IMPROVING DESIGN PRACTICES FOR DRIP IRRIGATION SYSTEMS INSTALLED IN THE PUNJAB PROVINCE, PAKISTAN

A Thesis submitted by

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ABSTRACT

Most of the drip irrigation systems installed in Pakistan in mega projects have been abandoned due to lack of expertise in design procedure and evaluation of performance of the systems to be installed. Performance evaluation is the key factor to initiate the cycle of improvement in working and efficiency of the irrigation systems. After realising the need of performance evaluation of Pakistani drip irrigation systems a field experiment have been designed to replicate the typical Pakistani drip irrigation system in Australia. Results were obtained in field and using the Eaucadi and Hydrocalc software packages. Data analysis was performed using the Eaucadi and Hydrocalc software packages in comparison with measured field results. The emission uniformity in terms of performance evaluation and emitter discharge and pressure regime along the length of the pipe in measured and simulated results was compared and analysed. The validation and accuracy of the software packages is tested, and an improved design procedure is formulated using a mixture of two simple software packages that also facilitates with the performance evaluation of the already installed systems. This design procedure is tested and recommended to evaluate and improve the performance of already installed and future drip irrigation systems to be installed in Punjab in Pakistan. The procedure formulated will be an optimised tool to ensure the continuous cycle of performance evaluation and improvement of the drip irrigation systems in Punjab, Pakistan.

CERTIFICATION OF THESIS

This thesis is entirely the work of Madeeha Waseem except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors' signatures of endorsement are held at USQ.

Dr Joseph Foley

Principal Supervisor

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ABBREVIATIONS

- GLs: Giga Litres
- Kms: Kilometres
- m: Metres
- $m^{3:}$ Cubic Metres
- ha: Hectares
- ML: Mega Litres
- L/h: Litres/ hour
- mm: Millimetres
- m/s: Metre/sec
- min: Minutes
- kPa: Kilo pascal
- kWh: Kilowatt-hour
- Psi: Pounds per Square inch
- Ppm: Parts per million
- %: Percentage
- ASABE: American Society of Agricultural and Biological Engineers
- *Du*: Distribution uniformity
- *Eu*: Emission Uniformity
- *Cv*: Coefficient of variation
- mm/day: Millimetres/Day
- mil: Thousandth of an inch
- *Kd*: Minor loss coefficient
- *Cu*: Christiansen’s coefficient of uniformity
- $q_{\text{var:}}$ Emitter flow rate variation
- *AE*: Application efficiency

- Ag-Plot: Agriculture Plot area in the University of Southern Queensland
- PIPIP: Punjab Irrigated Agriculture Productivity Improvement Project

CHAPTER 1 INTRODUCTION

1.1 Background

Pakistan is a highly populous country with abundant water and a monsoonal climate. The main sources of irrigation water are river supplies, with 70% contribution of water from annual melting world's largest glacial region and 30% from monsoon rainfalls (Ahmad et al., 2014). Pakistan is blessed with wide riverine floodplains and according to (Iqbal & Iqbal, 2015), it has 4th largest irrigated area in the world and has the single world's biggest contiguous irrigation system. The total area under cultivation is 22 million hectares, out of which 14.6 million hectares is irrigated.

Figure 1.1 shows a political map of Pakistan displaying the international boundary, provinces, territory and capital territory boundaries with their state capitals and national capital. The study area selected for this study is Punjab, which is a province in Pakistan can be seen in green colour in the map below. Pakistan is a country in South Asia with a coastline bounded by the Arabian Sea in the south. The country is bordered by Afghanistan, China, India and Iran and the capital is Islamabad.

Figure 1.1: Political map of Pakistan displaying the international boundary, provinces, territory, and capital territory boundaries with their capitals and national capitals (Compare Infobase Limited, 2013).

Pakistan is mainly an agricultural country and lies in arid to semi-arid region and its agricultural production depends on the abundant available irrigation water resources. The study area selected for the present research project is Punjab, Pakistan. Rice and wheat are the major crops of Punjab and its climate is semi-arid with long and hot summers with maximum temperature ranging from 21◦C to 49◦C from April to September. While winters lasts from December through February with maximum temperature up to 27 ◦C in December and January and minimum temperature falling below zero. Average annual rainfall is approximately 400 millimetres (mm) (Masih et al., 2014).

The rainfall in Pakistan is neither enough nor regular to meet the growing needs of most agricultural crops. About 70 per cent of the annual rainfall occurs in the months of July to September, causing floods in more than quarter of the country and eventually gets sacrificed to the Arabian Sea after creating havoc in agricultural capitals (Iqbal & Iqbal, 2015). The rainfall received in Pakistan can be divided into two main seasons, summer or monsoon and winter precipitation. The monsoon rainfall enters the country from east and north east during the month of July to September. During this period a good amount of rainfall is received in the north and north eastern areas of the country. Winter precipitation (December to March) is mainly received from western disturbances entering from Iran and Afghanistan. The difference in the maximum temperature in cities of Punjab is very small; however, it indicates that the temperature tends to increase as moving from north to the south of the Punjab. In these areas, more water is required to compensate high evaporation losses caused due to high temperature range and Salma et al. (2012) also concluded that most of the parts of Pakistan experience a dry climate.

Annual average rainfall data of major cities of Punjab province for five years (2007- 2011) has been provided in Figure 1.2. The major cities of Punjab Province are given in red vertical lines, showing a yearly average rainfall from 180 millimetres to 1550 millimetres per year between different cities of Punjab Province. While major cities of Sindh, Khaber Pakhtun Khan and Baluchistan provinces are given in green, blue and orange vertical lines respectively.

Rawalpindi and Jhelum cities lie in the north of Punjab Province while Lahore, Sargodha and Faisalabad lie in the centre with Multan and Bahawalpur towards the south of the Punjab Province. Thus, the northern cities receive more rainfall as compared to the cities that lie in the middle and southern region of the Punjab, and humidity decreases from north to south in Punjab Province.

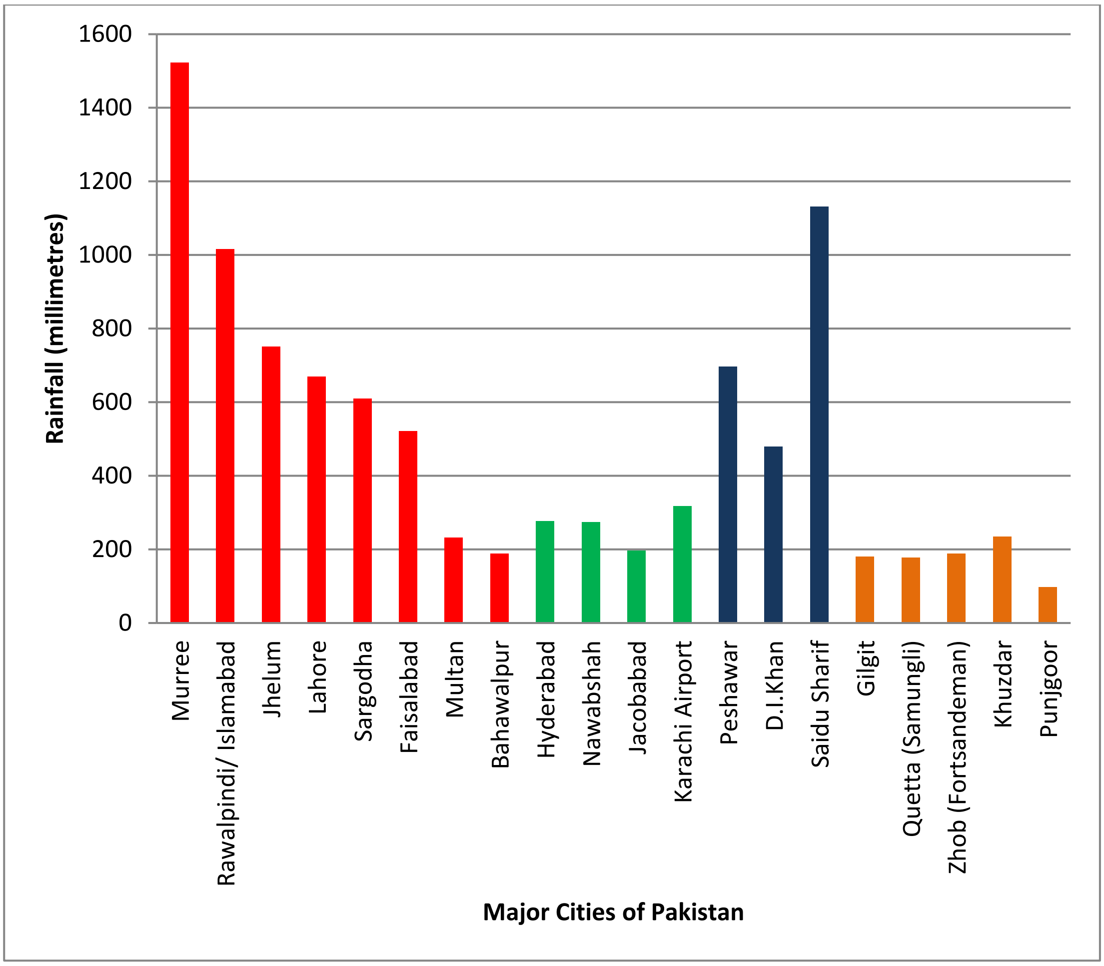


Figure 1.2: Five-year average annual rainfall data of 20 major cities of four provinces Punjab, Sindh, Khaber Pakhtun Khan, and Baluchistan of Pakistan (Pakistan Bureau of Statistics, 2012).

The Punjab province can be divided into three hydrological zones. The districts of upper Punjab where average annual rainfall is above 500 mm is considered as high rainfed/humid areas. In the central Punjab average annual rainfall ranges between 300-400 mm, therefore these areas can be characterized as medium rainfed areas. In the lower Punjab districts, the annual distribution of rainfall shows the picture of essentially an arid region, with average annual rainfall ranging between 100-150 mm. The cropping patterns in all these zones depends on the distribution of rainfall, availability of surface water and groundwater resources and the quality of available groundwater (Qureshi & Akhtar, 2003).

The major irrigated winter crop is wheat, while cotton, maize, rice, sugar cane and fodder crops are the main crops grown in the summer season. The soil typically has low infiltration rates and the salinity and sodicity have aggravated the situation and are now major problems due to poor drainage from fields (Trimmer, 1990).

As the rice is grown during the monsoon season (kharif), while wheat is grown in the winter (rabi) season. It is observed that the total crop water use or evapotranspiration requirement (ETc) for the rice–wheat rotation is more than double the annual rainfall (Masih et al., 2014).

The results obtained in the research conducted by (Masih et al., 2014) in Punjab showed that the wheat is generally under irrigated due to the lack or absence of canal water during winter. The results also show a wide variation in total irrigation application to rice and wheat over the years due to the difference between farm and soil conditions, water availability, sowing and harvesting dates and variability of climate from site to site. Evapotranspiration, on the other hand has shown less variability and is significantly lower than total water input (irrigation and rainfall). Which results into substantial deep percolation that contributes to recharging the groundwater aquifers and increasing soil moisture storage in the root zone during rice growth season. Later, these groundwater resources and soil moisture storage are available for reuse during wheat growing season.

About 14% of the rice-wheat shared production comes from Indus basin and most of the irrigated area is included in the Indus basin. While, Punjab’s rice and wheat zone covers about 65% of the area of total rice and wheat cropping systems and contributes to the country’s major food grain production (Masih et al., 2014).

The total agricultural production in Punjab was 53.5 million tonnes during 1994 to 1995, and by 2010 it has increased to 70.2 million tonnes. Similarly, the approximately 10% agricultural area have increased from 15.63 million hectares in 1994 to 1995 to 17.12 million hectares in 2009 to 2010 (Afreen et al., 2013). This massive increase in the agricultural production and area under cultivation has put an immense pressure over the water resources.

The irrigation canal network has been developed over the last 140 years. These canals get water from Indus river and its tributaries and deliver limited water over a large area, at a cropping intensity of approximately 65% (a ratio of total harvested area within a year to available land for cultivation) in order to prevent crop failure, starvation and to create employment and income (Masih et al., 2014).

Approximately 820 mm of surface water is available for each irrigated hectare and in the major irrigated areas of the Indus Basin the annual average evapotranspiration measured ranges from 1000 to 1300 mm per year and irrigated lands contributes up to 90% of the total agricultural production (Qureshi et al., 2010).

The Indus River irrigation system of Pakistan contains three major reservoirs named Tarbela , Mangla and Chashma, as well as 23 barrages, 12 link canals and 45 canal systems, with a total length of 60,800 kilometres, and more than 140,000 irrigation channels with a total length of 1.6 million kilometres (Shaikh, 2003; Bakhshal & Masood, 2012; Ahmad et al., 2014; Iqbal & Iqbal, 2015).

The annual flow of water in the Indus River system on an average is 172,687 GLs. The months of peak-flow are June to August during the monsoon season with the flow of 145,550 GLs (84%) during summer and in winter it is 27,137 GLs (16%). Indus is the Main River contributing 65% of water supplies, with Jhelum and Chenab River giving 17% and 19% respectively. Nearly all of the 19 million hectares of irrigation in Pakistan is completed with traditional surface irrigation. This mostly consists of border, basin and furrow irrigation. The overall irrigation efficiency levels are up to 30%, which include approximate conveyance losses of 25% and 30% in water distribution canals and watercourses respectively, and in field application losses of 25-40% (Kahlown & Majeed, 2003; Ahmad et al., 2014).

Total water flows to the canals is about, 130749 GLs, out of which about 15% is lost in main and branch canals. So, 111013 GLs reaches the distributary minors and about 8% water is lost. Then 102379 GLs reaches to the irrigation channels and losing about 30% water during this flow. Therefore, only 71542 GLs of water is reached at field head and due to flood irrigation method, 30% water is lost in field. Thus, 50573 GLs water is applied out of total 130749 GLs that is delivered to the canal network and the efficiency of our irrigation system is only 42 to 45% (Qureshi et al., 2010; Iqbal & Iqbal, 2015).

Although the century old system is gravity fed and does not need any energy source to deliver water to the fields, the efficiency of the system recorded was very low (about 35%) due to water losses in the form of conveyance and application losses (Hussain et al., 2011; Ahmad et al., 2014).

The ground water table was about 30 m below ground level in Punjab before the initiation of surface irrigation system and was about 12-15m deep in Sindh province. (Wolters & Bhutta, 1996). A natural hydrological balance between the rivers and the groundwater table got disturbed due to the extensive expansion of surface water irrigation in the 19th and 20th centuries. The continuous seepage from this massive system has raised the groundwater table to the surface or very close to the root zone at some locations in Punjab and Sindh. As a result the waterlogging and secondary salinity have generated, which has severely affected the agricultural productivity (Afreen et al., 2013; Masih et al., 2014).

