65	43.18	37.57	39.96	39.19	42.3
4	38.21	38.56	37.96	40.12	44.26	44.62	42.11	37.13	43.46	44.87
5	39.82	42.27	36.62	44.4	38.41	44.2	45.79	41.25	39.62	36.88
6	43.58	42.74	39.14	41.43	43.09	46.49	40.91	40.67	41.7	37.64
Pressure= 55.16 kPa/8 psi/5.623 m										
1	43.73	52.67	49.58	47.52	41.6	44.21	50.19	42.96	45.42	45.18
2	44.19	50.02	50.86	49.06	48.11	52.9	45.05	48.38	42.95	47.78
3	48.93	43.96	49.18	48.88	50.21	49.52	43.26	46.1	44.89	48.82
4	43.84	44.36	43.65	46.05	50.85	51.41	47.4	42.5	49.88	51.48
5	45.79	48.87	41.94	51.04	45.9	50.68	52.5	47.51	45.58	42.59
6	49.78	49.18	45.05	47.87	47.74	53.88	47.31	47.34	49.43	43.25
Pressure= 68.95 kPa/10 psi/7.03 m										
1	47.7	58.86	54.75	53.43	46.77	49.96	56.73	48.99	51.06	51.06
2	49.71	56.75	55.96	55.45	54.04	51.08	50.61	54.8	48.24	53.89
3	54.57	48.87	54.36	55.22	56.19	55.94	48.66	51.88	50.64	54.7
4	48.98	49.36	47.92	51.79	57.01	57.68	54.71	47.86	56.2	57.74
5	51.06	54.69	46.36	56.49	49.04	56.83	59.08	53.79	51.26	51.21
6	55.71	54.69	49.96	55.34	55.31	60.67	53.29	53.17	54.85	48.68
Pressure= 103.42 kPa/15 psi/10.54 m										
1	59.11	71.38	67.61	64.92	57.06	60.76	68.71	59.68	62.28	61.89

Table A.1 Continued

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
2	60.67	69.35	69.3	66.98	65.87	62.09	61.33	66.66	58.69	65.52
3	67.15	59.79	67.21	66.89	68.47	67.64	58.93	63.01	53.23	66.5
4	60.09	60.43	59.38	62.75	69.19	70.07	66.26	58.05	67.8	70.56
5	62.73	67.14	57.6	69.66	59.7	69.02	71.46	64.83	62.36	58.1
6	68.19	66.78	61.43	65.53	67.64	74.12	64.12	64.85	66.53	58.91
Pressure= 137.9 kPa/20 psi/14.20 m										
1	68.37	82.65	78.11	74.94	66	68.91	79.66	69.01	72.12	72.68
2	70.07	79.96	79.69	77.26	76.17	71.3	71.15	76.98	67.94	76.97
3	77.54	69.15	77.6	76.88	78.85	78.09	68.28	73.07	71.34	77.98
4	69.66	70	68.53	72.05	79.8	80.88	76.9	78.25	78.59	81.96
5	72.23	78.08	66.47	80.14	69.27	79.78	82.66	74.77	72.02	68.28
6	78.76	76.63	71.07	75.57	78.38	85.52	74.5	74.78	77.11	69.22
Pressure= 310.26 kPa/45 psi/31.63 m										
1	101.36	122.53	114.98	110.87	97.99	103.96	117.49	102.4	106.59	106.65
2	104.21	117.35	117.05	114.13	112.9	105.71	104.69	113.5	100.29	112.48
3	106.96	102.25	114.76	114.81	116.6	115.54	101	108.4	105.78	113.28
4	102.91	104.76	103.66	107.35	118.5	119.19	113.74	99.31	116.14	119.61
5	107.14	115.23	105.04	118.56	106.9	117.64	122.37	111.4	106.65	99.77
6	116.95	114.33	107.83	112.35	111.2	126.95	110.32	111.2	114.01	101.02

Table A.2 Flow rates of Geoflow WFPC 162-24-500 (ml/min)

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
Pressure= 13.79 kPa/2 psi/1.41 m										
1	15.54	16.21	16.37	16.39	16.11	17.03	15.78	17.56	16.48	16.93
2	15.45	16.65	15.95	16.39	16.33	16.06	16.13	15.74	14.07	16.34
3	16.28	15.68	15.1	17.99	17.85	16.23	14.36	16.47	14.95	15.68
4	15.54	15.99	17.1	16.41	16.99	16.49	16.49	15.9	16.14	14.21
5	18.21	15.38	16.75	14.99	16.65	17.75	16.91	15.89	16.49	15.14
6	14.74	14.9	15.83	15.9	19.54	15.45	15.93	16.12	13.91	15.58
Pressure= 27.58 kPa/4 psi/2.81 m										
1	22.35	23.12	23.72	23.55	22.71	24.54	22.84	22.84	23.59	24.09
2	21.74	24.23	20.91	23.4	22.82	22.98	23.04	22.6	19.83	23.59
3	23.21	22.57	21.7	24.51	22.44	23.14	20.88	23.5	21.5	22.26
4	22.47	22.85	24.51	23.15	23.93	23.13	23.48	22.65	23.19	20.57
5	25.41	22.65	23.88	21.54	23.35	25.55	22.96	22.81	23.58	22.36
6	20.95	20.5	22.18	22.72	22.79	22.49	22.52	23.04	19.82	22.41
Pressure= 41.37 kPa/6 psi/4.22 m										
1	25.77	28.57	29.31	28.87	27.91	30.09	27.87	28.09	28.9	29.55
2	26.68	29.43	27.54	28.99	28.41	28.27	28.41	27.68	24.36	29
3	28.47	27.83	26.7	29.92	27.93	28.54	25.62	28.82	26.22	27.31
4	27.3	28.1	30.09	28.57	29.92	28.69	28.8	27.86	28.12	25.23
5	31.31	27.7	29.22	28.06	29.03	31.39	28.26	27.95	28.83	27.26
6	27.9	24.99	26.43	28	28.21	27.88	27.67	28.49	24.28	27.55
Pressure= 55.16 kPa/8 psi/5.62 m										
1	30.25	33.24	33.87	33.59	32.87	34.83	32.24	32.55	33.38	34.26
2	30.88	34.04	31.73	33.31	31.92	32.31	32.79	32.12	27.97	33.63

Table A.2 Continued

Sample Locations	Lateral Index									
3	32.87	32.19	30.79	34.62	32.33	32.92	28.89	33.4	30.03	31.5
4	31.55	32.53	34.87	33.09	34.48	33.07	33.33	32.34	32.74	29.31
5	36.07	32.31	33.68	32.53	33.4	36.19	32.32	32.52	33.48	31.63
6	32.17	29.09	31.2	32.21	32.74	32.43	32.31	33.29	28	32.11
Pressure= 68.95 kPa/10 psi/7.03 m										
1	32.94	36.74	37.39	37.17	36.28	38.55	36.41	34.06	35.33	37.61
2	34.25	37.35	33.4	36.89	35.78	35.54	35.63	35.11	31.35	37.07
3	36.42	35.51	32.39	37.81	35.45	36.74	28.65	35.77	30.18	34.73
4	34.9	35.79	38.72	35.69	38.04	36.69	36.7	35.36	36.44	32.59
5	39.16	35.54	34.76	35.99	35.87	39.41	32.89	35.02	36.46	35.22
6	35.73	32.09	33.75	34.08	35.3	34.95	35.79	36.45	30.95	35.81
Pressure= 103.42 kPa/15 psi/10.54 m										
1	32.47	37.61	37.02	37.99	36.29	39.1	38.61	33.14	33.65	35.91
2	36.35	36.84	31.45	37.65	34.56	37.05	34.9	33.97	32.82	36.57
3	37.6	35.79	31.15	37.65	34.35	39.19	27.06	34.15	29.23	33.75
4	35.96	35.43	40.42	34.72	38.95	36.82	37.24	35.21	37.06	34.34
5	39.71	35.46	31.92	36.12	35.51	38.22	31.18	33.99	35.62	35.56
6	36.97	32.88	33.9	33.46	34.69	34	39.42	38.1	31.24	36.25
Pressure= 137.9 kPa/20 psi/14.20 m										
1	31.69	36.88	36.28	36.39	34.65	37.97	37.47	30.63	31.95	33.39
2	36.5	35.27	30.92	35.55	31.56	35.55	33.68	32.79	32.47	35.37
3	36.4	33.8	29.99	36.42	32.5	38.69	26.79	32.76	28.21	31.83
4	35.16	33.38	38.95	32.99	36.98	35.1	35.17	32.71	36.36	33.86
5	37.45	34.13	30.68	34.32	33.6	36.54	30.13	32.55	33.77	34.39
6	34.6	32.78	32.38	32.39	33.4	32.69	35.72	37.4	31.93	34.73
Pressure= 310.26 kPa/45 psi/31.63 m										
1	34.02	39.04	31.88	29.32	32.71	41.45	42.28	30.66	33.27	34.96
2	42.82	26.37	28.56	36.68	28.88	32.21	34.65	32.28	38.28	36.67
3	34.02	35.83	30.36	35.65	32.83	37.71	29.62	32.27	31.16	31.19
4	40.95	33.12	38.49	29.49	31.14	31.34	31.59	33.06	38.21	39.66
5	34.86	36.52	26.26	37.02	33.32	34.81	32.55	31.93	34.23	35.7
6	37.91	38.72	29.92	33.17	32.1	30.7	38.46	38.01	38.87	35.17

Table A.3 Flow rates of Geoflow WFPC 164-24-500 (ml/min)

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
Pressure= 13.79 kPa/2 psi/1.41 m										
1	24.54	23.95	24.56	20.47	23.83	19.5	24.65	22.96	24.35	24.96
2	24.88	21.67	24.52	24.29	24.43	22.67	20.28	23.78	19.93	21.86
3	22.06	25.71	21.13	23.36	24.55	21.89	24.89	24.9	25.15	22.29
4	21.94	19.47	20.88	18.51	25.56	21.08	21.84	24.42	19.63	24.01
5	24.17	24.75	19.98	19.38	24.74	24.32	23.97	22.74	23.47	21.01
6	20.52	23.69	19.24	19.3	23.35	23.73	22.01	21.82	24.78	17.99
Pressure= 27.58 kPa/4 psi/2.82 m										
1	35.29	34.2	36.09	29.47	34.24	28.95	36.16	33.34	34.9	36.6
2	35.46	31.99	34.82	34.74	35.21	32.47	29.68	34.66	28.64	31.22

Table A.3 Continued

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
3	30.9	36.12	31.59	32.99	34.99	31.97	35.66	35.14	36.03	31.3
4	30.11	27.21	30.41	26.74	35.16	30.38	30.83	35.61	28.24	34.79
5	33.98	35.17	28.63	27.95	34.98	34.56	35.32	32.43	33.64	30.15
6	29.83	33.66	28.08	27.94	33.32	34.63	32.2	32.36	35.06	25.45
Pressure= 41.37 kPa/6 psi/4.22 m										
1	42.99	41.95	44.5	36.06	41.85	35.17	44.01	41.53	43.4	44.5
2	43.06	39.64	43.18	43.32	44.04	39.81	36.42	42.36	35.89	39.36
3	38.35	44.6	39.13	40.92	43.46	39.19	44	43.36	44.93	39.36
4	37.06	34.24	37.71	32.69	44.01	36.96	38.94	44.12	34.9	42.98
5	42.09	43.44	36.15	35.57	43.66	42.15	43.73	40.47	42.1	37.73
6	36.28	42.75	34.27	35.27	41.15	42.22	39.54	40.14	43.2	31.27
Pressure= 55.16 kPa/8 psi/ 5.62 m										
1	49.8	48.71	51.65	42.54	48.52	40.61	50.91	48.47	50.15	52.07
2	50.38	44.31	50.08	50.29	50.66	46.05	42.51	49.35	41.95	45.34
3	44.37	50.76	44.98	47.21	50.01	46.32	51.13	50.8	52.13	46.14
4	43.39	40.24	43.76	37.3	51.56	43.21	44.78	50.88	41.89	50.15
5	48	49.93	41.62	41.06	50.02	49.18	50.83	47.42	48.18	44.28
6	42.34	49.31	40.38	40.7	47.38	49.42	45.71	46.75	49.84	37.17
Pressure= 68.95 kPa/10 psi/7.03 m										
1	55.69	53.34	57.47	47.32	54.71	46.47	57.37	54.76	57.05	59.07
2	56.1	49.65	56.7	56.22	57.37	52.65	48.04	55.67	47.57	50.98
3	50.01	55.76	51.76	52.35	56.79	51.79	57.23	57.07	59.32	51.6
4	48.33	44.15	48.74	42.78	57.2	49.09	51.41	57.09	46.44	56.1
5	54.67	54.94	46.91	46.23	56.72	54.96	57.09	53.04	54.5	49.35
6	47.51	54.27	45.75	46.11	52.53	55.04	51.98	49.68	57.19	41.8
Pressure= 103.42 kPa/15 psi/10.54 m										
1	62.03	62.59	63.93	49.31	60.98	53.25	64.2	62.57	60.56	65.67
2	62.56	57.84	61.88	59.35	64.26	57.81	53.95	61.02	49.25	53.91
3	55.39	62.88	56.53	58.17	65.3	57.17	64.93	60.83	65.51	57.43
4	53.86	50.63	55.39	47.4	61.37	54.4	57.98	60.88	50.47	62.77
5	58.96	63.58	53.06	51.24	62.11	60.86	63.92	57.32	53.94	54.84
6	53.72	64.05	50.93	50.6	58.28	63.8	57.4	58.71	64.81	46.91
Pressure= 137.9 kPa/20 psi/14.20 m										
1	62.55	62.11	64.22	48.6	59.3	53.34	62.42	62.06	59.63	65.18
2	61.62	58.22	62.63	61.51	63.63	57.31	52.83	60.32	49.92	54.17
3	55.27	61.59	57	58.13	64.39	57.36	63.6	60.24	64.64	56.58
4	53.8	51.69	55.46	46.87	59.94	54.52	58.21	61.02	50.6	60.91
5	58.09	62.5	52.11	51.54	60.44	60.02	62.65	56.91	53.84	55.52
6	54.31	63.99	51.14	50.61	57.46	61.26	59.5	58.4	63.64	46.92
Pressure= 310.26 kPa/45 psi/31.63 m										
1	63.7	60.97	68.99	53.76	62.76	51.4	66.68	63.51	50.04	60.6
2	62.39	58.12	65.68	63.88	64.82	54.38	55.56	60.53	49.69	56.93
3	61.81	64.74	59.9	55.62	64.61	62.81	64.89	56.47	62.65	56.96
4	55.1	57.98	55.3	47.27	64.26	56.93	58.8	65.45	45.65	64.35
5	53.87	64.68	54.17	58.24	63.92	62.99	63.88	61.83	57.64	60.02
6	54.7	64.65	53.84	51.07	56.28	56.35	58.94	61.38	62.72	48.85
Pressure= 13.79 kPa/2 psi/1.41 m										

Table A.4 Flow rates of Netafim Bioline 08WRAM0.6-24V (ml/min)

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
1	29.51	33.64	34.27	32.56	33.6	30.78	29.75	29.15	38.04	24.96
2	29.18	29.52	32.98	29.39	26.49	28.38	28.97	29.49	32.07	21.86
3	29.47	29.12	28.87	34.18	29.56	30.6	27.9	31.22	31.91	22.29
4	32.04	30.38	28.75	28.73	27.81	27.41	34.73	33.87	32.88	24.01
5	28.77	30.55	30.12	32.92	32.27	29.95	33.93	30.69	30.6	21.01
6	29.4	27.54	30.41	29.52	29.59	29.45	30.32	30.29	29.36	17.99
Pressure= 27.58 kPa/4 psi/2.81 m										
1	43.58	35.81	43.8	44.84	43.55	44.64	41.1	39.17	37.96	43.52
2	42.5	38.51	37.89	42.59	39.26	35.2	37.18	38.31	37.12	42.32
3	38.45	38.37	38.69	38.6	44.57	39.05	39.57	36.79	39.96	40.89
4	37.78	41.68	38.91	38.04	38.68	35.91	36.59	42.09	43.34	41.17
5	40.13	36.69	39.37	38.79	43.85	42.41	38.51	44.86	40.67	38.44
6	36.39	39.1	36.1	38.58	39.17	39.31	36.45	39.38	39.83	38.52
Pressure= 41.37 kPa/6 psi/4.22 m										
1	45	40.52	45.56	46.8	44.73	46.07	42.02	42.25	41.68	46.61
2	44.69	41.8	41.91	45.49	43.45	40.33	39.96	42.09	40.91	46.8
3	42.15	41.63	42.4	40.8	45.91	41.39	41.68	41.56	42.71	42.89
4	41.73	45.18	40.97	42.77	42.61	40.44	40.87	43.79	46.66	42.75
5	42.55	40.89	43.39	41.68	45.64	44.77	41.46	46.56	43.67	42.91
6	41.44	42.91	41.44	41.01	43.27	42.02	41.16	41.59	41.98	42.47
Pressure= 55.16 Kpa/8 psi/5.62 m										
1	44.67	40.81	45.37	46.46	44.21	45.12	41.35	41.92	41.82	47.55
2	44.36	41.71	41.81	44.56	43.55	40.4	39.66	41.96	41.85	50.47
3	42.36	41.38	42.43	40.55	45.6	40.78	41.56	41.89	41.74	43.23
4	42.16	45.03	40.73	42.76	42.64	40.71	41.2	42.72	46.33	43.03
5	41.88	41.07	43.58	42.83	45.11	44.06	41.08	46	43.2	43.12
6	41.65	44.47	41.45	40.66	43.24	41.4	41.72	41.13	41.67	42.54
Pressure= 68.95 kPa/10 psi/7.03 m										
1	43.98	40.41	44.55	44.99	43.28	44.04	40.67	41.35	41.75	48.06
2	43.42	41.21	41.56	44.15	42.95	40.22	39.13	41.62	40.77	50.05
3	41.55	40.89	41.7	40.12	45.01	40.04	40.99	41.41	41.32	42.05
4	41.03	44.42	40.3	42.45	42.24	40.08	40.6	41.89	45.27	41.99
5	41.74	40.55	42.91	40.99	44.58	44.09	40.46	45.51	42.65	42.13
6	41.05	43.18	41.18	40.07	42.79	40.91	41.13	40.64	40.82	41.51
Pressure= 103.42 kPa/15 psi/10.54 m										
1	42.68	40.01	42.88	44.34	41.92	42.64	39.66	40.51	40.28	48.57
2	42.75	40	40.56	42.92	41.34	39.02	38.19	40.54	40.45	46.29
3	40.5	39.88	41.19	39.17	43.44	38.89	39.87	40.37	40.71	42.38
4	40.39	42.89	40.13	41.88	41.02	39.24	39.88	40.77	44.4	41.55
5	40.85	39.82	42.1	40.29	43.15	43.08	39.47	44.34	42.08	41.11
6	40.83	42.07	40.26	38.86	41.59	39.64	40.07	39.37	40.28	40.53
Pressure= 137.9 kPa/20 psi/14.20 m										
1	42.34	40.18	43.06	43.7	41.21	41.26	38.39	39.51	39.06	47.52
2	41.92	40.92	39.67	42.4	40.35	38.01	38.67	39.3	39.4	44.65
3	40.05	39.78	40.85	39.12	42.46	38.82	39.75	39.93	39.68	40.65
4	40.1	42.68	39.4	41.82	40.69	39.14	39.67	40.28	42.56	40.38
5	40.1	39.49	41.83	39.38	42.27	41.44	39.03	42.54	40.74	40.65

Table A.4 Continued

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
6	39.94	41.38	39.87	38.38	40.78	38.76	40	38.66	39.2	40.01
Pressure= 310.26 kPa/45 psi/31.63 m										
1	40.08	43.44	42.36	39.53	42.22	39.99	40.61	39.72	45.06	60.6
2	35.73	39.13	41.27	41.45	39.26	39.2	40.24	39.22	41.18	56.93
3	40.37	40.73	39.35	42.37	38.96	38.4	39.79	40.1	35.89	56.96
4	41.05	39.6	40.14	40.87	39.62	40.47	38.56	42.02	41.65	64.35
5	40.19	40.67	40.16	41.86	41.32	38.82	41.45	41.32	40.96	60.02
6	41.41	40.71	39.29	40.17	38.84	40.35	39.06	39.3	41.87	48.85

Table A.5 Flow rates of Netafim Bioline 08WRAM1.0-12500 (ml/min)

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
Pressure= 13.79 kPa/2 psi/1.41 m										
1	46.63	43.01	43.13	41.74	44.23	45.19	49.22	43.79	50.69	55.97
2	42.67	44.7	46.93	44.38	43.85	46.8	47.2	44.21	48.15	52.51
3	45.87	40.47	42.55	41.15	42.85	44.65	44.08	41.55	43.07	42.42
4	43.81	43.35	43.66	48.45	43.15	44.62	43.77	45.78	45.11	44.4
5	42.89	47.47	43.52	41	46.36	43.54	43.7	44.03	42.06	42.08
6	42.92	42.77	46.32	42.74	47.39	46.74	44.65	41.94	48.38	42.81
Pressure= 27.58 kPa/4 psi/2.81 m										
1	58.21	55.51	56.25	54.92	56.53	62.97	60.59	57.84	58.04	60.16
2	54.98	58.92	58.6	60.23	57.3	62.23	57.9	57.33	58.17	60.08
3	56.51	54.57	55.31	55.21	56.66	58.15	56.41	54.63	54.7	54.59
4	57.29	56.77	55.87	61.34	55.59	58.89	55.97	59.98	57.32	56.94
5	55.92	59.6	58.01	54.46	60.26	57.39	57.28	58.49	56.14	56.17
6	54.76	55.75	57.01	57.06	61.37	56.28	58.16	55.7	56.57	55.32
Pressure= 41.37 kPa/6 psi/4.22 m										
1	60.7	57.32	59.06	58.76	59.04	65.5	62.06	60.62	62.39	63.98
2	57.6	61.21	60.84	61.78	60.04	64.11	60.37	61.14	59.93	62.94
3	59.13	59.65	58.16	59.24	59.77	61.28	59.08	58.89	58.61	58.99
4	60.1	59.23	58.41	60.93	60.5	61.11	59.35	64.16	60.97	62.31
5	58.72	60.96	59.26	57.74	60.75	61.48	59.3	61.31	60.35	62.32
6	59.57	60.7	60.24	58.03	64.17	61.09	59.59	58.95	61.17	60.18
Pressure= 55.16 kPa/8 psi/5.62 m										
1	59.9	57.36	58.51	57.98	58.39	64.53	61.56	60.2	61.85	62.91
2	57.28	60.57	61.65	60.93	59.48	64.55	60.23	60.16	59.44	61.15
3	58.78	59	57.63	58.72	59.1	60.09	58.13	58.49	59.24	58.2
4	59.45	58.63	57.81	60.91	59.93	60.64	58.54	63.74	60.09	61.78
5	58.55	59.48	58.33	56.12	59.73	60.47	59	60.65	60.2	60.72
6	59.21	59.98	58.7	57.61	63.15	60.16	59.5	58.74	62.05	59.58
Pressure= 68.95 kPa/10 psi/7.03 m										
1	59.47	56.86	57.76	57.32	58.86	63.64	62.46	59.2	61.33	61.1
2	56.77	60.39	58.45	60.37	59.42	64.04	59.76	59.56	59.27	60.29
3	58.34	58.45	56.97	58.15	58.73	59.04	57.74	57.82	58.24	58.1
4	59.16	57.84	57.26	60.65	59.03	59.61	57.83	63.16	60.21	61.09
5	58.14	59.2	57.95	55.31	59.43	59.95	58.87	59.85	58.9	60.18
6	58.99	59.82	59.09	56.59	63.06	59.77	59.12	57.68	60.68	58.71