To reduce and control this issue a public ground water project named “Salinity Control and Reclamation Projects” (SCARP) was implemented. Rapid growth of privately owned and farmer’s owned tube wells took place due to the decreased surface water supplies, inequity in access to canal water between head and tail users and increased government subsidies on energy and pump equipment (Afreen et al., 2013). So, more than a million tube wells were installed, out of which 83% are diesel operated and the remaining are electricity operated (Mongat et al., 2015).

Even though the excessive ground water pumping has allowed farmers to increase their farm income and production, but the current rate of ground water pumping is unjustifiable in terms of dropping ground water levels, quality deprivation and increased salinity and pumping cost Due to the over drafting, the ground water levels have fallen at a rate of 2-3 m annually and now they are inaccessible in almost 5% and 15% of the irrigated areas of Punjab and Baluchistan provinces respectively. Roughly 23% and 78% of the area has poor ground water quality in Punjab and Sindh respectively (Qureshi et al., 2010).

Common traditional irrigation method in Pakistan is surface irrigation and will continue to be used as an old-style method of irrigation. Water application efficiency of the surface irrigation is less than 40%, producing yields much lesser than other countries. Due to the threatened water resources and incompetent traditional irrigation methods, agriculture sector is facing intense pressure to efficiently manage the available water resources (Qureshi et al., 2015).

The most common and traditional methods of irrigation used in Pakistan are furrow irrigation, level basin flood irrigation and border irrigation as shown in Figure 1.3, Figure 1.4 and Figure 1.5.

Figure 1.3: Furrow irrigation in Pakistan (Alfredobi, 2004).

Figure 1.4: Level basin flood irrigation in Pakistan (Vanuga, 2002).

Figure 1.5: Border irrigation at a farm site in Punjab province, Pakistan (Ammarkh, 2007).

Pakistan is faced with one of the most critical concerns of this time i.e. food and water shortage, and now more than ever needs a solution to eliminate this risk. More than 200 million people are depending on diminishing water assets and it is high time that the government, consultants and the farmers find sustainable solutions to these concerns.

It can be seen that Pakistan’s water availability is shrinking while demand is increasing, and vast amounts of water are lost due to deteriorating watercourses and wasteful on-farm water use (Shaikh, 2003).

Astonishingly, 90% of all freshwater is consumed for agriculture in Pakistan and approximately 50% is wasted due to poor irrigation practices and according to World Bank estimates traditional irrigation methods in Punjab such as flood irrigation resulted into significant water losses of 20% to 25%. Meanwhile, uneven fields and poor farm design further added to agricultural losses. Although Punjab receives 6.9 million MegaLitres of water only 3.2 million MegaLitres reaches to the farm gate due to heavy losses in canals and watercourses (Eleazar, 2018).

According to Pakistan Bureau of Statistics (2014) a total of 18.63 million hectares metres of land was irrigated through various sources including tube wells, canals and wells.

Bakhshal & Masood, (2012) stated that the agricultural productivity and crop yield per unit of water can only be increased with the promotion and application of efficient and environmentally friendly water management techniques and rain fed areas in Pakistan has the highest potential of increase in yield with better water management.

In this case, latest and modern drip irrigation systems offered the first alternative to the surface irrigation and has become the world's most valued innovation in agriculture (Iqbal & Iqbal, 2015).

Therefore, the researchers are currently more inclined towards developing or studying high efficient irrigation application methods to use threatened water resources proficiently and to increase the crop yield by providing sufficient root zone moisture (Qureshi et al., 2015).

It is observed that severe water shortage and trend towards growing higher value crops has motivated farmers in other countries with similar growing conditions (India, China, Thailand and Near-East countries) to invest in high efficiency irrigation systems. Hence, Pakistan needs to introduce technologies like sprinkler and drip irrigation. Drip irrigation is a comparatively modern irrigation technique that has the potential to save water and nutrients by allowing water to drip slowly into the roots of plants. The basic aim is to apply water directly into the root zone and minimise evaporation. Drip irrigation systems distribute water through a network of valves, pipes, tubing and emitters. This irrigation method enables the effective and timely application of water, fertilizer and nutrients as per the plant’s requirement at various stages of its growth. This irrigating system is very efficient for variety of soil conditions such as uneven topography, odd field configurations, rolling sandy areas and long stretches of crops. So, drip irrigation is ideal for the orchards and high value row crops. Moreover, saline water can be applied using drip irrigation systems using correct filtration techniques, emitter sizing and regular drip flushing in the areas where fresh water is not available, due to reduced evaporation losses. Depending on how well designed, installed, maintained, and operated it is, a drip irrigation system can be more efficient than traditional irrigation methods used in Pakistan. Substantial enhancements have been observed in the yield, quality and water efficiency in comparison to the conventional irrigation methods. Although no data is available these installed systems have not been evaluated in terms of hydraulic performance and efficiency.

Several internationally funded projects were completed to implement pressurised irrigation systems but have failed due to a lack of knowledge and expertise in design procedure, installation and maintenance. Recently (2012-2017), the $381 Million AUD was spent on the Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP), which has started with the assistance of the World Bank in Punjab Province focussed on the installation of pressurised irrigation systems. PIPIP aimed to install “high efficiency” pressurised irrigation systems across 120,000 hectares in Punjab on a 60% subsidized rate (Director General Agriculture, 2011). Although these objectives do not rely on the selection of type of irrigation system but on the design and management of the irrigation systems to be installed.

The PIPIP project intended to achieve maximum productivity from irrigation water by motivating farmers to adopt modern methods of irrigation like drip and sprinkler irrigation systems instead of traditional, less efficient flood irrigation method.

In Punjab, Pakistan total area under drip irrigation is approximately 32374.85 hectares and the average operational efficiency measured in the recently installed drip irrigation systems in Punjab lies between 50% to 65% (Khan, 2019). While existing area under traditional irrigation systems still needs to be investigated.

In Pakistan, drip irrigation systems are being designed with manual calculations using simple spreadsheets. These spread sheets are developed for “standard designs”. Efficiency and performance of most of the drip irrigation systems in the region is low (Kahlown et al., 2007), which may be caused by the design procedure and use of these “standard design sheets”. Design of drip irrigation systems is a highly complex process and is dependent on many factors including type of crop, soil characteristics, land slope, climatic conditions, source of water, and water quality. All these features should play a vital role in the design and selection of drip irrigation system components and therefore the use of standard spread sheets is too simplistic and may lead to poorly performing systems (Kahlown & Kemper, 2007).

On this basis, focussed research is proposed to determine if modern software packages used for the design of drip irrigation systems in Australia can be used to improve the design procedure and implementation of drip irrigation systems in the Punjab region of Pakistan. The scope of this work will be limited to hydraulic design issues associated with surface dripline irrigation systems, and the calibration of modern software packages for the hydraulic design of drip irrigation for the selected characteristics of the components in common use in Pakistan. No drip systems in Pakistan have currently been analysed and measured for their irrigation performance. Hence, it is expected that some means of assessing these systems may arise with the use of these modern irrigation software packages.

1.2 Project aims and objectives

The lack of hydraulic performance evaluation of already installed drip irrigation systems have led to generate this research project to develop a process to regularly monitor, improve and maintain the performance in terms of uniformity throughout the crop growth stages. The authenticated data on the efficiency and performance evaluation of current drip irrigation systems is not available, as the systems have not been evaluated in terms of hydraulic performance. Only the operational performance in terms of crop yield and total amount of water saved has been discovered. While the observations made and anecdotal references from colleagues such as (Khan, 2019) specified that the overall average operational efficiency of currently installed systems is approximately 50% to 65% and can be improved up to the desired application uniformity in the future designs with the correct sizing and selection of the components.

The basic research aim is to improve the drip irrigation design procedure in the Punjab region of Pakistan, and potentially, the irrigation performance of these drip systems. This project aims to investigate the feasibility of improving the design of drip irrigation using different existing design and simulation computer models. In particular, it is the goal of the project to find the most feasible and applicable commercially available computer simulation model to assist in drip irrigation system design. To achieve these aims and goals this project will first evaluate the causes of the low performance of existing standard designed drip irrigation systems in Punjab Province, Pakistan. The selected software packages will be validated in terms of the accuracy to replicate the Pakistani drip irrigation design and produce improved designs.

This work will be justified by the literature review conclusions drawn from CHAPTER 2. That will highlight the failure of pressurised irrigation systems in Pakistan.

The following research questions are proposed for this study:

- Can a mixture of modern computer software design packages and particular field measurements accurately predict the performance of Punjab drip irrigation systems in terms of uniformity?
- Can modern computer software design packages be parameterised correctly to match the hydraulic performance of drip irrigation systems in the Punjab region of Pakistan?

Hence, the summarised objectives are to:

1. Develop an understanding of operational problems, reliability, and grower skill set and drip irrigation performance of the existing “standard designs” from Punjab Province, Pakistan.
2. Replicate elements and reproduce key elements of the hydraulic design of the Punjab drip irrigation “standard designs” here in Australia to allow appropriate measurement and characterisation.
3. Investigate the reliability, usefulness and capability of commercially available software design packages for the replication and improved design of drip irrigation systems in Pakistan.

   Validate the accuracy of software packages by comparison with measured characteristics of drip systems in the field.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This work will be justified by the literature review provided in this chapter regarding the inefficiency of Indus basin irrigation system and failure of pressurised irrigation systems in Pakistan. A typical drip irrigation system and its important components are introduced along with the need for improved irrigation performance and the necessity for promotion and potential of drip irrigation systems in Pakistan are discussed in detail. Further constraints in adoptability of drip irrigation systems in Punjab and prevailing design practices in Pakistan for drip irrigation systems are reviewed thoroughly. The significance of irrigation performance evaluation of drip irrigation systems particularly for Pakistani systems will be justified. Analysis of the possibilities of the software packages for the simulation will be discovered and the selection of suitable software packages matching with the hydraulic design of standard Pakistani drip irrigation system will be accomplished. Broad characteristics of drip irrigation and components are discussed in detail in the sections below:

2.2 Characteristics of drip systems

In order to understand the broad characteristics of drip irrigation systems and its components, it is important to identify and understand the basic water balance principle.

Inflow-outflow=change in storage, which is considered as the basic water balance principle in hydrology. Inflow consists of water from irrigation (canal and/or ground water), rainfall, surface runoff (drainage) from the adjacent farms and capillary rise (where ground water tables are close to the root zone). While the outflow consists of water lost as evapotranspiration, deep percolation below the soil profile, and surface runoff outside the field margins. Thus, water stored in the soil is the result of change in moisture, but it is critical to understand the leaching requirement to avoid secondary salinization. To increase the beneficial use of water and reduce the irrigation cost, irrigation application and water losses need to be reduced. Water is mainly wasted through seepage and drainage, evaporation from soil surface and standing water and transpiration from weeds (Masih et al., 2014).

Unlike surface irrigation, drip irrigation maintains the soil moisture around the plant in growing period, therefore plant gets the precise amount of water which leads to the increase growth and production. It has not only improved the farm output by increasing income and reducing cost but has settled the major issue of water scarcity (Dursun & Ozden, 2012).

Drip irrigation is the type of irrigation in which water is applied regularly and slowly, close to the soil root zone of plants through mechanical applicators called emitters. Proper management is compulsory for water application as both the quantity and timing of water applied has a great effect on the crop production; too much or too little water can harm the crop. A high irrigation performance can only be achieved by drip irrigation systems if they are well designed, well installed, and well maintained (Raine et al., 2001).

Therefore, uniform water distribution plays the most significant role in the design, management and adoption of the drip irrigation system. A system that applies nearly equal amount of water to each pant meeting crop water requirement and which is economically feasible is considered as a well-designed system. While, in real field conditions the flow rate vary due to manufacturing variations, pressure differences, emitter plugging, aging, frictional head losses, irrigation water temperature changes and emitter sensitivity (Arya et al., 2017).

Drip irrigation can also be used to apply saline water. Drip irrigation allows water with higher salt content to be used than other delivery methods, as evaporation losses are minimal. Drip irrigation can also reduce the effects of salinity by maintaining continuously moist soil around plant roots and providing steady leaching of salt to the edge of the wetted zone. Drip irrigation systems are suitable to both brackish and fresh water available in different regions of Punjab, Pakistan.

Past experience and recent studies conducted in different countries has recommended that introduction of high efficiency irrigation systems such as drip irrigation is effective in conserving surface as well as groundwater resources. These systems have distinct advantages over surface irrigation system (Iqbal & Iqbal, 2015), which are as follows:

1. Drip irrigation systems can be used in hilly regions and on saline and alkali soils where other systems may not perform satisfactorily.
2. Uniform water and fertilizer application can be achieved, as well as fertilizer and nutrient losses can be minimised due to limited application and reduced leaching.
3. It has the high-water application efficiency, as an acre can be irrigated in 15-25 minutes depending upon the crop and soil type, even though the field is levelled or unlevelled and irregular shaped such as highly terrains can be easily accommodated.
4. Drip irrigation is the best and safe technology to be used, where only recycled non-potable water is available and the areas where traditional methods of irrigation cannot be used due to the shortage of water e.g. deserts. Furthermore, the reduction in the crop yield in case of drought that is approximately from 20% to 80% can be prevented with this irrigation method as the moisture in the root zone can be maintained at field capacity.
5. In Pakistan soil erosion is reduced by drip irrigation technique, as compared to the traditional flood irrigation technique.
6. Using drip irrigation has shown massive reduction in weeds growth due to the precise application of water only into the root zone of each crop.
7. Drip irrigation ensures highly uniform distribution of water with the controlled flow rate from each emitter.
8. Labour cost is less in drip irrigation method than other irrigation methods as the minimum labour is engaged to carry out the irrigation practices.
9. Variation of supply can be controlled by regulating the valves and drippers.

10. Fertiliser use efficiency is enhanced to 70% to 90%, which is the percent increase in the yield per unit of applied fertilizer, with minimal waste as they are applied directly into the plant root zone.
11. Foliage remains dry as the drip irrigation applies water in the root zone of plants only, which reduces the risk of different disease, typically the fungal diseases that arises in moist conditions.
12. Quality and yield of the crops is improved, and the drip irrigation system is generally suitable for row crops, vegetables fruit trees and high value cash crops.
13. Drip irrigation system minimises the energy use as compared to other pressurised irrigation techniques like sprinkler irrigation, as it is operated at lower pressure.

Other benefits associated with drip irrigation as given by (Pakistan Agriculture Research Centre, 2010) are:

1. Waterlogging and salinity are controlled.
2. Land and water resources are conserved.
3. Farmers' income is increased.
4. System is environmentally friendly.
5. Employment for rural population is generated.
6. Enhancement of crop productivity by 30% to100%.
7. Cropping intensity is expected to increase by 40% to 45%.
8. Use of herbicides and pesticides is expected to be minimized.
9. Allow effective use of liquid fertilizers and marginal quality of irrigation waters.
10. Saving about 40% to 45% of irrigation water, allowing the farmers to increase

their area under cultivation.

11. Land development cost is minimised.

Growers also have a high level of control over water and fertilizer applications with drip irrigation systems. This can be achieved by adjusting the operational parameters, such as the frequency and duration of water application, the emitter specifications and the placement of drip tubes (Skaggs et al., 2004).

The main components of drip irrigation systems include pumps, filtration equipment, control valves, chlorinators, pressure gauges, water meters, fertilizer injectors, check valves and vacuum breakers between water supply and field. Mainline, sub main line, laterals and emitters are provided at the field level along with other auxiliary components such as venturi assembly, pressure gauges, flow control valves, pressure regulators, back flow preventers (Non-return valves), air release valves and flush valve or end caps. Venturi assembly is used to inject fertilizers and chemicals through drip irrigation systems. Laterals are made up of Low-Density Polyethylene (LDPE) and are available in different nominal diameters e.g. 12 mm, 16 mm and 20 mm. Sub mains are generally made up of Poly-Vinyl-Chloride pipes (PVC) of 32 mm, 40 mm, 50 mm, 63 mm and 75 mm nominal diameter. The main components of a typical drip irrigation system are shown in Figure 2.1.

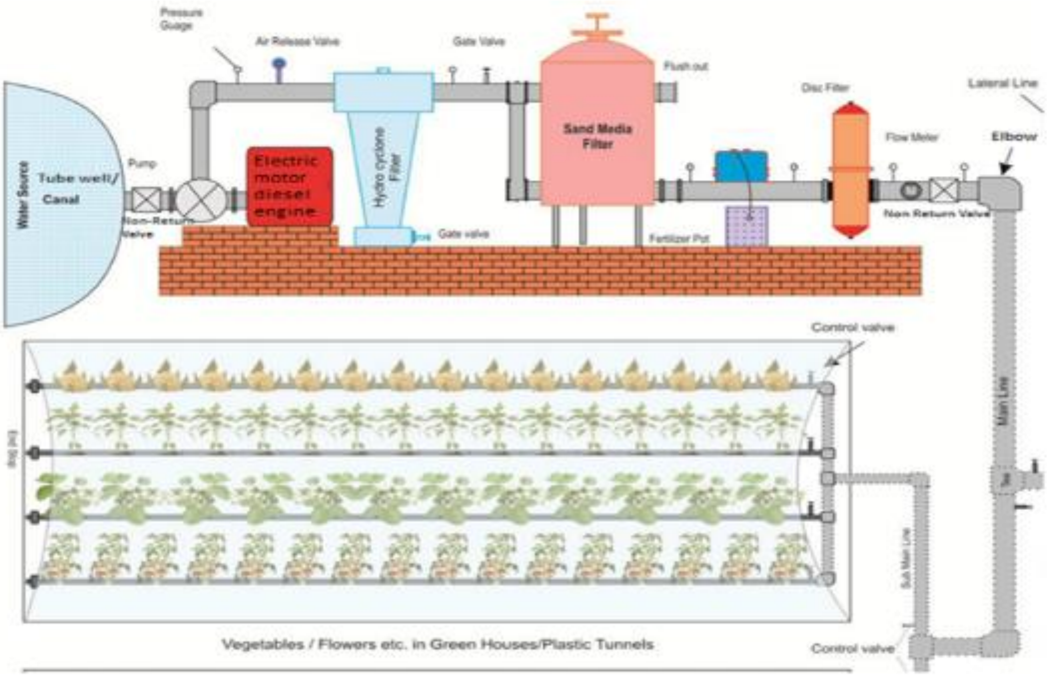


Figure 2.1: Schematic diagram of a typical drip irrigation system presenting main components of the system (Director General Agriculture, 2011).

In Pakistan most of the drip irrigation systems are designed for a 10 to 15 year of lifetime and drip tapes are rolled up between the seasons for intercultural and other agronomic practices (Akhter, 2012). It has been observed that quite a few vegetable farmers around the world are retrieving drip tapes to reuse in the next growing season and this process of retrieving drip tapes comprises of factors like machinery, fuel, and labour etc. The management cost involves in retrieval, storage and reuse of the drip tapes along with the life of the drip tape are significant in the selection of drip tapes and emitters. It is not clear if this practice has been factored into the selection of drip pipes and or emitters which are included in the standard designs.

2.3 Filtration

Filtration equipment is very important, as it is necessary to provide clean water for the smooth and satisfactory operation of drip irrigation system. Clogging of emitters is arguably the most important problem that is faced during operation of the system. Consequently, filtration is the most important aspect of drip irrigation design and good quality design is required to ensure that these systems will function in an appropriate way, over extended periods. The selection of filters depends on the water quality and source.

Water available in Punjab is both brackish and fresh. The drip irrigation is the only type of irrigation that can be used to apply saline water due to the reduced evaporation losses, while the size and selection of emitter along with the filtration needs to be selected according to the quality of water. Drip irrigation can additionally reduce the effects of salinity by maintaining continuously moist soil around plant roots and providing steady leaching of salt to the edge of the wetted zone. Most of the drip irrigation systems in Punjab are designed for one source of water and ground water is used when surface water is not available at the site and only few places use both, and filtration is selected accordingly. Different types of filters can be selected for the filtration process, depending upon the water source, quality and size of unwanted particles present in the water. These particles can be inorganic or organic e.g. algae, diatoms, fish, snails, larvae, bacteria, parts of plant, sand and silt. Some of the most commonly used filters are sand media filter, screen filters and gravel filters which each are effective for removing different types of particles from the water (Howell et al., 1980; Director General Agriculture, 2011).

Screen filters are normally used for clean water sources with no presence of algae, clay and suspended particles. Gravel or sand media filters are effective in removing all types of physical impurities organic or inorganic, algae, silt, clay and suspended particles etc. Gravel and sand media filters are mostly recommended in case of open wells, river, canal, and where the quality of water in the source is expected to vary with rainfall or runoff. Hydro cyclone filters are also called centrifugal filters and are mostly used to separate sand, silt and particles heavier than water but cannot remove algae and clay.

A study conducted at Postgraduate Agricultural Research Station (PARS), Faisalabad, Punjab, Pakistan on maize crop using drip irrigation and raised bed technology and using good quality, marginal and hazardous water to explore the effect of irrigation methods and water quality on maize yield and water use efficiency. It was concluded that drip irrigation system was more efficient irrigation system over raised bed irrigation system even in marginal and poor-quality water. The crop yield and water use efficiency were higher in drip system producing 19% more crop production over raised-bed irrigation system using good quality water. For marginal and hazardous water crop yield was increased by 23% and 25%, respectively. Therefore, drip irrigation system was more efficient for saline water. Although crop production using drip irrigation and raised bed was reduced by 5% and 12% with marginal water while the crop reduction was 10% and 17.9% using hazardous water. It is concluded that drip irrigation can be implemented where groundwater quality is marginal to hazardous quality to get high crop production and water use efficiency (Irfan et al., 2014).

2.4 Emitter characteristics

A basic component of emitter characteristic is the flow rate versus pressure head relationship, which is very important for the emitter selection and system design. The relationship between emitter operating pressure and flow rate is defined as:

$$Q = kH^{x} \qquad 2.1$$

Where Q is the emitter flow rate (L/h), while k is the constant, H is the pressure (m) and x is the emitter exponent. Exponent x is an indication of the flow regime and emitter type. It is an indirect measurement of the sensitivity of flow rate to the change in pressure. The value of x ranges between 0 to 1.0 and a low value of x shows lower sensitivity and higher value of x shows higher sensitivity.

For pressure compensated emitters (PC) the emitter's exponent x should be less than 0.1 and should approach 0, while for non-pressure compensated (NPC) emitters it should approach 0.5 (Cuenca, 1989). Pressure compensated emitters provide almost constant flow rate over a wide range of operating pressures due to the characteristics of manufacturing material. While non-pressure compensated emitters, produce a variety of flow rates as the operating pressure changes in the lateral, generally the flow rate increases in a non-linear fashion with the increase of pressure according to the characteristics of the emitter.

Therefore, emitter flow and their flow regime are critical for the drip irrigation design and this information is gained through the manufacturing variation coefficient and the emitter characteristic equation (flow-pressure relation) (Thebaldi et al., 2016). It is observed that these emitter characteristics have not been evaluated in already installed drip irrigation systems in Pakistan.

Variation in supply pressure and heat variability during the emitter manufacturing, as well as, the use of a heterogeneous mixture of building materials used for the production results in the variances in emitter geometry (Kirnak et al., 2004). Although the ideal drip irrigation system is the one in which all emitters deliver the same amount of water during an irrigation period, so that each plant receives similar amount of water. It is observed that the pressure and discharge variation in drip irrigation system is unavoidable due to material quality standards, emitter's hydraulics or less emission uniformity (Mangrio et al., 2013).

Drip irrigation performance is drirectly influenced by the emitter flow-pressure relation, head loss along the main line, submain line and lateral driplines as these parameters constitute hydraulic characteristics that influences the irrigation performance. These characteristics vary according to emitter type, its constituent material, manufacturing process and connection to the line (Frizzone et al., 2012; Thebaldi et al., 2016).

Other factors affecting emitter flow rate are clogging, flow regime, variation in water passage dimensions, emitter design and emitter manufacturer variation, as not all the emitter designed can have the exact same water passage dimensions and design. The variations in emitter passage size, shape, and surface finish that do occur in absolute small magnitude but represent a relatively large percent variation. While operating pressure range and temperature can be another important factor for the difference of emitter flow rate of particular emitters and this difference in the flow rates of emitters represents the varying characteristics and working of specific emitters.

Moreover, along with the emitter discharge, water application, emitter spacing, the soil–water relationship and soil texture also plays significant role in drip irrigation designing (Shan et al., 2011). Emitter selection and emitter spacing can be further improved by studying the detailed soil wetting patterns in terms of depth and width of wetted soil to improve the drip irrigation design procedure (Zin El-Abedin et al., 2015). While the soil moisture distribution under field conditions are highly affected by air temperature and humidity which are necessary to be evaluated to fulfill the crop water requirement and efficiently design a drip irrigation system accordingly. While hydraulic parameters of drip emitters play a vital role in uniform and efficient water application (Shareef et al., 2016).

2.5 Review and analysis of Indus Basin irrigation system

As the Indus basin irrigation system is contributing to the major agricultural production in Pakistan, thus it was important to review and analyse the whole irrigation system to evaluate and eradicate the inconsistencies and inadequacies at ground level. Therefore, the issues are evaluated at both the structural and management level of Indus Basin irrigation system.

Only 15 to 17% of country’s budget is used for the maintenance of irrigation infrastructure and due to lack of enough investment on the irrigation and drainage system about 50% of culturable command area and 37.5% of the gross culturable command area is under water logging and salinity that result in 40 to 60% production losses (Bakhshal & Masood, 2012).

To fulfil the country’s food and fibre demands, 90% is contributed by Indus basin, while 10% is contributed by rain fed regions and (Bakhshal & Masood, 2012) similarly specified that the major reasons for the incompetency and deterioration of the Indus basin irrigation system are the separate management and lack of coordination between different major sectors like agriculture, irrigation, environment and social divisions.

While the poor water policies, poor operation and maintenance of surface and ground water system, lack of modern technologies for improved water application and the lack of interaction among different water related stakeholders resulted into the low efficiency and outcome. According to (Iqbal & Iqbal, 2015) another reason for the low efficiency is the lack of strategic system to overcome the issue of water crisis.

However, the researchers and governments are seeking combined decision making across the conventionally separated sectors of water, energy and agriculture in Pakistan as the rising energy costs and energy outages have direct negative impacts on water and food availability (McMahon & Price, 2011). A key limitation is the lack of knowledge about nature and extent of the interdependencies, which is required to make informed decisions (Rothausen & Conway, 2011).

Even though the ground water resources has been a key element in the planning and management of Indus basin, there is a lack of research on its impacts on agriculture, water and energy sources (Afreen et al., 2013). In some selected areas groundwater level and quality are monitored, but the data and research has not been included in the conjunctive surface and ground water management and planning at provincial level (Qureshi et al., 2010).

Farmers need more education about the management of conjunctive water resources to grow the suitable crops. Another constraint is the limited and inadequate information and data available on groundwater resource’s availability, quality and withdrawal etc (Qureshi et al., 2010).

Besides, the farmers at the end of the water supply chain are mostly water buyers and frequently face water uncertainties, which result into the inefficient water application. So, (Watto & Mugera, 2015) suggested that additional policies need to be implemented to improve the allocation security and equity of access for water buyers. Likewise, farmers need to be educated and informed regarding the state and quality of groundwater resources. Prevailing issue of water scarcity can be resolved by attaining higher irrigation water efficiency.

Iqbal & Iqbal (2015) advised to use the surface water wisely and judiciously due to the water shortage as Pakistan is currently dealing with a huge power crisis with the increase in electricity prices. That is putting pressure on ground water resources and increasing tube well prices making it an unreliable source to meet the crop water requirements.

Despite the serious energy shortages, there is a little knowledge and data available on energy use in different sectors in Punjab and the energy consumption in ground water pumping is mostly overlooked (Siddiqi & Anadon, 2011) and with the continuous decrease in ground water level and rising energy prices, pumping cost will increase drastically, that will in turn severely affect the farm yield and income (Cook et al., 2009).

Therefore, extensive research is required on detailed energy consumption in different sectors, ground water pumping and crop production to evaluate the current and future energy needs. Assessing the energy needs will help in taking informed decision to fulfil future water, energy and food demands (Afreen et al., 2013).

Spatial sampling and surveys can be designed and conducted to gather and link water data at canal command, district and aquifer level. These analyses will help with the conjunctive water management for different types of crops with varying seasons and cultivation practices and will improve the knowledge and understanding of farmer’s needs, informed decision making for the efficient water management (Afreen et al., 2013) .

To reduce the ground water use the government needs to make changes in canal water deliveries and provide support to the farmers in on farm water management and adoption of advanced irrigation technologies like drip irrigation to reduce the water and energy consumption (Afreen et al., 2013).