Table A.5 Continued

Sample Locations	Lateral Index									
	A	B	C	D	E	F	G	H	I	J
Pressure= 103.42 kPa/15 psi/10.54 m										
1	58.65	55.07	56.74	55.92	57.63	62.28	60.23	58.34	57.15	59
2	55.57	58.45	56.75	60.15	57.54	65	58.8	58.44	57.71	60.31
3	56.9	56.79	55.64	56.32	57.13	57.81	55.87	56.49	55.45	56.21
4	57.28	56.02	55.35	61.02	56.62	58.24	56.52	61.01	55.83	59.54
5	57.45	57.86	57.12	53.44	57.69	58.16	57.41	58.7	55.69	58.87
6	58.55	58.21	57.38	55.22	60.25	57.92	58.09	56.31	57.41	56.67
Pressure= 137.9 kPa/20 psi/14.20 m										
1	57.49	54.8	56.77	54.02	57.07	61.41	60.96	60.16	57.91	58.47
2	54.81	58.73	59	60.22	55.67	63.93	58.76	57.76	59.61	60.33
3	56.06	57.83	54.7	55.27	57.43	57.14	56.37	56.46	57.6	54.68
4	56.12	56.18	53.54	60.02	55.72	58.18	54.91	60.53	56.07	55.98
5	56.51	58.56	56.68	52.92	58.09	57.65	57.66	57.5	55.48	57.06
6	55.77	57.43	56.34	54.96	64.94	59.48	60.39	55.69	58.53	55.23
Pressure= 310.26 kPa/45 psi/31.63 m										
1	62.77	57.09	60.03	58.39	57.98	65.81	67.25	62.29	59.53	59.52
2	58.83	61.66	60.48	65.11	63.31	70.25	63.07	58.9	62.41	62.32
3	61.8	64.45	56.68	57.17	61.12	59.87	61.47	63.39	58	55.53
4	56.69	59.91	55.29	62.02	56.38	59.5	56.26	62.36	61.42	59.16
5	57.04	63.42	60.35	54.5	63.47	63.44	61.95	60.36	57.3	63.21
6	57.46	57.59	57.56	58.41	69.28	61.74	63.24	55.97	59.17	58.69

APPENDIX B

Appendix B includes the sample volume data of three types of emitters in different scenarios applied in Chapter III and corresponding pump performance data.

Geoflow WFCL 164-24-500

Scenario 1: Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure

Table B.1 Pressurization time (scenario 1, Geoflow WFCL 164-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	172.38	173.06	174.44
End Pressure (kPa)	137.90	137.90	137.90
Time (min:sec)	1: 07	1: 35	1: 46

Table B.2 Water samples (ml) (scenario 1, Geoflow WFCL 164-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	Average
Inlet	56.51	65.97	67.45	63.31
12.2 m (40 ft)	44.59	54.82	55.67	51.69
24.4 m (80 ft)	33.14	41.12	43.02	39.09
36.6 m (120 ft)	25.46	32.36	34.27	30.69
48.8 m (160 ft)	17.81	26.10	28.89	24.27
End	11.01	18.99	19.67	16.56

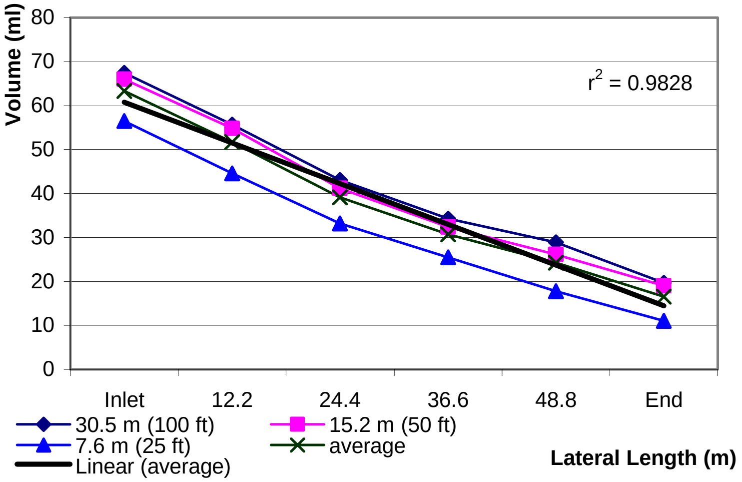

Figure B.1 Water emitted between 0 and 14.1 m (20 psi) (scenario 1, Geoflow WFCL 164-24-500)

Table B.3 Pump flow rate (m^3/hour) (scenario 1, Geoflow WFCL 164-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
15	4.35	3.53	3.80
30	4.14	3.43	3.65
45	4.02	3.36	3.53
60	3.95	3.31	3.47
68	3.62	3.31	3.47
75		3.29	3.41
90		3.00	3.25
95		2.83	3.25
107			2.94

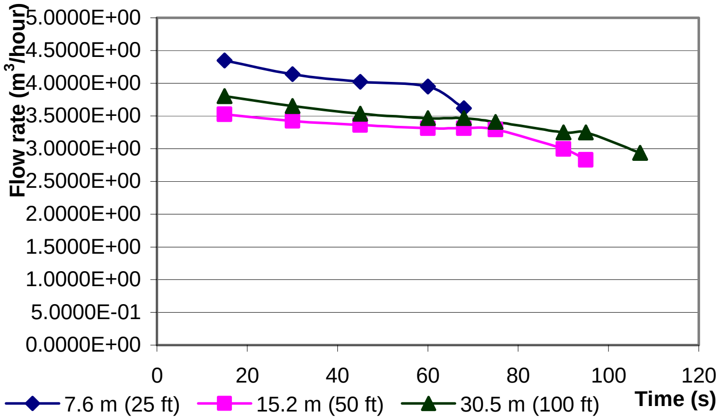

Figure B.2 Pump performance (scenario 1, Geoflow WFCL 164-24-500)

Scenario 2: 137.9 kPa (20 psi) pressure regulator & intermittent flushing

Table B.4 Pressurization time (scenario 2, Geoflow WFCL 164-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	137.90	137.90	137.90
End Pressure (kPa)	112.38	110.32	103.42
Time (min:sec)	1: 02	1: 05	1: 16

Table B.5 Water samples (ml) (scenario 2, Geoflow WFCL 164-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	Average
Inlet	56.72	55.77	57.76	56.75
12.2 m (40 ft)	45.24	43.42	45.16	44.61
24.4 m (80 ft)	30.60	29.12	30.09	29.93
36.6 m (120 ft)	21.05	19.10	20.08	20.08
48.8 m (160 ft)	14.89	13.44	13.97	14.10
End	8.48	6.50	7.72	7.57

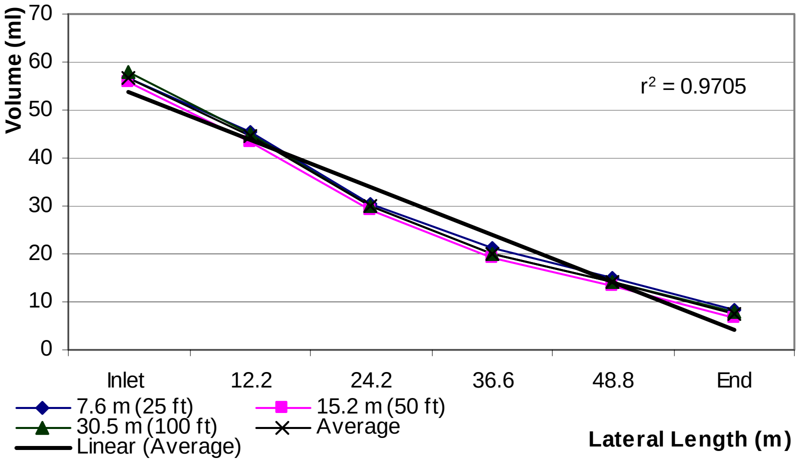

Figure B.3 Water emitted between 0 and end pressure (scenario 2, Geoflow WFCL 164-24-500)

Table B.6 Pump flow rate (m^3/hour) (scenario 2, Geoflow WFCL 164-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	5.32	4.98	5.26
15	5.06	4.93	5.06
30	4.66	4.43	4.45
45	4.2	4.02	3.9
60	3.7	3.87	3.72
62	3.7	3.86	3.71
65		3.83	3.63
75			3.49
77			3.46

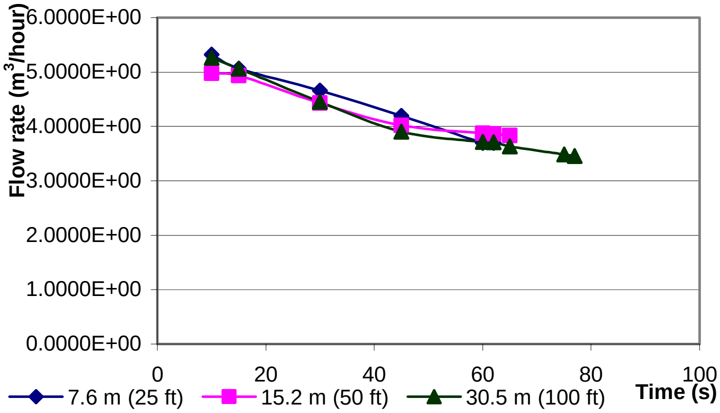

Figure B.4 Pump performance (scenario 2, Geoflow WFCL 164-24-500)

Scenario 3: Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure

Table B.7 Pressurization time (scenario 3, Geoflow WFCL 164-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	137.90	137.90	137.90
End Pressure (kPa)	106.87	102.73	97.91
Time (min:sec)	1: 20	1: 25	1: 26

Table B.8 Water samples (ml) (scenario 3, Geoflow WFCL 164-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	61.49	61.04	61.06	61.20
12.2 m (40 ft)	51.73	46.65	47.10	48.49
24.4 m (80 ft)	35.91	34.13	33.97	34.67
36.6 m (120 ft)	25.55	23.70	23.85	24.37
48.8 m (160 ft)	19.02	16.72	16.50	17.41
End	11.99	10.23	10.71	10.97