As the crop productivity and cropping pattern varies provincially. Prevailing cropping patterns need to be reviewed in the areas with insufficient ground water resources in Punjab and then separate strategies need to be formulated for large commercial and small poor farmers, as the small farmers are only dependant on ground water resources. Farmers also need to be educated about the current available water resources and their practical management. Possible technical, scientific and political tools need to be implemented to preserve the ground water quality and resources. Modern irrigation technologies need to be introduced to preserve the current water resources (Qureshi et al., 2010).

Due to poor performance, low distribution efficiency and poor maintenance, farmers at the tail end receives reduced or no water. Moreover, high conveyance losses, lower water allocations, regular canal breaches are observed in the canal irrigation system. Major problems related to groundwater use were increasing (diesel) fuel costs, regular cuts in electricity (load-shedding) and dropping groundwater tables (Masih et al., 2014). It is evident that the Pakistan’s water availability is decreasing, and enormous amounts of water are lost due to deteriorating watercourses and wasteful on-farm water use.

According to Kahlown and Majeed (2003) the major challenges that Pakistan must overcome in improving irrigation performance can be summarised as follows. Despite massive development in the irrigation sector in Pakistan, agriculture continues to suffer from low productivity relative to world levels.

This may be attributed to poor management and uncertain supply, overexploitation of ground water, water losses through evaporation and seepage, inequitable distribution of water between canals, watercourses and head and tail users, and low prices of surface irrigation water (Mellor, 1996; Hussain et al., 2001).

2.6 Need for improved irrigation performance in Pakistan

Agriculture is the backbone of Pakistan’s economy as its contribution to the national gross domestic product is approximately 21.4% and 74% of cultivated area is irrigated (14.6 million hectares) out of 22 million hectares (Iqbal & Iqbal, 2015).

Iqbal & Iqbal (2015) recognized that while other developing countries of the world are using approximately 70% to 80% of their freshwater resources for agriculture, Pakistan is using 98% of freshwater resources for agriculture and the water consumption is continuously rising from last ten years. It is estimated that the flow of water from the shrinking Himalayan glaciers to the Indus river will also reduce by about 8% over the next four decades.

Briscoe & Qamar (2006) has indicated that Pakistan has already fallen below the water-stress threshold and will reach water scarcity by 2035 and according to (Iqbal & Iqbal, 2015) per capita water availability was 5600 cubic meter in 1947 and it shows a constant decline and will continue to drop in future. Agricultural water availability is decreasing with each passing year, mainly due to reduction in Pakistan's water storage capacity, increasing population and climate change. (Masih et al., 2014) similarly indicated that the water availability has declined to about 1000 m^3/capita and will reach to 915 m^3/capita by 2020. To overcome this situation and increase water productivity, efficient water application is crucial as the water productivity has been reported to be as low as 0.1 kg /m^3 of water (GOP, 2011; Bakhsh et al., 2015) and it is estimated that this amount would further decrease to 600 m^3 by 2025 (Javed et al., 2015).

Moreover, Pakistan is the world's sixth most populous country with the population of 185 million, which has increased by over 25% in just last ten years and is expected to reach more than 230 million by 2030. As more than 50% of the population is already characterised as food insecure (with less than 2000 calories /person/day) and 28% as severely food insecure (with less than 1700 calories/person/day) and this will be generating alarming food security issues (Masih et al., 2014). This estimated population growth will demand the substantial increase in food production and related increase in either water availability or efficiency of use of water (Archer et al., 2010).

Primarily irrigation system was developed to irrigate large area with limited water at a cropping intensity of approximately 65 percent (Ahmad et al., 2007), but to meet the food and fibre demand of ever-increasing population, cropping intensity has increased up to 150% or even more in some areas due to the accessibility to additional ground water supplies (Ghulam et al., 2019).

Table 2.1: Pakistan's water scenario (Ahmed et al., 2007)

Year		**2004** ($\times 10^3$ GLs)	**2025** ($\times 10^3$ GLs)
Water resource availability		128	128
Water requirement (including drinking water)		142	166
Overall shortfall (deficit) = availability		13	38

Table 2.1 shows the estimated quantity of water available and required to fulfil the demand of Pakistan in 2004 and 2025. The predicted shortfall is 13 568 GLs in 2004

and 38 238 GLs in 2025, which represent a significant issue for the country.

Trimmer (1990) reported that there are total of 10,000 watercourses in Pakistan and about four million farmers; the maximum annual water requirement for crops can be 1600 mm with farmers receiving only about 75% of that amount for intense cropping, so the system is 25% under irrigated.

The average water allowances over the year for the older main canal systems in Pakistan is 0.23 litre /sec /ha or 7.25 ML/ha/year. The secondary level distributaries also have a similar uniform pattern of water allowances. However, a contrasting situation exists in the tertiary level watercourses with highly variable water allowance (Bandaragoda, 1996).

As given in Section 1.1 that due to heavy losses in canals and watercourses, out of 6.9 million MegaLitres of water only 3.2 million MegaLitres reaches to the farm gate while, uneven fields, poor farm design and traditional irrigation methods resulted into significant water losses on farm (Eleazar, 2018). Which depicts the low water efficiency of conventional irrigation systems on farm.

Hussain et al., (2011) stated that the water availability in the Indus basin is declining; the total available water is 274 billion m^3, of which 130 billion m^3 is available for use, while system losses are almost 62 billion m^3. Further, the gross water supply for agriculture is 190 billion m^3 with a shortfall of 20 billion m^3. This is predicting an increase to 27 billion m^3 by 2015. The introduction of water-management policies and high-efficiency irrigation techniques has been suggested, to conserve the remaining assets.

Additionally, despite the increase in storage capacity of Indus Basin Irrigation system it cannot accommodate the changing water demands (Qureshi et al., 2010).

Iqbal & Iqbal (2015) have also specified that "this would not have been the case if Pakistan would have enough water reservoirs for the water storage. The reservoirs can be further used to generate electricity and increase the area under cultivation in arid areas of the country, in turn strengthening the agricultural backbone of the country".

Irrigated agriculture area has lost its sustainability due to the number of factors including: growing water demand with increasing population, lack of appropriate canal system maintenance, waterlogging, salinization, inadequate participation of consumers, improper pricing of water, misuse of ground water resources and lack of field drainage system, which has placed large areas out of reach for poor farmers. Thus, the rainfed areas require more attention to increase the crop production by efficient water management, equitable water distribution, effective drainage interventions and institutional reforms to make the managing organizations more involved and approachable (Bakhshal & Masood, 2012).

Basharat et al., (2014) explained that “The insufficiency of canal water resources, as well as the variability of rainfall and high runoff during the monsoon season resulted into the overexploitation of groundwater. Groundwater resources have been heavily exploited in Pakistan in the past three to four decades. About one million tube wells are located throughout various irrigated parts of the country. These tube wells pump about 53 MAF groundwater, annually. According to depth to water table (DTW) position in Indus Basin Irrigation System for June 2011, 20% irrigated area of Punjab province is facing groundwater depletion i.e. having DTW more than 12m. On the other hand, 99.5% area in Lower Indus (Sindh & Balochistan) falls within 4.5m depth, out of which 53.7% falls in waterlogged category i.e. within 1.5m, depth to groundwater. That has put an extra burden on the farmer communities and stress on the energy resources. Under this scenario it is direly needed that every drop of water must be counted and used wisely and efficiently. "More crop per drop" slogan must be turned into reality.

Watto & Mugera (2015) obtained results from a cross-sectional dataset of 172 cotton growers, including 92 tube-well owners and 80 water buyers. Technical as well as water application inefficiencies were observed due to poor irrigation management practices. The major reasons are the lack of information about the prevailing and future availability of ground water resources, the consumptive crop water requirement and the conventional irrigation application practices.

More systematic measurements are required to analyse and study the water balance components at farm to system scale using hydrological modelling. Water balance components are the changes in groundwater recharge, surface runoff, water depletion and soil moisture storage in the root zone. Therefore, effective conjunctive water management and understanding of the impacts of surface and ground water use on salinity and water logging is essential to secure the Pakistan’s agricultural future. The major factor governing this is the farm size as the small farmers are the majority and the small net water savings may not be reused on farm. alternatively, water savings could allow large and medium farmers to get more safe and substantial water supply. Real water savings can only be achieved by providing incentives to small farmers and limiting the ground water use by medium and large farmers, improving the performance of canal water supply systems, promoting evaporation reducing technologies in Punjab, investing more on data collection, evaluation and monitoring water productivity using resource conservation technologies at all scales from farm, to canal system and to basin level (Ahmad et al., 2007).

Other ways that can be used to improve irrigation efficiency and production are the lining of canals, repairing and maintenance of water delivery systems, land levelling, improved and equitable distribution of water system, developing plans and policies for surface and ground water management. However, adopting water saving techniques like pressurized irrigation methods in preference to traditional surface irrigation is the main technique chosen to solve these irrigation performance issues. The current water policies, depletion of ground water due to over exploitation, imbalance between supply and demand and inequitable water distribution has created hindrance in adoption of these technologies.

2.7 Review and analyses of drip irrigation systems in Pakistan.

This project aims to investigate the factors associated with the failure of previously installed drip irrigation systems to provide an improvement in the broad technological performance of drip irrigation systems in Punjab. Potential and need for the promotion and adoption of drip systems, constraints in adaptability of drip irrigation systems and need for hydraulic performance evaluation of these systems are discussed in detail. Already installed drip irrigation systems in Punjab, Pakistan are comprehensively examined and discussed in detail in terms of design, installation, monitoring and maintenance after installation.

2.7.1 Potential and need for the promotion and adoption of drip systems in Pakistan

As stated by (Afreen et al., 2013) the total agricultural production in Punjab was 53.5 million tonnes during 1994–95, and by 2010 it has increased to 70.2 million tonnes. Likewise, roughly 10% agricultural area have increased from 15.63 million hectares in 1994 to 1995 to 17.12 million hectares in 2009-10.

This massive increase in the agricultural production and area under cultivation has also put an immense pressure over the water resources and according to World bank (2005) report Pakistan falls in the category of water deficit countries with low water availability and it is necessary to get “more crop per drop”. According to (Jehangir et al., 2007) the crop water productivity can only be improved either by increasing the crop yields or by minimising the water losses or managing both. Thus, (Muhammad et al., 2010) have suggested to adopt water saving irrigation technologies like drip irrigation technology to enhance the crop water productivity, yield and quality of agriculture products.

In Pakistan, surface irrigation is the most common traditional irrigation method practised by farmers. Its application efficiency is no greater than 50% due to a lack of management, poor farm design, misuse of water resources, and water losses at various places (Director General Agriculture, 2011).

Also the yield per unit of water in Pakistan is lowest in the world (Alam et al., 2006). Though, research in drip and sprinkler irrigation has shown appreciable saving of water and high crop yields (Dagnino & Ward, 2012) because the drip irrigation method enables the effective and timely application of water, fertilizer and nutrients as per the plant’s requirement at various stages of its growth.

Pakistan is the fourth largest rice exporter of the world, producing about 2.6-6 million tons of rice annually and exporting roughly one million ton annually. Punjab and Sindh are producing 95% of rice production and has a potential to increase the export up to $4 billion annually with precise management of water resources. Farmers are losing interest in rice cultivation and rice production have decreased significantly due to the water shortage and flood irrigation method (Iqbal & Iqbal, 2015).

Then, implementing drip irrigation can give more rice production but also uses 70%

less water than traditional paddy rice with highly reduced methane emissions and arsenic uptake (Netafim Ltd, 2020).

A sample analysis performed by (Reddy & Satyanarayana, 2010) on 12 different fields of sugar cane in India, shows that 1.2 ML of precious ground water and 1365 kWh of energy can be saved for each hectare using drip irrigation system. Drip irrigation system has similarly shown improved crop productivity and is highly recommended as it can achieve efficiency as high as 95%, compared to the traditional flood and furrow irrigation. (Mangrio et al., 2013) have also agreed that the efficient utilisation of irrigation water is possible by the adoption of highly efficient irrigation system, such as, drip irrigation.

Baqi a farmer described that at his farm 4 hours of water supply was not enough to irrigate even 2 acres of land through the conventional flooding method. However, after using drip irrigation system 4 to 5 acres of land can be irrigated in less than one hour. He explained that the productivity of the system adding drip irrigation allows better fruiting on every plant. Plant health doesn’t get compromised, while the survival rate of saplings is 97% which was 60% on flood irrigation (Bank, 2014).

In another case study the yield of sunflower in both drip and furrow irrigation is recorded as 3098 kg/ha and 2467 kg/ha respectively. The results show 26% increase in yield with drip irrigation over furrow irrigation method due to precise irrigation management and effective utilization of fertigation in drip irrigation (Qureshi et al., 2015).

Moreover, drip irrigation is an efficient and financially practical irrigation method for vegetables as the roots of most of the vegetables are confined in upper layer of soil and required regular irrigation. Drip irrigation has the highest potential for the efficient use of water and fertilizers as compared to the conventional irrigation methods as it can increase water use efficiency (60-200%), saves water (20-60%), reduces fertilization requirement (20-33%) through fertigation, improve crop quality and yield (7-25%) (Arya et al., 2017).

Bakhsh et al., (2015) conducted a field experimentation on wheat using drip irrigation, perforated pipe and conventional irrigation to review the causes for low water productivity and address the farmers concerns in Punjab. Major concerns of majority of the farmers were canal water shortage, energy and fertilizer related issues that are contributing to the low water productivity. Water productivity measured using drip irrigation was 2.26 kg/m^3 for wheat crop with 40% water saving as compared to the traditional irrigation method. Also, water productivity measured using perforated pipe was comparatively better i.e. 1.46 kg/m^3 with 20% water saving. Benefit cost ratio recorded for drip irrigation, perforated pipe and conventional were 2.47, 2.20 and 1.96, respectively. Further irrigation efficiencies calculated for drip irrigation, perforated pipe irrigation and flood irrigation were 95-98%, 65-76% and 50-59% respectively. The results showed that the losses can be minimised, and water productivity can be improved using suitable high efficiency irrigation methods.

According to Shakeel Abbas, Deputy District Officer, Water Management Body, District Layyah, “the results gathered from the evaluation studies for drip irrigation show that it increases the efficiency of water use by 50%, enhances the yield from 35 to 100%, reduces the mortality rate of the plants and also gives the ease of efficient nutrient distribution. Additionally, it reduces the labor work of a farmer by about 20%” (Bank, 2014).

After conducting another field study, (Qureshi et al., 2015) stated that drip irrigation can be successfully adopted in Pakistan and has the potential to save up to 56% water and can increase the sunflower yield by 26% over furrow irrigation and there is a possibility of further expansion with the cost effectiveness and steady management of drip irrigation.