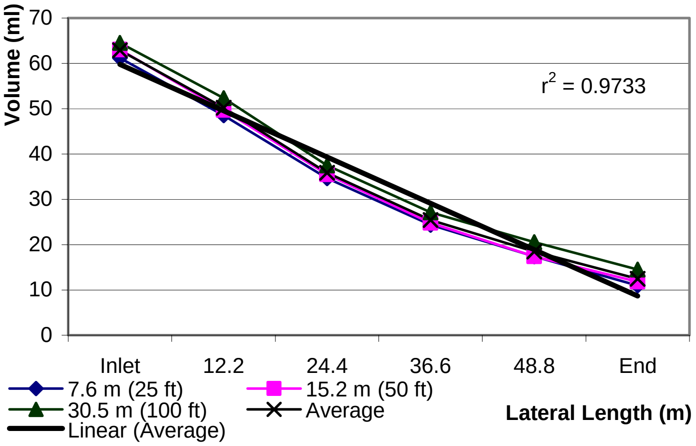

Figure B.5 Water emitted between 0 and end pressure (scenario 3, Geoflow WFCL 164-24-500)

Table B.9 Pump flow rate (m^3/hour) (scenario 3, Geoflow WFCL 164-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.53	4.56	4.26
15	4.33	4.27	4.12
30	3.79	3.75	3.65
45	3.61	3.53	3.4
60	3.51	3.43	3.28
75	3.16	3.36	3.2
85	2.63	2.56	2.86
90	2.61	2.67	2.71
95			2.4
98			2.4

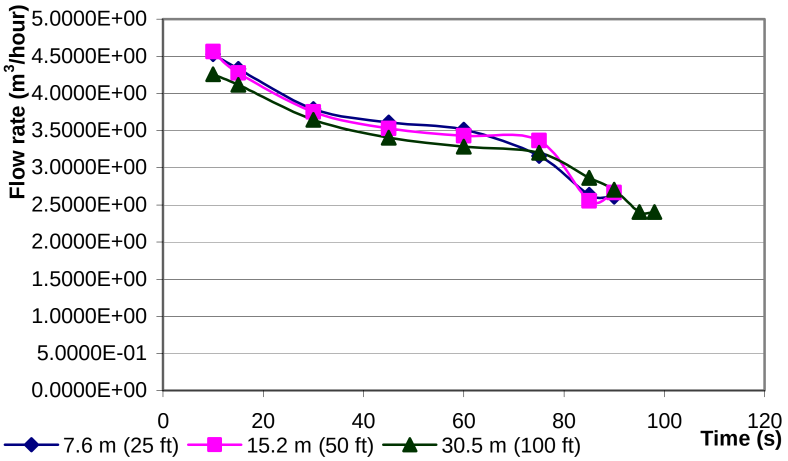

Figure B.6 Pump performance (scenario 3, Geoflow WFCL 164-24-500)

Scenario 4: Flow restriction (gate valve on return line) & continuous flushing & 137.9 kPa (20 psi) end pressure

Table B.10 Pressurization time (scenario 4, Geoflow WFCL 164-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	237.18	239.94	239.25
End Pressure (kPa)	137.90	137.90	137.90
Time (min:sec)	1: 01	0: 59	1: 11

Table B.11 Water samples (ml) (scenario 4, Geoflow WFCL 164-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	65.98	65.42	71.14	67.51
12.2 m (40 ft)	53.30	53.57	57.42	54.76
24.4 m (80 ft)	37.86	37.77	42.00	39.21
36.6 m (120 ft)	27.42	27.46	31.50	28.79
48.8 m (160 ft)	21.26	20.78	25.00	22.35
End	15.57	15.24	18.95	16.59

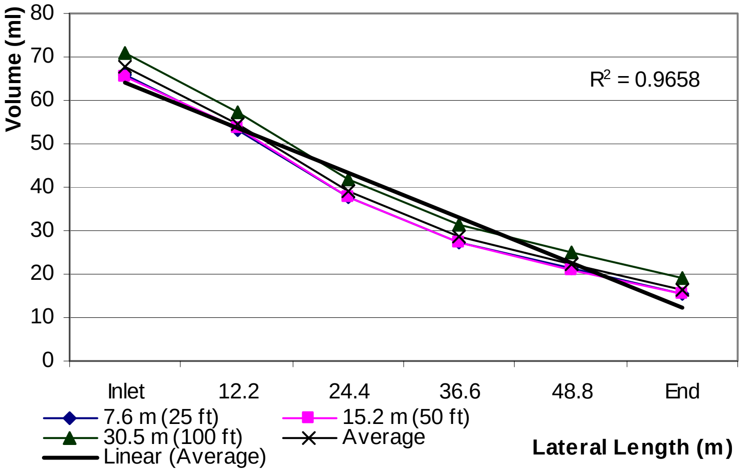

Figure B.7 Water emitted between 0 and 14.1 m (20 psi) (scenario 4, Geoflow WFCL 164-24-500)

Table B.12 Pump flow rate (m^3/hour) (scenario 4, Geoflow WFCL 164-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	5.86	5.63	5.67
15	5.55	5.38	5.29
30	5.10	5.00	4.92
45	4.92	4.83	4.72
60	4.23	4.22	4.45
62	4.22		4.44
68			4.24
72			4.02

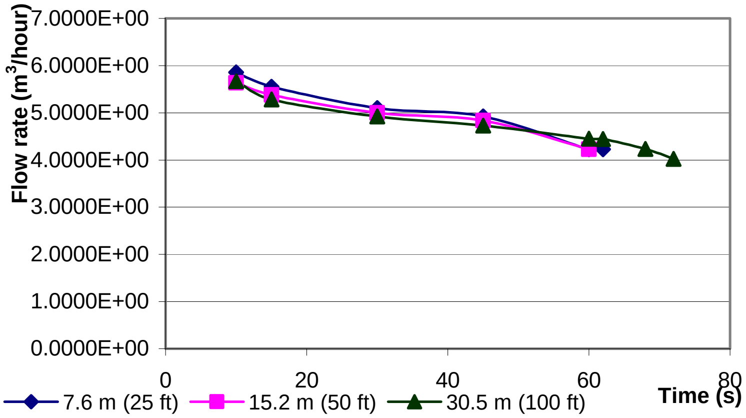

Figure B.8 Pump performance (scenario 4, Geoflow WFCL 164-24-500)

Geoflow WFPC 162-24-500

Scenario 2: 137.9 kPa (20 psi) pressure regulator & intermittent flushing

Table B.13 Pressurization time (scenario 2, Geoflow WFPC 162-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	144.79	144.79	146.86
End pressure (kPa)	62.05	62.05	62.05
Time (min:sec)	2 :56	2: 56	3: 03

Table B.14 Water samples (ml) (scenario 2, Geoflow WFPC 162-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	99.46	99.98	102.70	100.70
24.4 m (80 ft)	98.63	98.12	100.3	99.02
48.8 m (160 ft)	77.35	77.15	77.79	77.43
73.2 m (240 ft)	44.31	43.89	44.81	44.33
97.6 m (320 ft)	27.36	26.40	27.22	26.99
End	13.35	12.04	12.93	12.77

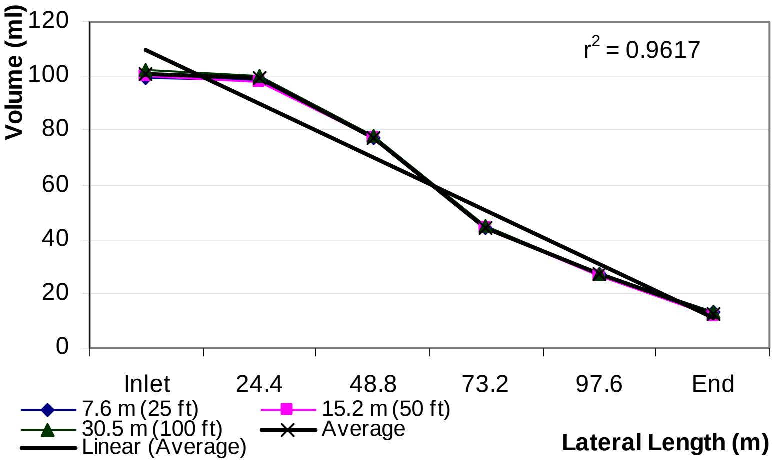

Figure B.9 Water emitted between 0 and end pressure (scenario 2, Geoflow WFPC 162-24-500)

Table B.15 Pump flow rate (m^3/hour) (scenario 2, Geoflow WFPC 162-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	3.34	4.00	3.86
15	2.77	2.75	2.75
30	2.22	2.24	2.18
45	2.03	2.04	2.00
60	1.93	1.93	1.91
75	1.87	1.87	1.83
90	1.83	1.82	1.80
105	1.80	1.80	1.77
120	1.78	1.78	1.75
135	1.77	1.76	1.74
150	1.76	1.75	1.73
165	1.61	1.68	1.72
175	1.46	1.44	1.61
180			1.45
182			1.45

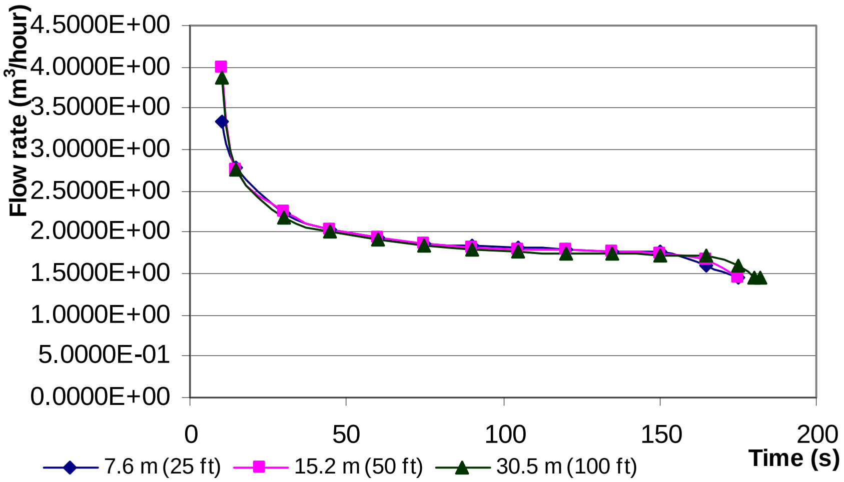

Figure B.10 Pump performance (scenario 2, Geoflow WFPC 162-24-500)

Scenario 3: Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure

Table B.16 Pressurization time (scenario 3, Geoflow WFPC 162-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	137.89	137.89	137.89
End Pressure (kPa)	62.05	62.05	62.05
Time (min:sec)	3 :09	3: 15	3: 30

Table B.17 Water samples (ml) (scenario 3, Geoflow WFPC 162-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	107.93	108.68	114.8	110.47
24.4 m (80 ft)	99.47	100.49	104.06	101.34
48.8 m (160 ft)	70.32	71.46	75.21	72.33
73.2 m (240 ft)	38.53	39.30	43.18	40.34
97.6 m (320 ft)	18.97	21.24	23.49	21.23
End	6.20	7.78	11.42	8.47

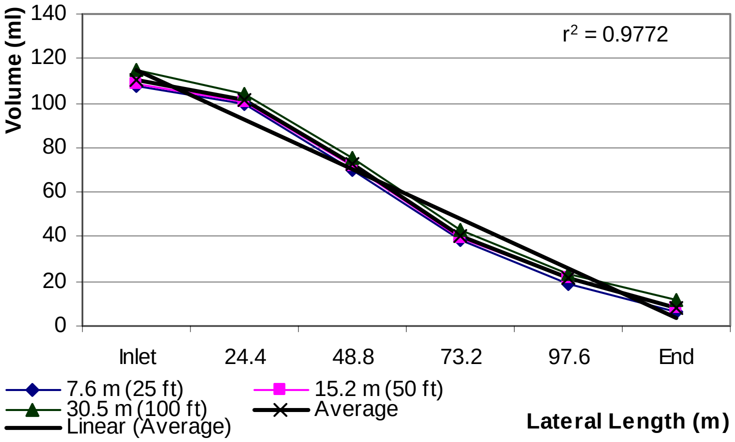

Figure B.11 Water emitted between 0 and end pressure (scenario 3, Geoflow WFPC 162-24-500)

Table B.18 Pump flow rate (m^3/hour) (scenario 3, Geoflow WFPC 162-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	3.59	4.16	4.02
15	2.77	3.27	3.70
30	2.13	2.24	2.34
45	1.94	1.99	2.00
60	1.83	1.86	1.86
75	1.78	1.79	1.78
90	1.74	1.74	1.74
105	1.71	1.71	1.70
120	1.69	1.69	1.68
135	1.68	1.68	1.66
150	1.66	1.66	1.65
165	1.66	1.66	1.64
180	1.65	1.65	1.64
195	1.48	1.46	1.61
208			1.43

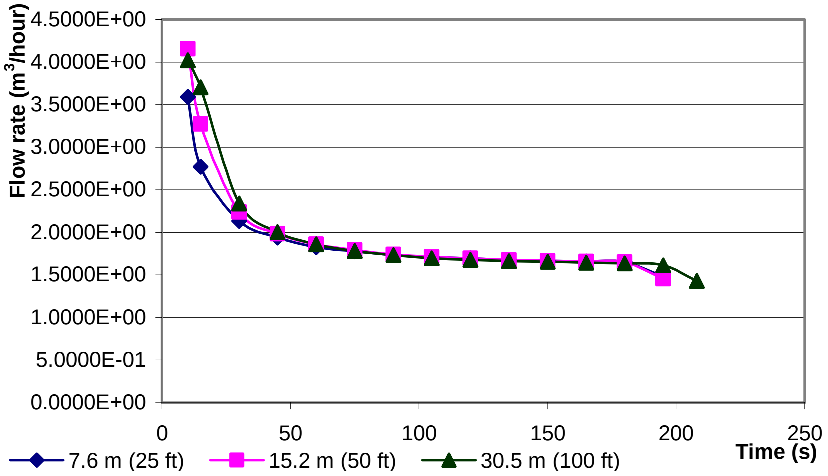

Figure B.12 Pump performance (scenario 3, Geoflow WFPC 162-24-500)

Scenario 6: Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure

Table B.19 Pressurization time (scenario 6, Geoflow WFPC 162-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	387.49	389.55	388.17
End Pressure (kPa)	275.79	275.79	275.79
Time (min:sec)	2: 03	2: 01	2: 14

Table B.20 Water samples (ml) (scenario 6, Geoflow WFPC 162-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	73.85	71.27	78.95	74.69
24.4 m (80 ft)	66.45	64.39	71.26	67.37
48.8 m (160 ft)	66.31	62.00	67.30	65.20
73.2 m (240 ft)	47.13	45.77	52.55	48.48
97.6 m (320 ft)	29.99	28.21	34.81	31.01
End	18.82	16.75	23.45	19.67

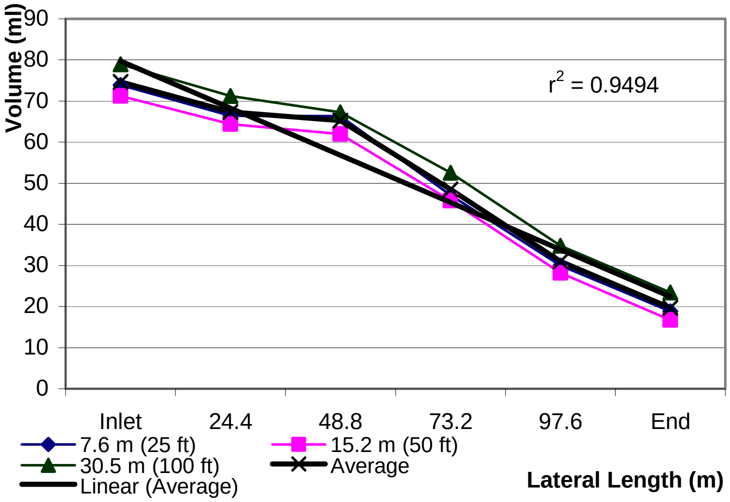

Figure B.13 Water emitted between 0 and end pressure (scenario 6, Geoflow WFPC 162-24-500)

Table B.21 Pump flow rate (m^3/hour) (scenario 6, Geoflow WFPC 162-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.47	4.15	4.45
15	3.71	3.63	3.86
30	3.04	3.01	3.00
45	2.78	2.76	2.73
60	2.65	2.63	2.61
75	2.57	2.55	2.52
90	2.51	2.51	2.48
105	2.15	2.19	2.41
120	1.65	1.65	1.64
124	1.64	1.69	1.62
135			1.62
147			1.61

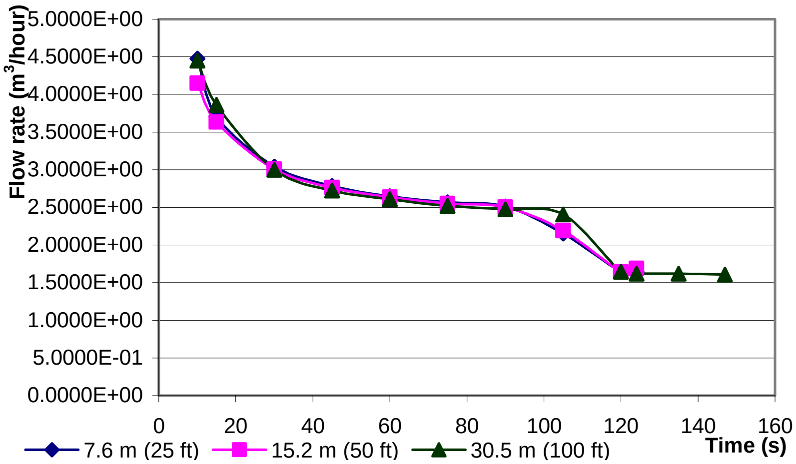

Figure B.14 Pump performance (scenario 6, Geoflow WFPC 162-24-500)

Scenario 7: Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure

Table B.22 Pressurization time (scenario 7, Geoflow WFPC 162-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	277.17	277.86	275.79
End pressure (kPa)	213.74	210.29	208.22
Time (min:sec)	2: 50	3:12	3: 00

Table B.23 Water samples (ml) (scenario 7, Geoflow WFPC 162-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	94.92	106.7	97.09	99.56
24.4 m (80 ft)	90.71	101.7	91.77	94.71
48.8 m (160 ft)	85.62	98.07	85.83	89.84
73.2 m (240 ft)	56.32	66.42	56.02	59.59
97.6 m (320 ft)	38.81	49.51	38.43	42.25
End	28.17	39.08	27.87	31.71

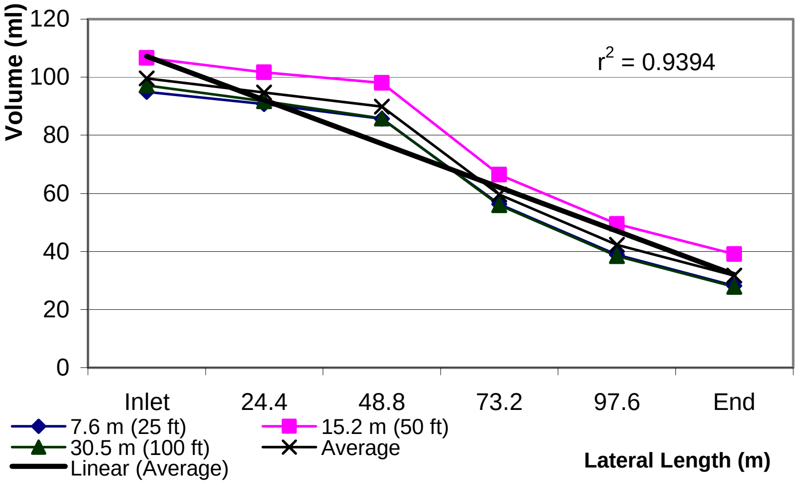

Figure B.15 Water emitted between 0 and 28.2 m (40 psi) (scenario 7, Geoflow WFPC 162-24-500)

Table B.24 Pump flow rate (m^3/hour) (scenario 7, Geoflow WFPC 162-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	3.97	4.93	4.75
15	3.27	3.91	4.20
30	2.63	2.73	2.77
45	2.41	2.45	2.45
60	2.27	2.29	2.29
75	2.21	2.22	2.21
90	2.17	2.17	2.16
105	2.14	2.13	2.12
120	2.12	2.11	2.10
135	1.84	2.09	2.08
150	1.38	1.42	1.57
165	1.37	1.36	1.37
180	1.36	1.36	1.36
196		1.35	

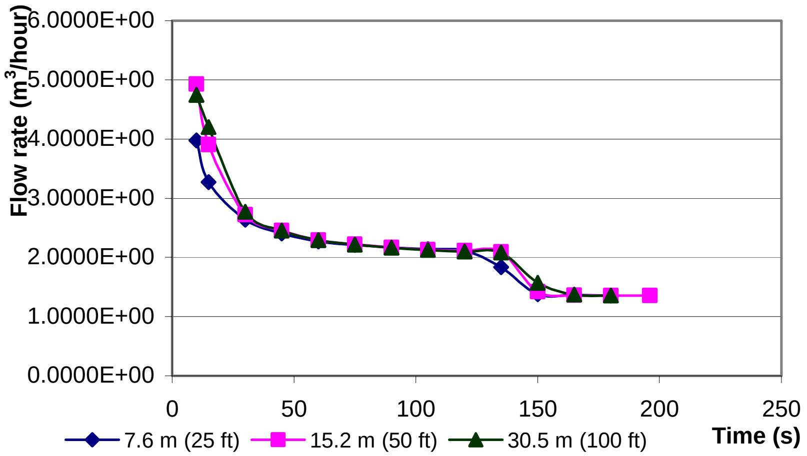

Figure B.16 Pump performance (scenario 7, Geoflow WFPC 162-24-500)

Scenario 8: 310.26 kPa (45 psi) pressure regulator & intermittent flushing

Table B.25 Pressurization time (scenario 8, Geoflow WFPC 162-24-500)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	313.71	310.26	310.26
End Pressure (kPa)	244.76	243.38	239.94
Time (min:sec)	2: 17	2: 21	2: 33

Table B.26 Water samples (ml) (scenario 8, Geoflow WFPC 162-24-500)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	80.26	81.85	87.79	83.3
24.4 m (80 ft)	74.39	77.31	80.94	77.55
48.8 m (160 ft)	69.6	76.71	76	74.1
73.2 m (240 ft)	51.51	53.71	58.5	54.58
97.6 m (320 ft)	32.61	35.38	39.01	35.66
End	22.08	24.22	28.53	24.94

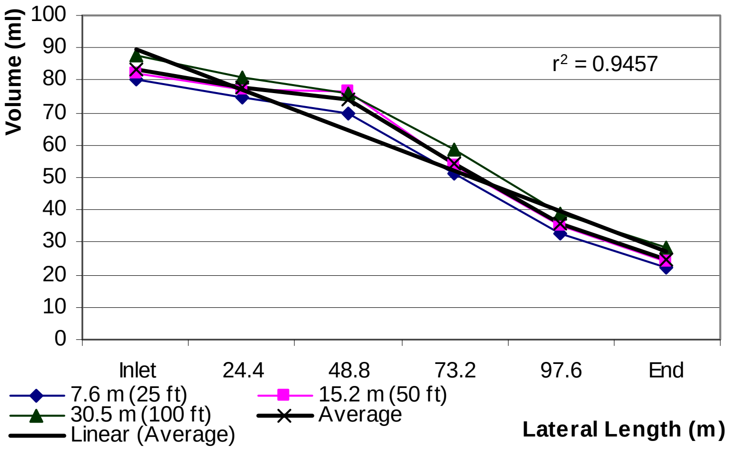

Figure B.17 Water emitted between 0 to end pressure (scenario 8, Geoflow WFPC 162-24-500)