In a study conducted in southern India, drip irrigation has shown significant water conservation with high yield and farm profitability and reduced cost of cultivation. The findings have shown that the drip irrigation technology increases the net sown area and net irrigated area and, in this manner, helps in achieving higher cropping intensity and irrigation intensity. It is concluded that drip method of irrigation helps the farmers to get more crop and income per drop of water. As the adoption and suitability of drip irrigation depends on the cropping pattern. It is recommended that it should be promoted in the areas where water and labour are scarce at alarming rate and farmers are shifting from annual crops towards high value and wide spaced crops, such as coconut, grapes and banana like vegetables, sugarcane. Also, because drip irrigation systems are widely adopted by large farmers as compared to medium and small farmers due to its high initial cost. Additionally, drip irrigation benefits are verified and the water use efficiency can be improved up to 100%, only if designed and managed precisely, although studies on its influence on the whole farming systems are limited and yet to be explored (Kumar & Palanisami, 2014).

The major factors contributing to the adoption of water conservation technologies are the increase in crop yields and farm productivity with reduced energy and labour cost and increased area under cultivation (mainly for the large and medium farmers). (Ahmad et al., 2014).

Due to the declining surface and groundwater supplies, agriculture water use needs to be reduced and is only possible with the implementation and adoption of water conservation technologies like drip irrigation. Similarly, higher yield of vegetables, higher water use efficiency and considerable water savings is recorded with the use of drip irrigation system. Surface irrigation system’s efficiency can be improved with improve design and maintenance, but the efficiency will not be higher than drip irrigation system (Ahmad et al., 2014).

There is a constant increase in demand for edible oil in Pakistan as the country’s production is only 24% of the total demand and the remaining 76% is imported. Therefore, it is required to increase the sunflower production by increasing the area under cultivation and yield per hectare and there is a great potential to increase the production and area using drip irrigation technology. Currently average yield of sunflower is very low i.e. 1801 kg/ha and it is grown on 343308 hectares of land with an oil production 211 tons. There is a potential to increase the cultivation of sunflower up to 535560 ha with the production up to 1659762 tons with the implementation of drip irrigation method (Qureshi et al., 2015).

Due to energy shortages and increase in electricity prices, a study has been conducted at Fateh Jang in the arid zone of Punjab, Pakistan to install and evaluate the solar operated and diesel operated drip irrigation system. These systems are evaluated in terms of the performance, efficiency and distribution uniformity and it was found that solar operated drip irrigation system was more efficient, energy saving, economical and environmentally safe as compared to the diesel engine operated system. however, the initial installation cost of solar operated system was high and with the emission uniformity values were between 85-90% at 8.3 l/h discharge. While, the application uniformity and distribution uniformity were 98-99% and 99% respectively at the same discharge for different supply pressures (kPa). It is observed that the uniformity measured is satisfactory with low operational cost with easy handling and it is best suited for arid zone of Fateh Jang located in Punjab (Mongat et al., 2015). Further adoption of fertigation needs to be promoted to gain real benefits from micro irrigation (Reddy & Satyanarayana, 2010).

Similarly, developments in manufacturing technology have also considerably decreased the initial cost of installation of pressurised irrigation systems that was a major deterrent for adoption of drip irrigation. Furthermore, acute water shortages and a trend towards growing higher value crops has motivated farmers in other countries with similar growing conditions to invest in pressurised irrigation systems (Pakistan Agriculture Research Centre, 2010).

Hence, to secure the future of agriculture in Pakistan advance high efficiency technology needs to be introduced to promote the crop diversification and improve water use efficiency, such as drip irrigation which can also enhance the crop yield and quality in conjunction with the increase farm profitability and crop diversification, growing high value crops.

2.7.2 Constraints in adaptability and successful implementation of drip irrigation systems in Pakistan

One of the main constraints in adoption of pressurized irrigation system is the rotational water supply system of Pakistan known as “*Warabandi*”.

This means that drip irrigation systems require an on farm storage of water which involves additional expenses (Kahlown et al., 2007). *“Warabandi*” is a traditional method of water delivery to all the farmers equitably on turn basis, not on demand basis and a farmer will get water on his turn on a predetermined day, time and duration, whether his crop need water or not. This is because of the fact that the whole irrigation canal network is gravity flow system. It is a continuous cyclic rotation of water. One cycle usually ends in 7 days. The farmer receives water supply for a duration relative to the size of the field and land holding (Bandaragoda, 1998).

Delivery of irrigation water to farmers is supply based. Therefore, crop water requirements are not met timely which negatively affect agricultural production (Director General Agriculture, 2011).

The main objective of “*Warabandi”* was to provide limited water resources over large area on an equitable basis with minimal maintenance and operational cost. A continuous flow of water is assigned to each watercourse through concrete outlets, which provide a constant discharge according to the size and area of land to be irrigated (Murgai, 1998).

From last 4 to 5 years farmers are not receiving their fixed share of canal water due to the unreliability and unpredictability of surface water availability. According to 75% of the farmers, the reasons for the poor performance of the irrigation system are low discharge rates, farm location in terms of the distance from the canal or water course head, poor maintenance, water theft, reduced time allocation and conveyance losses (Ahmad et al., 2007).

In Pakistan, farmers receive a canal water based on land holding size and have only fixed allocation of water per week (Termed as Warabandi) based on rotational scheduling. Due to the lack of opportunity to sell or store water, they try to utilize whole allocation each week. As the ground water abstraction has a lack of control and regulation authority and policies therefore, unregulated abstraction has resulted into the disruption of natural water balance at farm, system and basin levels (Masih et al., 2014).

Likewise, Bakhshal & Masood, (2012) stated that water scenario is no different in Sindh province. Major obstacles for the efficient water management and conservation are the unreliable and inequitable water distribution, water losses (seepage 55-66% and application 30-40%), lack of coordination among irrigated agriculture stakeholders and lack of enough investment on the irrigation system.

Another restriction in adoption of the pressurised irrigation systems in Punjab is the high initial cost and low availability and high prices of energy as majority of the farmers have small land holdings (less than 5 ha). There is a need to develop and introduce the cheap and innovative methods to improve the water productivity, irrigation efficiency and reduce the high initial cost. Also the prevailing efficient irrigation methods have not been evaluated in terms of suitability, economic viability, payback period and benefit cost ratios (Bakhsh et al., 2015).

Moreover, famers are mostly inexperienced and needs training regarding operation and maintenance of the drip irrigation (Qureshi et al., 2010; Mangrio et al., 2013; Bakhsh et al., 2015). Farmers also need support and expertise in irrigation scheduling and fertigation (Bakhsh et al., 2015). Although further studies are required on the irrigation application time and consumptive crop water requirements for different crops using drip irrigation (Watto & Mugera, 2015). As in real field conditions the drip irrigation systems can too show low performance and yield and can even result into the wastage of water if not carefully designed and installed.

There is a lack of capacity building of the manufacturers, suppliers, installers, and local technicians. Service Providers and farmers required support and assistance with irrigation scheduling and fertigation scheme for improving crop productivity (Bakhsh et al., 2015).

The study conducted by (Dagnino & Ward, 2012) verified that the drip irrigation system reduces the irrigation application and increases the crop yield and farm productivity, but the results showed that the evapotranspiration at the farm level is higher under drip irrigation as compared to the surface irrigation. Increase adoption of this technology will increase the water depletion at farm to catchment levels, reduce groundwater recharge, and will reduce the flows to the users at the tail end. Therefore, in such areas water application and depletion limits need to be implemented to maintain the water balance.

Drip irrigation will protect the security of Pakistan’s irrigated agriculture in future but the lack of knowledge regarding the advantages associated with drip irrigation technique, lack of experience with the technology and high initial cost are the main hinderances in its effective adoption and implementation. The cost of drip irrigation is 1043 AUD - 1137 AUD per acre, which is very high for financially suffering farming community. Therefore, its promotion and adoption solely depend on the government’s financial and technical support to make these systems affordable and feasible for small and medium farmers (Iqbal & Iqbal, 2015).

The approximate capital costs of drip irrigation for a 2-hectare row crop and vegetable farm is 3155 AUD per hectare and 3128 AUD per hectare respectively. Similarly, for a 4-hectare crops and vegetable’s farm the approximate cost is 2427 AUD per hectare 2787 AUD per hectare respectively.

These systems require careful study of all the relevant factors like land topography, soil, water, crop and agro-climatic conditions and suitability of drip irrigation system and its components are vital in its design and performance. In lighter soils, subsurface drip may be unable to wet the soil surface for germination, so in lighter soils, careful consideration of the installation depth is required. The main purpose of drip irrigation is to reduce the water consumption by reducing the leaching factor.

Another technical challenge with this system is that the sun can affect the tubes used for drip irrigation, shortening their usable life and solution for this can be wheat or rice straw that should cover the pipes and has the potential to prevent the direct striking of sun rays on pipes. Farmers should be made aware of the fact that if water is not properly filtered and the equipment not properly maintained, it can result in clogging. Farmers are also needed to be made aware of the time required for water application with drip irrigation system and extensive research is required on the evaluation of subsurface drip systems installed for irrigating different crops as the irrigator cannot see the water that is applied. This may lead to the farmer either applying too much water (low efficiency) or an insufficient amount of water and this is particularly common where the operators are not well experienced and trained. The drip irrigation technique can also lead to the waste of water, time and harvest, if not installed properly.

The areas where water is of high salinity or alkalinity the irrigation will rise the soil salinity due to the poor soil infiltration and the farm soil will slowly become unsuitable for growing crops. Thus, using drip irrigation in semi-arid and arid regions where rainfall is not enough to leach down the salts, the fields will turn barren, but this challenge can be resolved with occasional flood irrigation to leach the salts down the soil (Iqbal & Iqbal, 2015).

Increased petroleum prices and constant unscheduled electricity outages has in addition resulted into the decrease in crop yield particularly in rural areas. Electricity is used for pumping water for the agriculture use and due to the excessive electricity load shedding in rural areas, alternate energy sources like solar, wind, biomass, hydal and geothermal sources needs to be considered to sustain agriculture in future (Mongat et al., 2015).

Another major constraint is the lack of updated, efficient and technically suitable design for drip irrigation systems. While the current farmer friendly systems are designed by third party sales representatives, though technical professionals are required to design these systems. Although drip irrigation is the most efficient technique, but it requires technical knowledge as well as intensive training for its successful operation. Therefore, farmers and operators need to be trained by professionals regarding the operation and maintenance of the systems before the installation of the systems (Bakhsh et al., 2015).

Some of the other constraints and limitations in adoption of these new pressurized irrigation technologies reported by Alam et al. (2006) are extensive maintenance requirement of system components like emitter due to clogging, damage to the pipes due to rodents and insects causing leakages, salinity hazards due to reverse pressure gradient in saline areas. Economic and technical limitations observed are non-acceptability of these systems by farmers due to high initial cost, high skill requirements, lack of local manufacturing facilities and lack of expertise in sensitive technical areas regarding design, installation, maintenance and trouble shooting.

2.7.3 Need for the evaluation of hydraulic design and performance of Pakistani drip irrigation systems

The adoption of pressurised systems does not always deliver high efficiency for example in a case study by Latif and Ahmad (2008) on performance measures of a sprinkler irrigation system installed on a golf course, the results were evaluated and found that overall performance of the system was low due to excessive variation in pressures and, high relative humidity (43%), high wind speeds (3.6 m/s) in the day times. At pressure of 42.53 m (417 kPa), the *Cu* (coefficient of uniformity), *Du* (distribution uniformity) and application efficiency was 68.9%, 56.9% and 83% respectively and at a pressure of 45.80 m (449 kPa), *Cu Du* and *AE* was 61.7%, 50% and 78% respectively.

There is lack of updated, efficient and technically suitable design for drip irrigation systems and prevailing systems are designed by third party sales representatives instead of technical professionals (Bakhsh et al., 2015). Therefore, the already installed drip irrigation systems in Pakistan needs to be evaluated in detail in terms of design procedure and practices.

Further, extensive studies are required to be conducted on different soils at different locations to see the performance and adoptability of drip irrigation with respect to economics, material cost, payoff and constant management (Qureshi et al., 2015). Moreover, the prevailing efficient irrigation methods have not been evaluated in terms of suitability, economic viability, payback period and benefit cost ratios (Bakhsh et al., 2015).

This proves that besides the right selection of technology and irrigation method, the most vital element to achieve desired water productivity or water saving is the management of the system in terms of design, installation, and monitoring. The accurate management can be ensured by evaluating the systems is terms of performance and efficiency and needs to be tested with alternative energy sources to make it feasible in Pakistan.

It is also very important to have a clear understanding of the different water balance components along with knowledge of how certain interventions (e.g. drip irrigation systems) influence them in given field conditions (Ahmad et al., 2014).

Masih et al., (2014) proposed that the multi-disciplinary analysis and further research and development efforts are required in order to determine the adoption process and impacts of water saving technologies on food production and to verify the real water savings at field, farm and higher three-dimensional levels. Likewise, ground water is saline in Sindh province and these technologies can contribute to real water savings and sustainable food production by reducing the recharge to ground water.

Ever rising water shortages have impelled number of locals, irrigation industries as well as multinational companies to get interested and involved in the irrigation facilities and services to the farmers. However, the lack of quality check and control may have compromised the results in terms of suboptimal materials, poor design and services. Farmers completely lack knowledge and technical guidance and depends only on the service providers (Mangrio et al., 2013).

Asif et al., (2015) likewise suggested that in spite of increased popularity and acceptability of drip irrigation systems among the farmer community, the performance of these systems needs to be evaluated, tested and standardized. Because the drip irrigation systems can only apply irrigation water quite efficiently, if they are well designed. The water application uniformity calculated was more than 80% that specifies the correct designing in terms of selection and sizing.

Some performance evaluation assessment studies were conducted on drip/sprinkler irrigation on different crops by technical committees of Punjab Agriculture Department. The performance of the drip irrigation system showed 57% water saving in case of sugarcane while 50% for both citrus and potato crops against conventional irrigation methods. The increase in yield in drip irrigated areas was 34%, 39% and 105% for potato, sugarcane and citrus, respectively (Ashraff & Yasin, 2012).

According to the latest scenario in already installed drip irrigation systems in Punjab, the current operational performance is approximately 50% to 65% and no systems been evaluated in terms of hydraulic performance such as uniformity and emission measures (Khan, 2019). However, the past evidences have shown that the operational as well as the hydraulic efficiency can be increased up to 100%, only if the system is precisely designed and managed (Sivanappan, 1994). While, an efficient optimal design can be achieved using the selected software packages which can improve the hydraulic performance up to 100%, and following the suggestions provided regarding installation, monitoring and management, desired operational efficacy can also be attained. It is important to know that the efficiency can be highly affected by the slope and direction of the slope.