Table B.27 Pump flow rate (m^3/hour) (scenario 8, Geoflow WFPC 162-24-500)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.35	4.05	4.37
15	3.59	3.53	3.57
30	2.92	2.84	2.88
45	2.64	2.60	2.60
60	2.50	2.47	2.45
75	2.41	2.39	2.37
90	2.36	2.34	2.32
105	2.32	2.31	2.30
120	1.54	1.52	1.96
135	1.37	1.37	1.43
150	1.37	1.36	1.41
155			1.41

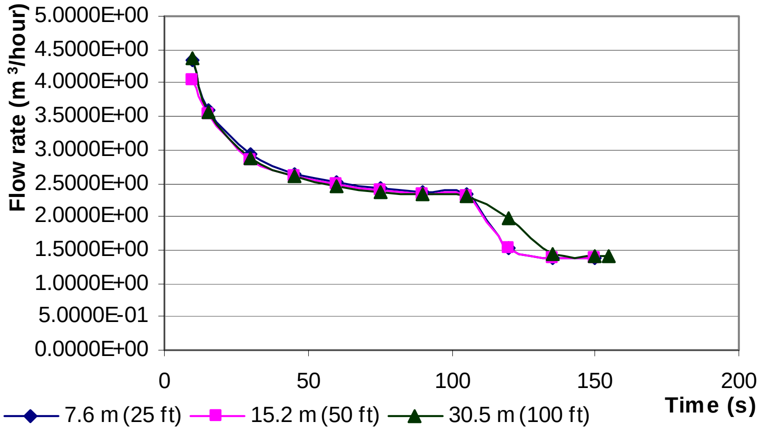

Figure B.18 Pump performance (scenario 8, Geoflow WFPC 162-24-500)

Netafim Bioline 08WRAM 0.6-24V

Scenario 1: Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure

Table B.28 Pressurization time (scenario 1, Netafim Bioline 08WRAM0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	175.13	174.44	178.57
End Pressure (kPa)	137.90	137.90	137.90
Time (min:sec)	10: 00	9: 54	9: 21

Table B.29 Water samples (ml) (scenario 1, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet	391.73	369.77	358.86
24.4 m (80 ft)	385.93	353.18	333.37
48.8 m (160 ft)	364.84	326.8	304.97
73.2 m (240 ft)	307.56	310.70	272.33
97.6 m (320 ft)	304.42	260.91	241.05
End	271.07	247.41	223.21

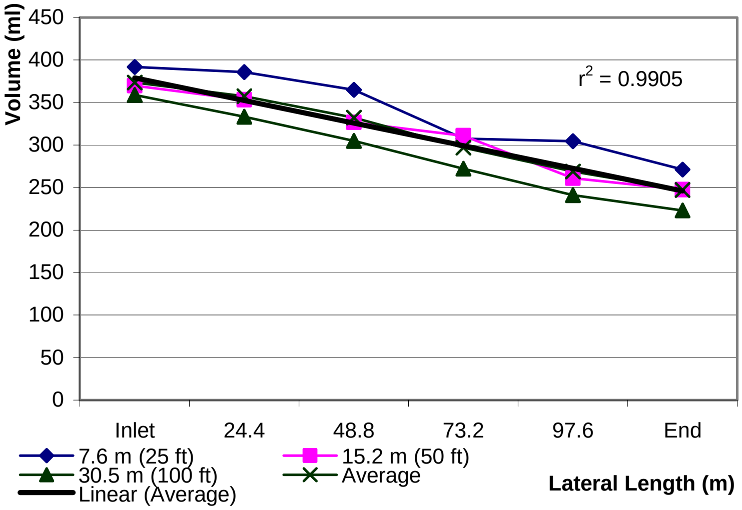

Figure B.19 Water emitted between 0 and 14.1 m (20 psi) (scenario 1, Netafim Bioline 08WRAM0.6-24V)

Table B.30 Pump flow rate (m^3/hour) (scenario 1, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	1.68	1.79	1.71
15	1.79	1.80	1.83
30	1.79	1.80	1.75
45	1.78	1.76	1.73
60	1.76	1.75	1.72
120	1.72	1.72	1.70
180	1.71	1.71	1.69
240	1.64	1.64	1.64
300	1.50	1.49	1.50
360	1.47	1.45	1.47
420	1.44	1.44	1.45
480	1.44	1.44	1.45
540	1.44	1.43	1.44
555	1.44	1.44	1.44
562	1.43	1.44	1.44
570		1.44	1.44
594		1.43	1.44
600			1.44

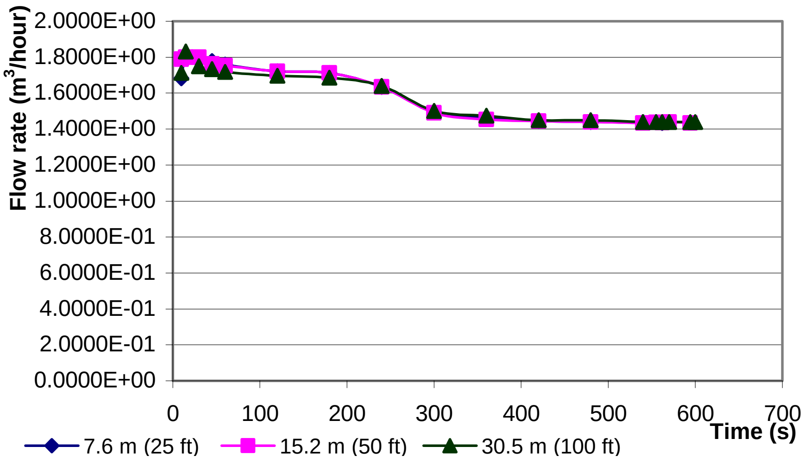

Figure B.20 Pump performance (scenario 1, Netafim Bioline 08WRAM0.6-24V)

Scenario 2: 137.9 kPa (20 psi) pressure regulator & intermittent flushing

Table B.31 Pressurization time (scenario 2, Netafim Bioline 08WRAM 0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	137.90	138.58	137.90
End Pressure (kPa)	110.32	108.94	105.49
Time (min:sec)	2 :17	2: 13	2: 22

Table B.32 Water samples (ml) (scenario 2, Netafim Bioline 08WRAM0.6-24V)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	85.01	86.63	92.41	88.02
24.4 m (80 ft)	82.03	83.82	89.81	85.22
48.8 m (160 ft)	68.28	70.15	77.85	72.09
73.2 m (240 ft)	46.84	48.34	54.66	49.95
97.6 m (320 ft)	27.57	28.31	31.28	29.05
End	10.38	14.16	15.10	13.21

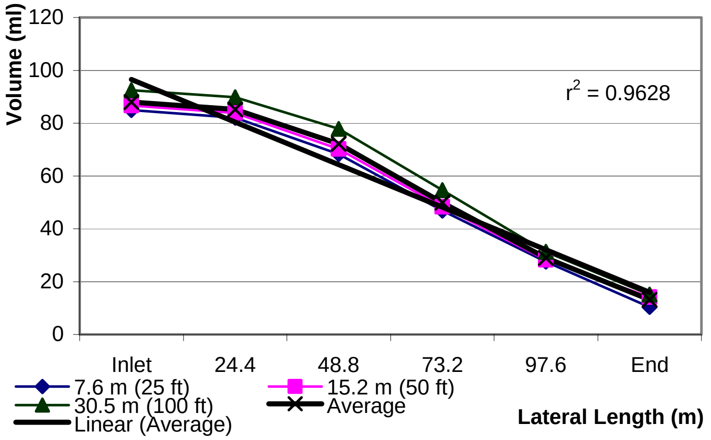

Figure B.21 Water emitted between 0 and end pressure (scenario 2, Netafim Bioline 08WRAM 0.6-24V)

Table B.33 Pump flow rate (m^3/hour) (scenario 2, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.52	4.63	4.43
15	3.76	3.57	3.78
30	3.02	2.96	3.01
45	2.73	2.70	2.71
60	2.60	2.57	2.55
90	2.46	2.43	2.45
120	2.39	2.37	2.39
135	1.72	1.73	2.33
137	1.66		2.19
142			1.58

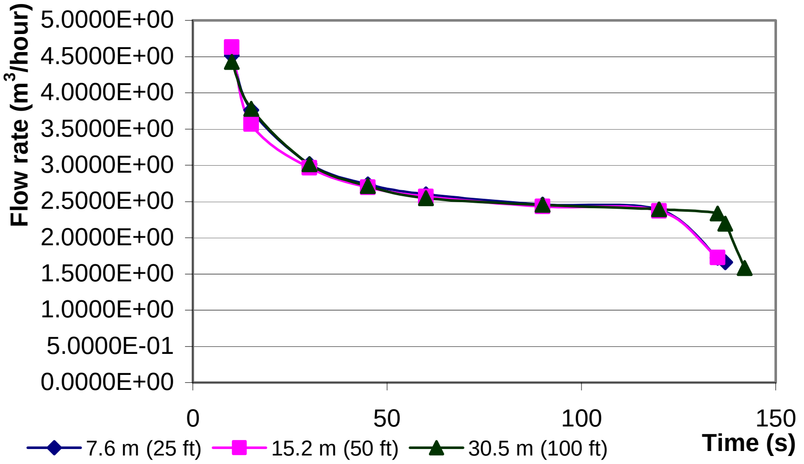

Figure B.22 Pump performance (scenario 2, Netafim Bioline 08WRAM0.6-24V)

Scenario 3: Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure

Table B.34 Pressurization time (scenario 3, Netafim Bioline 08WRAM 0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	137.90	137.90	138.58
End pressure (kPa)	91.70	88.94	85.49
Time (min:sec)	3:04	3:00	3: 12

Table B.35 Water samples (ml) (scenario 3, Netafim Bioline 08WRAM0.6-24V)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	115.50	111.00	115.10	113.90
24.4 m (80 ft)	113.60	108.40	110.40	110.80
48.8 m (160 ft)	98.59	93.47	94.35	95.47
73.2 m (240 ft)	67.87	70.32	59.22	65.80
97.6 m (320 ft)	42.16	35.84	35.76	37.92
End	26.15	19.19	20.07	21.80

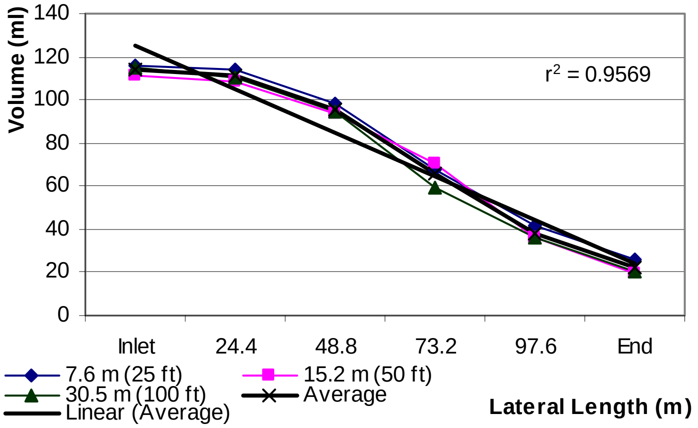

Figure B.23 Water emitted between 0 and end pressure (scenario 3, Netafim Bioline 08WRAM 0.6-24V)

Table B.36 Pump flow rate (m^3/hour) (scenario 3, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	3.56	3.70	4.22
15	3.18	3.52	3.96
30	2.67	2.76	3.17
45	2.46	2.49	2.57
60	2.34	2.36	2.38
75	2.27	2.28	2.28
90	2.23	2.22	2.21
105	2.20	2.19	2.17
120	2.17	2.17	2.14
135	2.16	2.16	2.13
150	2.14	2.14	2.11
165	1.62	1.96	2.10
180	1.56	1.57	1.80
184	1.55		1.69
192			1.56

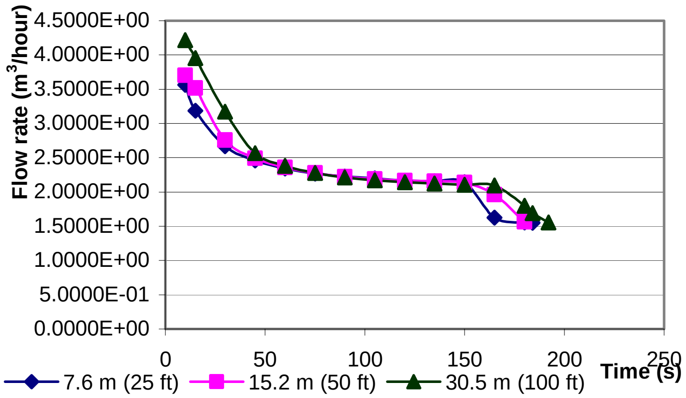

Figure B.24 Pump performance (scenario 3, Netafim Bioline 08WRAM0.6-24V)

Scenario 5: Flow restriction (gate valve on supply line) & intermittent flushing & 275.8 kPa (40 psi) end pressure

Table B.37 Pressurization time (scenario 5, Netafim Bioline 08WRAM 0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft) *
Inlet Pressure (kPa)	318.54	321.30	320.61
End Pressure (kPa)	275.79	275.79	275.79
Time	3: 40	7: 57	23: 00

*For 30.5 m (100 ft) supply line, it took 23 minutes to reach 275.1 kPa (39.9 psi)

Table B.38 Water samples (ml) (scenario 5, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet	140.64	303.77	874.30
24.4 m (80 ft)	126.35	290.70	871.60
48.8 m (160 ft)	115.88	307.32	861.80
73.2 m (240 ft)	93.19	263.11	849.00
97.6 m (320 ft)	74.44	245.18	824.50
End	57.58	226.27	807.40

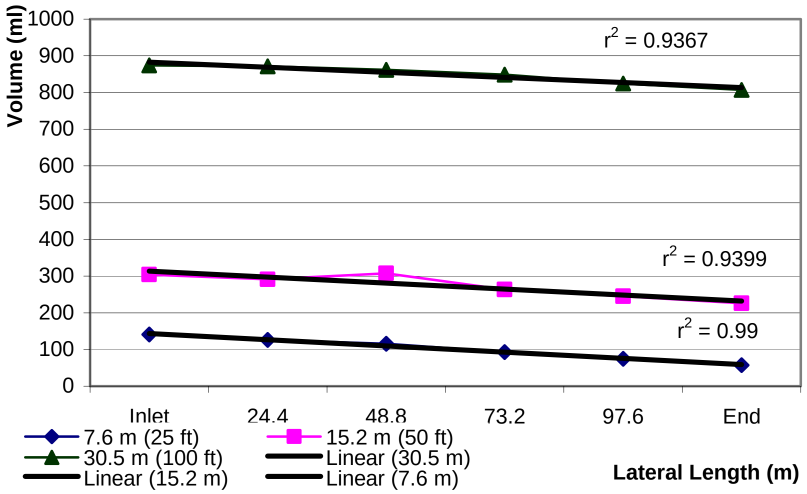

Figure B.25 Water emitted between 0 and 40psi/28.2m (scenario 5, Netafim Bioline 08WRAM 0.6-24V)

Table B.39 Pump flow rate (m^3/hour) (scenario 5, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	2.60	2.92	2.71
15	2.82	2.8	2.78
30	2.64	2.63	2.63
45	2.56	2.54	2.53
60	2.49	2.47	2.43
120	2.39	2.36	2.34
180	1.50	1.50	1.51
220	1.47	1.47	1.49
240		1.47	1.49
300		1.47	1.48
360		1.46	1.47
420		1.45	1.47
477		1.46	1.47
480			1.47
1380			1.46

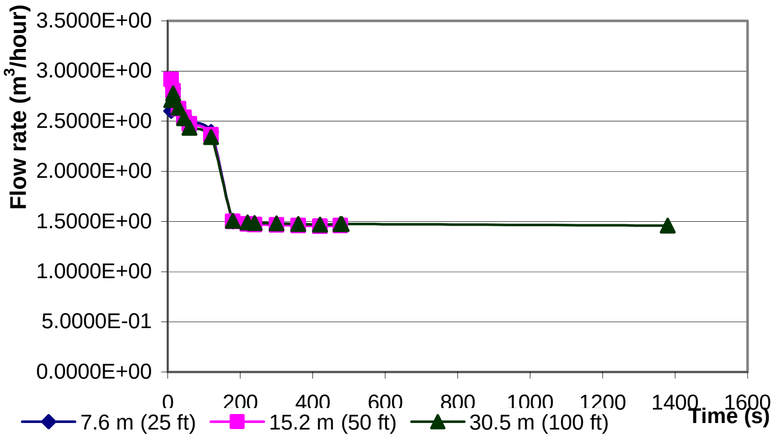

Figure B.26 Pump performance (scenario 5, Netafim Bioline 08WRAM0.6-24V)

Scenario 6: Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure

Table B.40 Pressurization time (scenario 6, Netafim Bioline 08WRAM 0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	275.79	277.19	275.79
End Pressure (kPa)	244.76	230.97	228.22
Time (min:sec)	2: 28	2: 22	2:51

Table B.41 Water samples (ml) (scenario 6, Netafim Bioline 08WRAM0.6-24V)

	Supply Line			
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)	average
Inlet	93.29	88.28	104.99	95.52
24.4 m (80 ft)	91.46	86.87	99.59	92.64
48.8 m (160 ft)	82.15	77.20	90.16	83.17
73.2 m (240 ft)	65.02	46.70	71.52	61.08
97.6 m (320 ft)	46.22	41.01	52.54	46.59
End	35.23	27.49	39.39	34.04

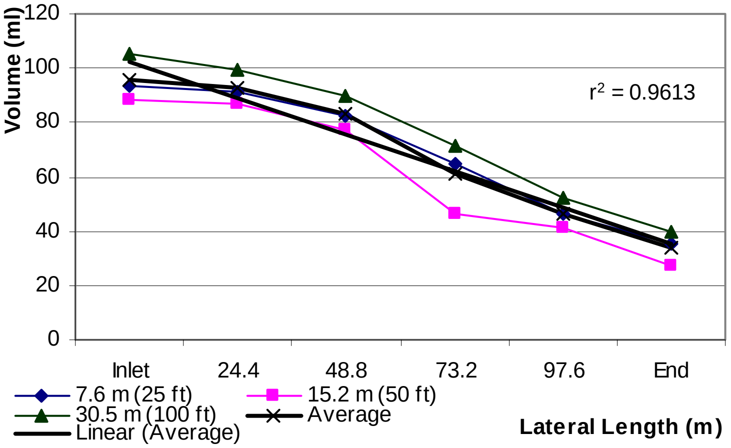

Figure B.27 Water emitted between 0 and end pressure (scenario 6, Netafim Bioline 08WRAM 0.6-24V)

Table B.42 Pump flow rate (m^3/hour) (scenario 6, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.41	4.54	4.78
15	3.95	3.98	4.45
30	3.34	3.34	3.45
45	3.06	3.05	3.09
60	2.92	2.9	2.90
75	2.83	2.81	2.80
90	2.78	2.76	2.73
105	2.73	2.72	2.70
120	1.59	1.80	2.66
135	1.52	1.53	1.91
142	1.36	1.52	1.52
148	1.29		1.51
151			1.51

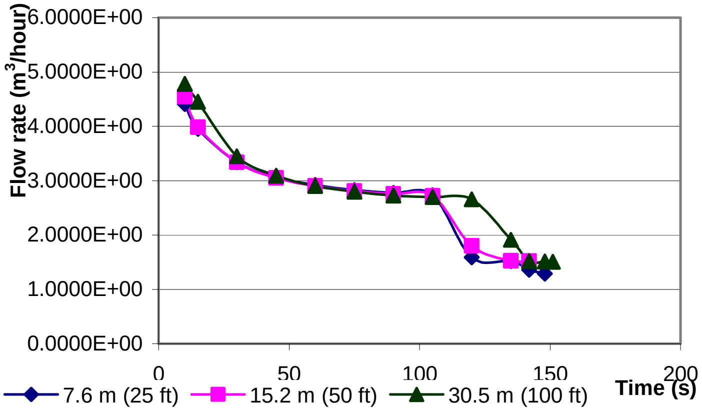

Figure B.28 Pump performance (scenario 6, Netafim Bioline 08WRAM0.6-24V)

Scenario 7: Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure

Table B.43 Pressurization time (scenario 7, Netafim Bioline 08WRAM 0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	346.81	351.63	353.01
End Pressure (kPa)	275.79	275.79	275.79
Time (min:sec)	2: 00	2: 03	2: 00

Table B.44 Water samples (ml) (scenario 7, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet	80.52	84.72	84.16
24.4 m (80 ft)	76.26	77.63	73.78
48.8 m (160 ft)	73.20	78.06	67.59
73.2 m (240 ft)	60.00	61.05	53.90
97.6 m (320 ft)	45.40	43.93	42.87
End	32.95	29.49	25.95

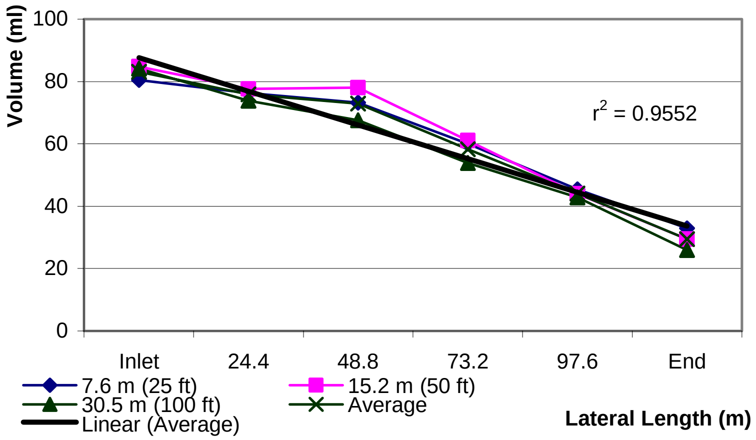

Figure B.29 Water emitted between 0 and 28.2 m (40 psi) (scenario 7, Netafim Bioline 08WRAM 0.6-24V)

Table B.45 Pump flow rate (m^3/hour) (scenario 7, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	5.09	4.79	4.70
15	4.87	4.44	4.38
30	4.05	3.87	3.83
45	3.70	3.61	3.55
55	3.57	3.50	3.45
60	3.51	3.45	3.40
75	3.40	3.35	3.30
90	2.14	2.16	2.22
105	2.11	2.11	2.04
120	2.10	2.10	2.02
123		2.10	