Besides, the availability of latest and new drip products have reduced the cost of system as the double drip tape with lower emitter flow rates have now been replaced with a single drip tape with higher emitter flow rates, that was unavailable previously in Punjab, Pakistan (Khan, 2019).

Additionally, improved irrigation efficiency does not always translate into” real” water savings as the real water savings depends on the hydrologic interactions between the field and farm, the whole irrigation system and the entire river basin. In fact, the water saving impacts of water resource conservation technologies are not well understood and documented beyond the field level. The real water savings can be much lower than the assumption, when field level calculations are applied to the bigger scales, because of water recycling and the conjunctive use of surface and groundwater in many areas, particularly rice based, cropping systems in Punjab (Ahmad et al., 2007). Pakistan is now moving from water scarce country to becoming water stressed country and has the potential to be a water famine country in coming ten years (Iqbal & Iqbal, 2015).

Over the years, considerable advancements have taken place all over the world because of computer-assisted design tools, better simulations, and analysis techniques to achieve the most reliable and optimal designs (Pakistan Agriculture Research Centre, 2010). Therefore, the already installed drip irrigation systems need to be evaluated in terms of water application efficiency and uniformity using advance software packages to make these systems affordable and suitable in Punjab, Pakistan.

2.8 Summary of previous drip irrigation projects in Pakistan

PARC (2010) has shown that only a few projects on a very limited scale had been undertaken in the past for introduction of pressurized irrigation systems in Pakistan. In these schemes, farmers have gained benefits and faced number of problems in different areas of design procedure and operation of the irrigation systems. None of these projects has obtained the desired level of success. A Summary of some of the projects is provided below:

1. "*Introducing Technology Irrigation Programmes in Punjab*" of almost $41, 300 AUD implemented from 1982-1986, installed 16 sprinkler irrigation systems and 3 of drip irrigation systems.

2. *Productivity Enhancement Programme (PEP)"* implemented from 1991 -1993 where 400 portable rain gun sprinkler irrigation systems were installed in Punjab region.

3. *"On Farm Water Management III Project"* of worth 18.31 Million AUD implemented from 1991-2000, 15 pressurized irrigation systems were installed.

4. *Second Barani Development Project, Rawalpindi"* of worth 0.39 Million AUD, implemented from 1990-1997. Total 53 hectares of drip and 50 number of sprinkler irrigation systems were installed.

5. "*High Efficiency Irrigation Programmes in Baluchistan*" installed 173 hectares of drip irrigation system from 1991-1992.

6. *"Introduction of trickle and sprinkler irrigation systems"* drip irrigation systems were installed on 164 hectares from 2000-2001 under this project.

7. *"Water Conservation and Productivity Enhancement through High Efficiency*

Irrigation Systems" implemented from 2007-2012 and 20, 000 pressurized irrigation systems were installed.

8. *"Punjab Irrigated agriculture productivity improvement project Revised"* of worth 0.68 Million AUD implemented from 2012-2021 and continue to install pressurised irrigation systems in Punjab.

9. *"Promotion of gram cultivation through life saving irrigation with sprinkler system under changing climate"* implemented from 2017-2020 of worth 0.038 Million AUD installing sprinkler irrigation systems.

Most of the drip irrigation systems installed in these projects implemented in the Punjab and Baluchistan Province of Pakistan failed or did not meet the designed requirements. The failure of drip irrigation systems could be defined as outright crop failure in terms of yield or crop quality, or hydraulic failure including an inability to uniformly distribute water, maintain flow rate due to emitter clogging, tape integrity or tape damage resistance or tape leaking during installation process. Furthermore, some systems were installed with insufficient system capacities to fulfill the crop water requirement due to in efficient design process. The concluding result is that many growers have abandoned these drip systems and according to (Reddy & Satyanarayana, 2010) both the industry and the projects require qualified and skilled manpower.

There could be number of possible factual reasons for the failure and low performance of the installed drip systems in Punjab, Pakistan. Anecdotal evidence from colleagues in the Pakistani government irrigation sector and private sector have suggested that a number of discrepancies are observed in existing drip irrigation designs that resulted in the low performance of drip irrigation systems in the Punjab. An understanding of operational problems (O&M Costs, quality of materials, farmer's concerns, technical issues, social constraints etc) reliability, lack of grower skill set and low drip irrigation performance of the existing "standard designs" from Punjab Province, Pakistan, have been established by interviewing farmers and gathering evidence from colleagues. The following sections will discuss the complications detected in data collection, design practices, installation and monitoring of already installed drip irrigation systems.

2.9 Analysis of typical drip systems of Pakistan

Different components of drip irrigation systems already installed around different cities of the Punjab region of Pakistan are shown below. View of drip irrigation pump shed installed including the components like filters, venturi assembly, pressure gauges, pump and flow meters along with the reservoirs are shown in Figure 2.2, Figure 2.3, Figure 2.4, Figure 2.7, Figure 2.9 and Figure 2.11. While the double dripline for orchards and single dripline for row crop installed can be seen in Figure 2.5, Figure 2.6, Figure 2.8, Figure 2.10 and Figure 2.11.

Figure 2.2 displays a view of pump shed installed in one of the sites in Punjab, Pakistan showing different important components like sand gravel filter, hydro cyclone filter, venturi assembly, pressure gauges and flow meter along with water reservoir.

Figure 2.2: View of a pump shed installed, showing filters, venturi assembly, pressure gauges, flow meter and water reservoir (Akhtar, 2010).

Figure 2.3 displays another pump shed installed, showing different components like filters, venturi assembly, pressure gauges and flow meter and separately constructed water storage tank.

Figure 2.3: Pump shed installed at a drip irrigation site in Punjab, displaying the major components and water storage tank (Akhtar, 2010).

It can be seen in Figure 2.4 that a pump shed is installed in a closed room showing different components like filters venturi assembly, flow meter, pressure gauges and pump etc.

Figure 2.4: View of another pump shed installed in a closed room including filters and other major components (Akhtar, 2010).

Figure 2.5 shows a double dripline installed in an orchard with each dripline at either side of plant rows. This dripline has button emitters installed directly on each dripline which provides water to the plants root zone from both sides.

Figure 2.5: View of a drip irrigation system presenting double drip tube with button emitters inserted along the dripline (Akhtar, 2010).

Figure 2.6 is a close view of double dripline installed in above-mentioned orchard showing individual button emitters installed.

Figure 2.6: Close view of a drip irrigation system installed at another site in Punjab showing double drip tube along each plant row with button emitters (Akhtar, 2010).

Another pump shed installed at one of the Punjab sites can be viewed in Figure 2.7. This drip irrigation system is designed for a cotton crop and a water reservoir have been constructed along with the pump shed.

Figure 2.7: View of another pump shed, and water reservoir installed in Punjab region of Pakistan (Director General Agriculture, 2011).

Single dripline with built in (integrated) emitters installed along the plant rows can be seen in Figure 2.8 and the pump shed and water reservoir installed at the same site can be seen in Figure 2.9.

Figure 2.8: Single dripline installed along the plant rows (Director General Agriculture, 2011).

Figure 2.9: View of a pump shed with main components installed at a site in Punjab region, Pakistan (Director General Agriculture, 2011).

Double dripline installed at either side of the plant rows in an Orchard can be seen Another double dripline installed along the plant rows in an orchard can be observed in Figure 2.10.

Figure 2.10: Double dripline installed in an orchard in Punjab region of Pakistan (Director General Agriculture, 2011).

Sand gravel, hydro cyclone filters along with control valves, pressure gauges, pump and venturi assembly installed at a pump shed and a single dripline watering two rows of plants on each side at the same site can be seen in Figure 2.11 and Figure 2.12 respectively.

Figure 2.11: View of a pump shed and its components installed in Punjab (Director General Agriculture, 2011).

Figure 2.12: View of a single dripline installed between two rows of plants in Punjab (Director General Agriculture, 2011).

2.10 Measures of irrigation performance

The intent to extensively install pressurised irrigation systems in Punjab and other provinces of Pakistan, failure of previously installed drip irrigation systems, the lack of performance measurement in Punjab, and an inadequacy of the current design procedure initiated the need for irrigation performance assessment results from design information and field measurements and to analyse the adequacy of the parameterisation of modern drip irrigation design software. These performance measures are introduced and explained below:

2.10.1 Introduction to the performance measures

Burt et al. (1997) explained that irrigation performance measures basically describe the partitioning of irrigation water. They assist in measuring and quantifying the amount of water, which enters the plant and root zone, how much is recoverable, and how much is added to the ground water and surface runoff. Most importantly, they explain how well the crop needs are met in terms of the irrigation water balance. Irrigation performance measures can be defined as the goodness of the irrigation, and the ability of irrigation system to irrigate well.

A farmer, a manager of an irrigation project, and a river basin authority will define water use efficiency differently and most efficiency definitions concern volume only because these are easy to measure. Uniformity is the term used to describe how water is distributed throughout the field, but uniformity is difficult to measure and is usually estimated (Hamdy, 2007). According to Soccol et al. (2002) the performance measurement of the operating irrigation system is important to be evaluated to determine the system’s efficiency during operation, total time required for effective operation, to measure the feasibility of improved performance, to improve the system management and comparing different systems and operating processes. Latif and Ahmad (2008) recommended that the performance should be determined under actual field operating conditions at regular short intervals, so that the system’s inadequacy or shortcomings may be detected in a timely fashion, and improvements can be made.

Maximum economic return and sustainability of water resources can only be ensured with efficient use of irrigation water, which can be monitored with suitable measures of performance. Excess or inadequate application of water leads to crop water stress, yield reduction or pollution of water sources due to leaching, runoff and soil erosion (Irmak et al., 2011). Larger populations increase in industrial and domestic water demands, potential of pollution of the water resource due to over irrigation, generation of salinity and water logging increase the importance of conservation of the water resource all over the world. Thus irrigation performance measures become necessary to be considered and measured, because efficient use of water is crucial in terms of economics and sustainability of farm (Burt et al., 1997).

Evaluation of irrigation systems is based on quantification of performance measures. Performance of the drip system may be affected by hydraulics, filtration, elevation, performance of the components and losses (Joseph et al., 2007).

2.10.2 Uniformity measures

Uniformity is the description of the evenness of the applied water depths in irrigation and is considered to be is the most important measure for an irrigation designer relating to the performance of drip irrigation systems. Uniformity of application of water depends on the smooth working of emitters, pressure variation and flow control during the whole irrigation event. Depth or discharge can be used in these performance measures.

According to Burt et al. (1997) uniformity and irrigation efficiency are sometimes confused with each other in terms of performance of irrigation systems and need to be elucidated e.g. Irrigation Efficiency, Distribution Uniformity, Application Efficiency, Adequacy. Efficiencies must be carefully defined as they have different purposes. The most widely used uniformity terms include Distribution uniformity (Du), Christiansen's coefficient of uniformity (Cu), emission uniformity (Eu), coefficient of variation (Cv), and emitter discharge rate variation (q_{var}) (Camp et al., 1997). The various uniformity terms are highly correlated to each other but each has different use and importance in the design and management of these systems (Barragan et al., 2006).

Burt et al. (1997) defined Distribution Uniformity as the measure of the uniformity with which the water is distributed to the different areas of the field of drip irrigation system and is calculated as:

$$Du_{lq} = \frac{d_{lq}}{d_{avg}} \tag{2.2}$$

where d_{lq} is the average depth of the lowest quarter number of depths, and d_{avg} is the average depth of water accumulated in all elements. d_{lq} can be calculated as follows:

$$d_{lq} = \frac{\text{vol.accum.in 1/4 total area of elements w/smallest depths}}{\text{1/4 of the total area of elements}} \tag{2.3}$$

Uniformity is normally used to describe the evenness of applied depths across the field but can also be calculated using catch can methodology after measuring discharge from a number of emitters (Sadler et al., 1995).

In a study conducted by (Hansona et al., 1997), it is analysed that the difference in the distribution uniformities measured for drip irrigation systems and furrow irrigation was statistically insignificant i.e. 89–92% for drip irrigation system and 89–90% for furrow irrigation.

In the past few decades, several coefficients of uniformity were developed to calculate the uniformity in pressurized irrigation systems. Christiansen's uniformity coefficient seems to be the most popular uniformity measure used by researchers all over the world. Assessment of the uniformity is the most important aspect of the system performance (Maroufpoor et al., 2010).

The Christiansen Coefficient of Uniformity (Cu) is the ratio of the individual depth of catch observations minus the average deviation from this depth, divided by the average water depth collected in all catch cans. It is defined by Christiansen in (Burt et al., 1997) and is calculated using the equation:

$$Cu = \left[1 - \frac{\sum_{i=1}^{n} \left| d_i - \bar{d} \right|}{n\bar{d}} \right] \tag{2.4}$$

where, n represents the number of emitters evaluated, d_i is the individual depth in a single catch can (mm) and $\bar{d}$ is the average water depth collected in all catch cans (mm).

The submain slopes steeper than 30% significantly decreases the CU and DU as the coefficient of uniformity has a linear relationship with either head or slope (Ella et al., 2009).

Uniformity is critical in selection, design and management of the irrigation system as the ideal uniformity is not always achievable because the under and over-irrigation result into the uneven water distribution during the irrigation (Mangrio et al., 2013).

Uniformity classifications based on uniformity coefficient by given by (ASABE Standards EP458, 1999) are presented in Table 2.2.

Table 2.2: Classification/standards of uniformity coefficient accroding to (ASABE Standards EP458, 1999)

Uniformity Coefficient CU (%)	Classification
Above 90%	Excellent
90-80%	Good
80-70%	Fair
70-60%	Poor
Below 60%	Unacceptable

The coefficient of variation (*Cv*) is used to calculate the amount of emitter flow rate variation along the drip irrigation system using the equation:

$$Cv = \frac{s}{\overline{q}} \qquad 2.5$$

where, *s* is the standard deviation of emitter flow rates and $\overline{q}$ is the mean emitter flow rate.

The coefficient of variation calculated by (Bralts & Kesner, 1983) for drip irrigation system was found to be 90% from a sample of 18 emitters. According to Hanson et al. (1995) emitter performance coefficient of variation of ≤ 0.05, and between 0.05 and 0.1, is considered to be excellent, and good acceptable hydraulic design criteria, respectively.

Variation in manufacturing of individual emitters results into the non-uniformity in emitter flow rate and is measured by coefficient of variation and it specifies the quality of the material used in emitter manufacturing. CV greater than 0 shows the incapability of emitters to deliver same amount of water at same pressure while, the friction coefficient determines the quality of material or the loss of pressure head and volume of water due to low standard of material (Mangrio et al., 2013). The low Cv indicates a good performance of the system during the cropping season.