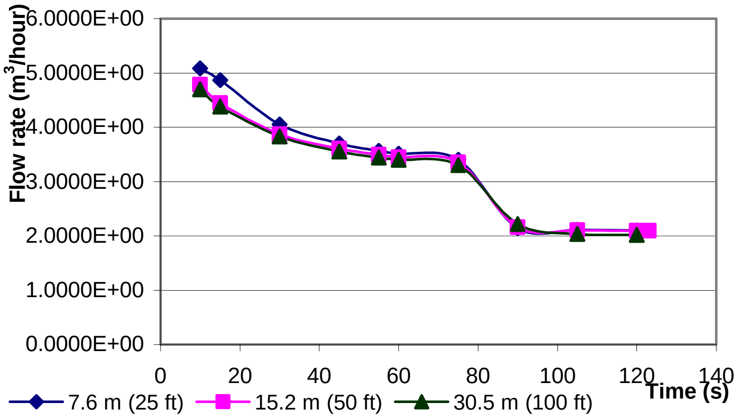

Figure B.30 Pump performance (scenario 7, Netafim Bioline 08WRAM0.6-24V)

Scenario 8: 310.26 kPa (45 psi) pressure regulator & intermittent flushing

Table B.46 Pressurization time (scenario 8, Netafim Bioline 08WRAM0.6-24V)

Supply Line	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet Pressure (kPa)	312.33	312.33	315.78
End Pressure (kPa)	265.45	270.96	268.90
Time (min:sec)	2: 55	4: 30	6: 23

Table B.47 Water samples (ml) (scenario 8, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Lateral location	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
Inlet	113.75	250.19	168.93
24.4 m (80 ft)	110.83	241.93	168.69
48.8 m (160 ft)	102.32	233.41	158.21
73.2 m (240 ft)	92.94	218.49	147.26
97.6 m (320 ft)	80.03	209.19	134.90
End	73.50	214.25	133.64

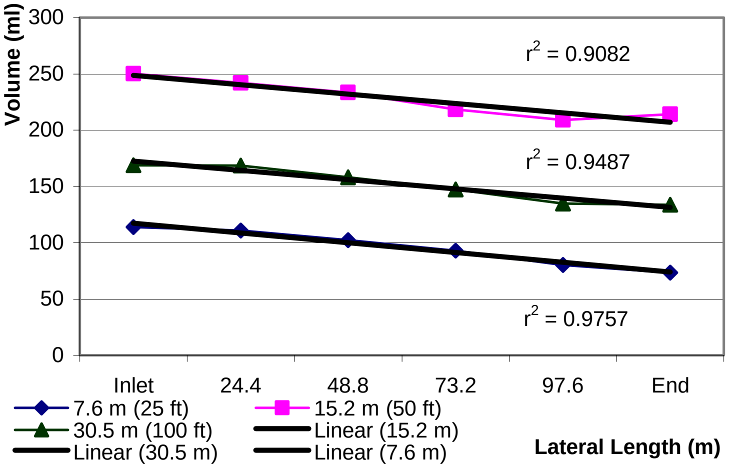

Figure B.31 Water emitted between 0 and end pressure (scenario 8, Netafim Bioline 08WRAM 0.6-24V)

Table B.48 Pump flow rate (m^3/hour) (scenario 8, Netafim Bioline 08WRAM0.6-24V)

	Supply Line		
Time (s)	7.6 m (25 ft)	15.2 m (50 ft)	30.5 m (100 ft)
10	4.96	4.88	4.95
15	4.56	4.49	4.62
30	3.93	3.89	3.87
45	3.64	3.44	3.51
60	3.48	3.25	3.37
90	1.64	1.54	2.42
120	1.53	1.53	1.53
150	1.51	1.52	1.51
180		1.51	1.52
210		1.51	1.50
240		1.51	1.51
270		1.51	1.51
300			1.51
360			1.50
384			1.50

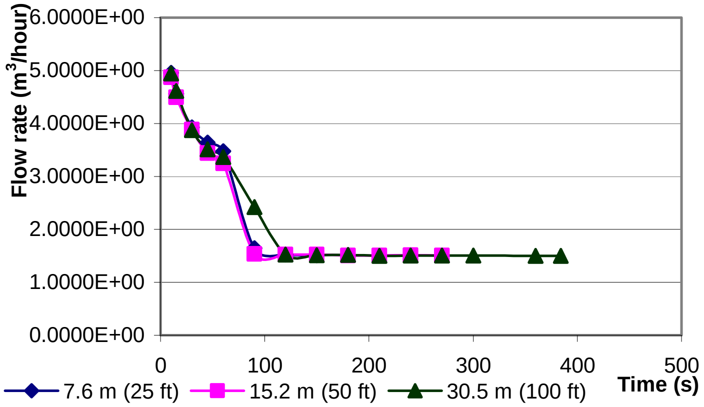

Figure B.32 Pump performance (scenario 8, Netafim Bioline 08WRAM0.6-24V)

APPENDIX C

Appendix C includes the drip zone pressurization time data of three types of emitters in different scenarios applied in Chapter III.

Table C.1 Dose time to pressurize the drip zone with Geoflow WFCL 164-24-500 tubing (seconds)

Supply line length		7.6 m (25 ft)			15.2 m (50 ft)			30.5 m (100 ft)		
Scenario 1	Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure	67	67	68	95	95	95	106	106	106
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	62	62	61	65	65	65	76	76	75
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	80	80	79	85	84	86	86	85	86
Scenario 4	Flow restriction (gate valve on return line) & continuous flushing & 137.9 kPa (20 psi) end pressure	61	61	60	59	61	58	71	69	73

Table C.2 Dose time to pressurize the drip zone with Geoflow WFPC 162-24-500 tubing (seconds)

Supply line length		7.6 m (25 ft)			15.2 m (50 ft)			30.5 m (100 ft)		
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	176	177	177	176	176	177	183	183	182
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	189	189	188	195	195	196	210	210	209
Scenario 6	Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure	170	170	171	192	192	191	180	180	179
Scenario 7	Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure	123	122	122	121	117	126	134	134	133
Scenario 8	310.26 kPa (45 psi) pressure regulator & intermittent flushing	137	138	137	141	142	141	153	155	152

Table C.3 Dose time to pressurize the drip zone with Netafim Bioline 08WRAM0.6-24V tubing (seconds)

Supply line length		7.6 m (25 ft)			15.2 m (50 ft)			30.5 m (100 ft)		
Scenario 1	Flow restriction (gate valve on supply line) & intermittent flushing & 137.9 kPa (20 psi) end pressure	600	603	598	594	592	596	661	659	664
Scenario 2	137.9 kPa (20 psi) pressure regulator & intermittent flushing	137	140	133	133	132	133	142	145	138
Scenario 3	Recirculation valve (bypass flow) & intermittent flushing & 137.9 kPa (20 psi) inlet pressure	184	180	188	180	182	177	182	176	188
Scenario 5	Flow restriction (gate valve on supply line) & intermittent flushing & 275.8 kPa (40 psi) end pressure	220	221	220	479	483	469	1350	1390	1400
Scenario 6	Recirculation valve (bypass flow) & intermittent flushing & 275.8 kPa (40 psi) inlet pressure	146	150	148	142	142	141	171	175	166
Scenario 7	Flow restriction (gate valve on return line) & continuous flushing & 275.8 kPa (40 psi) end pressure	121	118	121	123	120	125	120	113	126
Scenario 8	310.26 kPa (45 psi) pressure regulator & intermittent flushing	169	176	180	268	271	270	390	379	380

APPENDIX D

Appendix D includes the fill time computation of drip zone applied with two types of drip tubings in a same scenario. In this research, scenario 2 (137.9 kPa/20 psi pressure regulator & intermittent flushing) for both Geoflow NPC and Netafim PC emitters was used as an example throughout the following text and results section of Chapter III to illustrate the design calculation.

Total Dynamic Head (TDH) Computation

Total dynamic head is the energy that the pump must supply to meet demands of the various drip system components and operating schemes. Total dynamic head requires the preliminary selection and design for all components to determine applicable head losses. For this experiment, TDH was calculated for expected operating conditions to determine both controlling conditions and actual operating points for the pumps used.

Total dynamic head was calculated as:

$$TDH = H_z + H_v + H_e + H_f \tag{D.1}$$

where,

H_z, zone pressure head, exists during pressurized dripping stage.

H_e, elevation head, is the energy that must be provided to pump the wastewater to the various elevations within the system. In this study elevation difference is 0. Geoflow (2004) recommends that the maximum elevation head loss in a zone not exceed 6 ft for NPC tubing.

H_v, velocity head, the energy associated with the moving water within the system. As a part of the energy equation, velocity head can be ignored, since it is relatively small relative to other components.

H_f , friction head loss is composed of two parts.

1) the supply line and manifold friction loss (Adopted from Hazen-Williams equation) were calculated as:

$$H_f = 393.221 * (100/C)^{1.85} (Q_p^{\ 1.852} / D_i^{4.8655}) \qquad \text{D.2}$$

where,

H_f, friction loss of supply line and manifold, m of water per 100 m of pipe

C, flow coefficient, 150 for PVC pipe

Q_p, flow rate, m^3/min

D_i, pipe inner diameter, m

2) fitting's friction head loss, including PVC tee/orifice, elbows, filter, pressure regulator, was estimated using the friction loss data from the user manuals (Geoflow, 2004), (Netafim 2004).

Using pump characteristics curve (Figure 3-6); the pump's flow rate Q_p at any TDH could be obtained.

Engineering Calculation of Zone Parts Fill Time

1. Time to fill supply line and manifold (T_1):

$$V_{s\&m} = \pi D_s^{\ 2} * L / 4 \qquad \text{D.3}$$

$$T_1 = V_{s\&m} / Q_P \qquad \text{D.4}$$

Where, $V_{s\&m}$ is the capacity of supply line and manifold, D is the inner diameter of the supply line and manifold (the same diameter PVC pipe was applied on supply line and manifold in this study), Q_p is pump flow rate.

2. Lateral (T_2):

Capacity of a lateral $V_{lateral} = \pi * D_l^2 * L/4$ D.5

An orifice equation was presented to describe the relationship between flow rate through an orifice and pressure at the orifice (inlet of a lateral) (U.S.EPA, 2002):

$$Q(h) = 21.4 * D_o^2 * h^{1/2} \quad \text{D.6}$$

where,

Q, flow rate through orifice, m^3/s

D_o, orifice diameter, m; h, orifice pressure, m

$$V = \int_0^{T_2} Q(h)dt \quad \text{D.7}$$

where,

V, the discharged water volume in an assumed time $T_{2.}$

For the example system, it is assumed that orifice pressure increases evenly from 0 to 13.79 kPa (2 psi) when water fills the lateral volume. First assume a time T_2 to fill a lateral, volume V is obtained by integral calculus (Equation D.7). Compare V with a lateral's capacity $V_{lateral}$; if the absolute difference is less than 1% of $V_{lateral}$, the estimated T_2 is final result. If not, a new value of T_2 was assumed to compute V and compare it to $V_{lateral}$. This iterative process continued until the variance between them is less than 1% of $V_{lateral}$.

VITA

Xiaojing Duan

Xingtai Kuangyejituan Jiwei #403, Hebei, CHINA 054000

EDUCATION:

2004-2006 M.S., Biological and Agricultural Engineering, Texas A&M University, College Station, Texas

1997-2001 B.A., Civil Engineering, Hebei Institute of Civil Engineering & Architecture, Zhangjiakou, China

Permanent Address:

Xingtai Kuangyejituan Jiwei #403, Hebei, CHINA 054000