Table 2.3 demonstrates the ASABE’s recommended classification of manufacturer’s coefficient of variation for point source and line source emitters. Single emitters that can be inserted directly into the lateral or can be connected at the end of a micro-tube (spaghetti) are called point source emitters. Water is discharged from emission points that are individually and widely spaced, usually over 1 m. The main types of point-source emitters are single drip emitters, bubblers, micro sprinklers and spray emitters. Line source emitters consist of dripline with integrated emitters (orifices) to convey water before it enters the dripline where water passes through a labyrinth of flow paths to dissipate or compensate pressure and exits to one or more distribution orifices.

Table 2.3: ASABE’s recommended classification of manufacturer’s coefficient of variation (*Cv*) for point source and line source emitters.

Emitter Type	*Cv* Range	Classification
Point-source	< 0.05 0.05 to 0.07 0.07 to 0.11 0.11 to 0.15 > 0.15	excellent average marginal poor unacceptable
Line-source	< 0.10 0.10 to 0.20 > 0.20	good average marginal to unacceptable

Adopted from (ASABE Standards, 2008) EP405.1

Emission uniformity (*Eu*) is also used for drip irrigation systems to first assess that each individual plant receives an equal quantity of water and to identify the factors causing non-uniformity and can be described as:

$$E_u = (1 - 1.27e^{-0.5}C_v)(\frac{q_{\min}}{q_{av}}) \qquad 2.6$$

where e is the number of emitters per plant, Cv is the coefficient of variation of emitter discharges due to variations in the manufacturing of the emitter, q_{min} is the minimum discharge and q_{av} is the mean discharge. Mongrio et al., (2013) also stated that the *Eu* is a comparative index of the variability between emitters and measures the consistency of the water application in the field during irrigation and it can be used to evaluate the quality of the emitters.

Emission uniformity depends on the minimum and average emitter discharge in field and it is hard to predict before the system is installed (Mahrous et al., 2008). The recommended design emission uniformity range by the American Society of Agricultural and Biological Engineers (ASABE Standards, 2008) EP405 for point source and line source emitters with varying spacing (m), topography and slope (%) is provided in Table 2.4.

Table 2.4: Design emission uniformity's (*Eu*) range recommended by (ASABE Standards, 2008) EP405.

Emitter Type	Spacing (m)	Topography Slope	Slope, %	*Eu* Range, %
Point source on perennial crops	> 4	Uniform steep or undulating	< 2 > 2	90 to 95 85 to 90
Point source on perennial or semi-permanent crops	< 4	Uniform steep or undulating	< 2 > 2	85 to 90 80 to 90
Line source on annual or perennial crops	All	Uniform steep or undulating	< 2 > 2	80 to 90 70 to 85

Adopted from (ASABE Standards, 2008) EP405

Coefficients of variation and emission uniformity were measured by Tagar et al., (2012 from randomly selected laterals from drip irrigation system at Umarkot, Pakistan. The maximum coefficient of variation was found 0.8253 and emission uniformity was 90.85%.

Hansona et al., (1997) measured lateral emission uniformity for a 260-metre length of lateral in field i.e. 79–82%. It is recommended to achieve an emission uniformity of at least 90% along the lateral line to achieve field emission uniformity of 80–90%. Higher emission uniformity can be achieved by optimising the length and diameter of the pipe, but it will increase the cost of system. Emitter flow rate variation, q_{var}, can be calculated as:

$$q_{\text{var}} = \frac{q_{\max} - q_{\min}}{q_{\max}} \qquad 2.7$$

where, $q_{\max}$ is maximum emitter flow rate and $q_{\min}$ is minimum emitter flow rate.

Hanson et al. (1995) also recommended a statistical uniformity (CU) ≥ 80% before fertilizer injection and it can be improved by increasing number of emitters per plant, improving the hydraulic design and removing the damaged or plugged emitters. Design for a coefficient of variation of emitters of ≤ 10% is considered, best and less than 10 to 20% is considered to be good.

2.10.3 Emission measures

"Application efficiency (*AE*) is the ratio of the average depth of the irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied, expressed as a percentage" (Merriam et al., 1980). Burt et al., (1997) explained that efficiencies are difficult to evaluate rapidly and require detail record and quantification of final target and utility of water applied. Application efficiency (*AE*) is based on the target irrigation depth of single event. It is defined as:

$$AE = \frac{\text{avg. depth of irrig.water contributing target}}{\text{avg. depth of irrig.water applied}} \times 100\% \qquad 2.8$$

2.10.4 Adequacy measures

The adequacy expresses how well the irrigation system meets the demand of the crop in order to maintain the quality and productivity at an economical level (Soccol et al., 2002). Application rate can be attributed to adequacy of the system to meet the desired depth of applied water within a fixed time interval assuming perfect efficiency. Foley and Raine (2001) explained design system capacity and the managed system capacity are the time dependant variables.

The design system capacity can be expressed as capacity at which the irrigation system is designed assuming perfect efficiency and continuous 24-hour operation. It is calculated as the amount of water a system can deliver in mm / day. Drip irrigation systems are mostly designed at peak water requirements of the crop, so that a crop receive required amount of water at peak growth stage. It is measured as the volume of water applied divided by the irrigated area.

Managed system capacity is the actual volume of water delivered by the system in field and is measured in mm/ day. It can be calculated using pump flow rate, pumping duty and the period of the irrigation cycle. The managed system capacity is normally lower than design system capacity unless the system is operated continuously 24 hours per day. The managed system capacity accounts for the fact that the system for a given number of hours per day or days per week and attempts to factor scheduled maintenance times.

2.11 Design of pressurised irrigation systems

The overall performance of pressurised irrigation systems in terms of uniformity depend on decisions taken at the design stage. These decisions can be conflicting between maximizing reseller profit, reducing initial capital cost for the grower, minimizing environmental impacts, and maximizing irrigation uniformity. The performance of micro irrigation system to a lesser extent depends upon the quality of components, and component design (Pedras et al., 2009). Hydraulic design of drip irrigation systems is the most important component of the design to ensure good irrigation performance in a particular area. Good quality components will increase the overall life of the system but will also increase the cost of the system.

Different types of software packages are available for the design of tape or drip irrigation systems. The semi manual design packages available are Hydrocalc, Eaucadi, lspd, and a range of others. Online semi manual packages like Hydrocalc and Eaucadi are used for smaller systems (less than 10 ha).

The highly automated design packages available for drip irrigation include software packages like IRRICAD and WCADI. While there are many other software packages that are available for hydraulic design, these are specifically configured to solve issues of spatially varied pipe flow and are capable of automated sizing of mains and sub-main pipes tubes for spatially varied flow within the pipe network.

One significant component of these hydraulic software packages is the capacity to solve for pipe friction using either the Hazen Williams equation or the Darcy-Weisbach equation. Both these types of software packages contain a range of product characteristics from different manufacturers. The design process for multiple blocks involve the separate design of each block (one per valve) and then the design of the main line between valves.

Large projects encompassing areas more than 10 ha are typically designed using software packages like WCADI and IRRICAD. The typical design basis for non-pressure regulated or pressure compensating dripline is to keep the flow discharge variation throughout the system within a 10% range, by keeping the pressure variation within a 20% range. Therefore, for a system designed to operate at 100 kPa at the emitters, a 20 kPa pressure range along the lateral is the basis for the design.

Hence, for this project Eaucadi and Hydrocalc software packages were selected as being online available, easily accessible and suitable for the design of smaller systems (less than 10 ha), to promote the drip irrigation systems in Pakistan specifically for the majority of farmers with small land holdings and to make these systems affordable to all the farmers.

Australian designers of drip irrigation systems continue to simplify the design procedure by using rules of thumb during the design process, such as keeping the water velocity in the pipeline less than or equal to 1.5 m/s, while maintaining the head loss within a permissible range throughout the system. However, little optimization for capital cost versus operating cost occurs. Specifically, for tape types that are not pressure regulated or pressure compensated, Australian designers will typically choose a range of operating pressure for a typical tape type and limit designs in terms of lateral sizing and selection to operate within that pressure range, ensuring and achieving desired uniformity and performance using latest software packages. For example, for T-tape with a maximum operating pressure of 105 kPa the designers will design for pressure between 80 to 100 kPa to limit the outflow variation to 10%.

The second most important design parameter is to limit the sub main head loss to less than 2 m to keep the lateral velocity less than 1.5 m/s. Increasing the velocity more than 1.5 m/s will cause a significant increase in friction head loss along the dripline and to keep these losses minimum, lateral velocity is kept under 1.5 m/s (Waller & Yitayew, 2016).

Another important parameter in drip irrigation designing is the soil wetting patterns. Emitter spacing can be determined using the depth and width of wetted soil. Soil–water relationship, soil texture, air temperature, humidity and emitter’s hydraulic parameters are also vital features in order to design an efficient drip irrigation system (Ghumman et al., 2018).

IRRICAD is a computer programme that has been specifically developed to design all types of pressurised irrigation systems including drip irrigation systems, turf irrigation systems, orchard sprinkler or micro sprinkler irrigation systems. It is a software package under continuous development and provides excellent technical support. It has powerful hydraulic procedures to size pipes producing excellent hydraulic design and have special CAD tools to layout the irrigation system. This package also generates a bill of quantities representing a complete list of materials including fittings and their prices to calculate and manage total system cost. It helps in producing most cost-effective design, reducing the design time and stress at peak design periods (Lincoln Agritech Ltd, 1999).

WCADI is another irrigation design tool like IRRICAD. It provides precise hydraulic design, fast alternative comparisons, solutions to complex designs, and options for future alterations. It also helps by automatically producing bills of materials, along with the cost-effective hydraulic design. IRRICAD and WCADI both produce a bill of quantities for all the products and components of the system, manufactured by different companies to be used in the final design. The bill of quantities is the last step in the design and it assists the designers with the costing of the whole system (Wcadi.Org, 1980).

Bhutto & Bazmi (2007) reported that 81% of farms owned by farmers in Pakistan are less than 5 ha and 6.8% of farms are more than 10 ha in size. Farmers holding small farms are inclined to use labour intensive and less risky farming systems while farmers holding big farms choose advanced farming systems as they can afford to take risks in the hope of higher returns. In intent to promote the feasibility and adoptability of pressurised irrigation systems specifically among the farmers holding small farms (less than 10 ha), the Hydrocalc and Eaucadi design software packages have been selected from the available software packages here is Australia for this research project. As these software packages are freely available online and are capable of simple hydraulic design of drip irrigation systems for the farm sizes less than 10 ha.

2.12 Design practice for pressurised irrigation systems in Pakistan

Pressurised irrigation systems are currently designed by reputable organisations in Pakistan using predesigned spreadsheets. These design spreadsheets incorporate the field, crop, soil, water and climatic data collected from a field survey, and meteorological department and soil and water department available for the selected sites. After collecting the field data including the site address, field layout, (size and shape), type of crop and field slope, the field layout is incorporated into AutoCAD software. AutoCAD is a computer aided design tool that is used by designers to incorporate the field layout along with all the components of the drip irrigation systems to produce a final plan that helps in the manual installation of the system in the field. The field surveyors obtain elevation difference using auto levels and dumpy levels (Akhter, 2012; Khan, 2019).

The main line, submain line, laterals and other supplementary components are selected based on the farm area, crop water requirement and the permissible system head losses. Emitters are selected based on the crop water requirement. Peak water requirement (PWR) is calculated based on some estimated crop and water data taken from the nearest available meteorological station, using the following equation:

$$PWR = \left(\frac{Crop\ area \times PE \times Pc \times Kc \times wetted\ area}{Eu}\right) \qquad 2.9$$

where, PWR is a peak water requirement in litre/day/plant; crop area is in m^2 per plant and is obtained by multiplying row to row spacing and plant to plant spacing. PE is the maximum pan evaporation of the region in litre/m^2/day, Pc is a pan coefficient, and is approximately 0.7 to 0.8, Kc is a crop coefficient and it depends upon the foliage size at the largest crop growth stage, wetted area is the area shaded by canopy cover in m^2/m^2, and Eu is emission uniformity as a fraction.

Friction losses in the laterals, main and sub main are calculated using the Hazen and Williams (1933) and Watters and Keller (1978) equations. The Hazen and William's equation are used as:

$$S_f = h_f / L = K(Q/C)^{1.852} \times \mathrm{D}^{-4.87} \qquad 2.10$$

where, S_f is head loss gradient in m/m, K is conversion constant and is 1.212×10^{12} for metric units, h_f is head loss due to pipe friction in metres, L is the length of pipe in metres, Q is the flow rate in pipe in litres per second, C is friction factor (150 for PVC pipe) and D is the inside diameter of pipe in metres. The Watter-Keller equation is used as:

$$S_f = hf / L = K(Q)^{1.852} \times \mathrm{D}^{-4.75} \tag{2.11}$$

where S_f is head loss gradient in m/m, K is a conversion constant i.e. 7.89×10^7 for metric units, h_f is the head loss due to pipe friction in metres, L is the length of pipe in metres, Q is the flow rate in pipe in litres per second, and D is the inside diameter of pipe in mm.

These two equations are used to calculate the friction losses, and the maximum friction loss is taken, for further design of the system. The size and length of the laterals is selected based on the allowable frictional losses, discharge of the emitters and the number of emitters on one lateral. The design of sub mains depends on both the capacity and uniformity of application for the particular size of the field. Number of laterals and distance between the laterals determines the size and length of the sub mains. The total dynamic head is calculated by adding head losses for all components of the system (filters, fertilizer applicator, flowmeter, suction line, delivery line, head loss in lateral, sub main, main, fitting losses in all pipe lines, field fitting loss, and safety equipment loss) including suction head, delivery head, emitter operating pressure and elevation difference. Most of the land is levelled at 0% slope using laser land levellers. Pipe network head loss is restricted to less than 25% of total dynamic head. Head loss in sub mains is limited by ensuring the velocity remains less than 1.5 m/s. Pumps are selected based on the discharge and total head loss from all components of the system. Losses in other components of the system are taken from recorded measurements in other designed systems. The process of selecting a filter based on water quality is already explained in Section 2.3. Other components of the system are selected according to the system requirements.

It has been found that the proper design and management of drip irrigation system depends on the precise selection of dripline spacing, discharge, irrigation duration and time interval between consecutive irrigations (Cote et al., 2003). Hydraulic conductivity and texture of soil are critical in the precise selection of emitter discharge and spacing. However, additional studies are required for optimal design procedure for different soils and climatic conditions (Ghumman et al., 2018).

Pakistan Agriculture Research Centre, (2010) have stated in the proposal for the project “Water Conservation and Productivity Enhancement through High Efficiency

Irrigation Systems” that using rigid pre-designed systems is not feasible for all the locations around the country. The design needs to be flexible and compliant to meet the requirements of each and every site hence, field size, soil conditions, crop status, water source, crop water requirements, needs to be considered for individual site.

Such as, Bakhsh et al., (2015) stated that there is lack of updated, efficient and technically suitable design for drip irrigation systems and prevailing systems are designed by third party sales representatives instead of technical professionals. Therefore, the already installed drip irrigation systems in Pakistan needs to be evaluated in detail in terms of design procedure and design competency.

It has also been made sure and checked that the current hydraulic design procedure is analysed and updated in this research project. The manual hydraulic design procedure is same all over the Punjab, Pakistan. While few private organisations have been using new advanced tools for the designing, monitoring and maintenance of the systems installed. Although, the information and data regarding the performance and working of these tools and the design competency in terms of efficiency of drip irrigation systems are unknown. Therefore, this research project will not only give an opportunity to the government and private organisations to evaluate the performance of their hydraulic designs using the procedure outlined in this research but will also expand their insight and workability towards operational performance, maintenance and monitoring of drip irrigation systems after installation.

2.13 Justification for this work

One of the major restrictions to improve the irrigation performance in Pakistan is due to general behaviour of individuals involved in government and bureaucratic sector to be selfish for their personal benefits, neglecting the adverse effects of their activities on society. The stakeholders and service providers are not willing to evaluate the actual performance of the systems after installation. Most of the projects were not evaluated and reported as being satisfactory and even ‘perfect’, completely neglecting the actual results and circumstances. By misleading their customers, stakeholders to get the maximum financial benefit.

Due to the traditional irrigation methods and on farm conveyance the irrigation water use is wasteful. Pakistan has the lowest water productivity in the world and low irrigation efficiency (30%). Poor water conveyance is due to the use of earth bunds, poor levelling, unlined canals and low water charges. (Bhutta and Smedema 2007). Therefore, farmers should be encouraged to grow high value crops with the expensive groundwater to improve the income. Wheat yield in Pakistan is about 0.6 kg/m^3 as compared to India which is 1.0 kg/m^3 (Qureshi, 2011). Similarly, maize yields are 0.4 kg/m^3 which is nine times lower than Argentina (2.7 kg/m^3). While the on farm losses can be monitored and minimised, using efficient innovative irrigation methods such as pressurised irrigation system to improve irrigation efficiency at farm (Masih et al., 2014).

To ensure food security in future, the agronomists, engineers and researchers need to attempt for optimal drip irrigation design and management, considering the soil, water resources, climatic conditions and financial situation of farming community (Iqbal & Iqbal, 2015).

Javed et al., (2015) evaluated and redesigned the already installed drip irrigation system and observed that it is very important to test, design and evaluate the drip irrigation system to achieve the maximum irrigation efficiency with low initial cost. A well design system will consider the number of emitters per plant and emitter spacing for efficient water use and will leave no water for runoff, evaporation and deep percolation. The redesigning has substantially reduced the head losses in lateral, submain and main line but also reduced the installation cost from 12131.32 AUD to 10766.56 AUD.

Hence, it is necessary to test and evaluate already installed drip irrigation systems in Punjab so that the cost of the system can be reduced with improve water productivity and performance on drip irrigation systems in Punjab and likewise in other cities of Pakistan.

However, the impact of the reduced water application technologies on Indus Basin needs careful evaluation at different scales for varying climatic conditions, as they may increase the threat of soil salinization, and needs assessment before recommending them to the farmers on large scale adoption (Qureshi et al., 2010).

The procedure outlined in this thesis will not only improve the performance and adaptability of drip irrigation systems in Punjab, without disrupting the natural hydrological balance between the surface and ground water resources with efficient use of water and improve productivity ensuring the food security and agricultural sustainability in future.

Masih et al., (2014) also observed a significant reduction in the yield of sunflower seed due to the water shortage. Being deficit in edible vegetable oil production, Pakistan is importing edible oil worth of billion dollars. In 2007-2008 sunflower seed production was approximately 264000 tons by sowing sunflower seed on 457.30 thousand hectares. Using water saving technologies on oil seed crops will help improving the yield and area under cultivation.

Therefore in recent past the researchers have priorities the research on the evaluation of design, management, and application of drip irrigation systems as the drip irrigation being the best practical alternative to the surface irrigation techniques (Kandelous et al., 2012).

Hence, it is necessary to test and evaluate the system after implementation to improve the irrigation performance, Unfortunately, this is generally neglected, partly due to a lack of awareness and ignorance. Kahlown and Kemper (2007) conducted a study and discovered that approximately 71% of the drip irrigation systems installed in Baluchistan, Pakistan have been abandoned. The study concluded that the depletion of ground water and poor design and management was the main cause of failure of systems, along with the lack of farmer training in operation and maintenance. Limitations in design, poor handling, and non-availability of components of the system and rental conditions also lead to the failure of the systems.

Current facts and figures regarding the performance of recently installed drip irrigation systems is not available and needs to be discovered. Although from the anecdotal references its average operational performance has only been improved from 25% to 30% but no evaluation have been made in terms of hydraulic performance (Khan, 2019).

A lack of performance measurement, field testing and evaluation of pressurized irrigation systems as per approved designed and the absence of follow up assistance and complete technological package including crop establishment methods, fertilizer requirements, plant protection techniques and other agronomic practices resulted in low performance of systems.

This project aims to investigate the factors associated with the failures of previous installed drip irrigation systems, to provide an improvement in the broad technological performance of drip irrigation systems in Punjab and these factors are investigated in detail in CHAPTER 4. Design of drip irrigation systems is the first elementary component that can be improved to ensure the best performance of the system. Other components of the system management are installation, filtration, design, maintenance, monitoring and troubleshooting and these come after the basic design of the system. According to the resources and time available, this project will focus on the hydraulic design of the drip system, using the latest simulation models and design software available to substantially modify and alter the traditional method of drip irrigation design in Pakistan.

2.14 Conclusions

Due to the continuous reduction in the availability of land and ground water resources and low productivity of traditional irrigation methods used in Pakistan, so-called high efficiency irrigation systems have been suggested to the farmers to increase the conservation and productivity of water in Punjab, Pakistan. These systems are thoroughly investigated and understanding regarding drip irrigation system characteristics and design practice for these irrigation systems in Pakistan and Australia is developed.

Lack of irrigation performance evaluation and field testing for drip irrigation systems installed in Punjab, Pakistan has led to the failure of their overall design in terms of system adequacy and desired performance. To fill this gap of performance and design process evaluation, this study has been planned to analyse these systems in terms of data collection, design practice, installation and management. Many of the components are like elsewhere in the world, and the design practices are not up to date with the global practices.

With the limited resources and time available, this project has focussed on the hydraulic design and performance evaluation of the drip system to ensure the drip irrigation system competency to fulfil crop requirements. Possibilities of the software packages for the simulation and selection of suitable software packages matching with the hydraulic design of standard Pakistani drip irrigation system are selected. Broad characteristics of drip irrigation systems and components are discussed in detail. There is a range of proven software packages both light weight and sophisticated that may assist with the design of the systems. These software packages will be used to considerably modify the traditional method of drip irrigation design in Pakistan, and to investigate the viability of improving drip irrigation design. The competency and ability of the software packages to successfully replicate Pakistani selected drip irrigation design will also be tested through this project.

The selected software packages will be validated in terms of accuracy to replicate the Pakistani drip irrigation designs with the aim to find the most feasible and applicable commercially available computer simulation model to assist in drip irrigation system design. This project has been planned to include field experimentation in Pakistan and Australia, laboratory experimentation, parameterisation, and simulation with available software packages to match with the hydraulic design of “standard Pakistani” drip irrigation systems detailed in methodology through CHAPTER 3.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The findings and observations made and the review and analysis of already installed drip irrigation systems in Punjab provided in CHAPTER 2, have led to the need to replicate elements and reproduce key elements of the hydraulic design of the Punjab drip irrigation “standard designs” here in Australia. To allow the appropriate measurement and characterisation, a methodology is formulated for the field experimentation in Pakistan and here in Australia. To efficiently achieve this objective this methodology is divided into 8 major sections as given below:

1. Review of different components used in Pakistani drip irrigation systems.
2. Selection and replication of Pakistani design.
3. Laboratory experimentation and measurement equipment.
4. Methodology used for experimentation in Pakistan.
    i) Review and analyses of already installed drip irrigation systems in Pakistan.
    ii) Field experimentation at five case study sites in Punjab, Pakistan.
5. Methodology used for experimentation in Australia.
    i) Experimental design for the field test site.
    ii) Field experimentation.
6. Simulation with Eaucadi.
7. Simulation with Hydrocalc.
8. Measurement and instrument errors.

To successfully replicate and reproduce the hydraulic design of the Punjab drip irrigation systems a typical Pakistani drip irrigation system was selected and replicated here in Australia which is discussed in the following section.

3.2 Review of different components used in Pakistani drip irrigation systems

Drip irrigation systems are comprised of a large number of components including the main, sub main, laterals, drippers along with complementary components like filters, pump, control valves, pressure gauges, flush valves, air release valves, non-return valves, take-off valves, check valves, pressure regulators, control valves, chlorinators, water meters, fertilizer injectors and end caps. Before selecting components, it is important to consider manufacturing quality, hydraulic performance, materials, cost and availability of each component. A detailed list of the components commonly used in drip irrigation systems is provided in Appendix A.

The list of elementary components used in drip irrigation systems in Punjab region of Pakistan were reviewed and analysed. A summary of these components is as follows:

- Pumps and motors used are both imported and locally made by companies like SAER-Italy, DOMAC-Turkey, Kirlosker India, TECO India, Zirve-Turkey, ALARKO Istanbul, Felsom Italy, while local companies are like PECO, MECO, Siemens, KSB and Golden.
- Diesel engines are purchased locally from companies, like Chief and Golden.
- PVC pipes both purchased and manufactured locally and imported.
- All the drip components used are imported from different companies, while drip fittings used are both manufactured locally and imported.
- Sand media/gravel filters, disc filters, screen filters, hydro cyclone filters, semi-automatic cleaning / screening filters are used and purchased both locally and imported.
- Venturi assembly, fertilizer tank and fertigation manifolds along with pressure gauges are also used and purchased locally and imported.
- Driplines, drippers, foggers, spinNET, head unit fittings, dripline fittings (end caps, tees, joiners, couplers, adapters, gromet take off rubbers) are

mostly imported from the companies like John Deere, Euro, Al Zahoor and Netafim.

- Valves used in drip irrigation systems are PVC ball valves, non-return valves, air release valves, pressure release valves, PE mini valves, compression lateral valves, Flush valves, gun metal gate valves, butterfly valves, handle valves and compression ball valves etc. these are purchased both local and imported.
- Flowmeters are mostly imported from China, Elster, Kent, Valtech-Italy, Schlumberger- Germany, Babylon.
- Fittings and accessories are purchased both local and imported.

For each of the above components manufactured locally means they are purchased locally and are manufactured in Pakistan, purchased locally means they are sourced from local companies but are manufactured internationally, imported means they are purchased directly from international suppliers. The company of origin may be important because components from well-known international suppliers will be more likely to be included within the databases of design software tools. Conversely locally manufactured equipment might be designed to fulfil a specific requirement of the local farmers. According to (Reddy & Satyanarayana, 2010) imported parts and equipment also needs standardization. The observations made from the review of these components is discussed in detail in Section 6.6.

3.3 Selection and replication of Pakistani design

A typical Pakistani surface drip irrigation design was selected from the variety of pre-designed surface drip irrigation systems available in the Punjab region of Pakistan. This design has been selected as it is the most common design installed at a large number of sites in the Punjab and is commonly used for different types of vegetables and row crops. Additionally, the design process used for this system is the most common design practice used in approximately 80% of the projects previously implemented by the different government and private organisations in Punjab. The hydraulic design spread sheets used to manually design the selected system in Pakistan is provided in Appendix B. The Ali Akber Group of Pakistan has designed this system for a cotton crop for 8.09 hectares. The specifications of the major components of this hydraulic design are as follows:

- Dripline with outside diameter: 17 mm (manufactured by Eurodrip)
- Wall thickness: 0.9 mm
- Emitter spacing: 0.4 m
- Emitter discharge: 2.6 L/h
- Non-pressure compensated

A list of the equipment used in the selected design was prepared and equipment with similar specifications locally available in Australia were selected, purchased and installed at the agriculture plot area of the University of Southern Queensland. The closest available equipment was from Netafim, Australia with the following specifications:

1. Dripline:
    - Model: Netafim Tiran (16009): integral dripper (emitter) with coil length of 500 m.
    - Inside diameter (I.D): 14.20 mm
    - Wall thickness (Kd): 0.9 mm
    - Outside diameter: 16.0 mm
    - Maximum working pressure: 3 bar
    - Maximum flushing pressure: 3.9 bar
    - Emitter spacing: 0.4 m
    - Emitter nominal flow rate: 2 litres per hour at 1.0 bar pressure with maximum working pressure up to 3.0 bar, according to dripper line inside diameter
    - Non-pressure compensated
    - Water passage dimensions: 0.76 mm × 1.08 mm× 75 mm
    - Emitter discharge constant *k*: 0.693

  - Emitter discharge exponent *x*: 0.46
  - Dripline minor loss coefficient *Kd*: 0.40.

2. Take off adapter: 17 mm × 13 mm
3. Internal diameter of rubber grommet: 13 mm (ID)
4. Blue PVC lay flat supply hose, 50 m: 50.8 mm (N.B 2")
5. PVC submain pipe, 6 m: 50.8 mm (N.B 2")
6. Cartridge screen filter: 20 mm (130-micron, 120 mesh)
7. Female coupling: 38.1 or 50.8 mm (N.B 1.5" or 2")
8. Hose clamps: 50.8 mm (N.B 2")
9. Barbed fittings: 50.8 mm (N.B 2")

Table 3.1: Manufacturer's recommended maximum lateral length (metres) at 10% flow variation for selected Tiran-16009 with the above mentioned specifications.

Uphill	Slope %	Max lateral length (m)
	2%	48
	1%	52
	0%	55
Downhill	-1%	58
	-2%	60

Table 3.1 expresses the manufacturer's recommended maximum lateral length for Tiran-16009 dripline with different downhill and uphill slopes with the inlet pressure of 15 m. Downhill and uphill slope was replicated at the selected site by placing the water supply into the highest and lowest ends of the dripline, respectively.

As shown above, the Netafim dripline for use in the Australian experimental trials differs slightly from the Eurodrip dripline used in the designs installed in Punjab. Importantly these two products should have similar hydraulic behaviour given the identical emitter spacing and wall thickness, nominal emitter rate of 2 l/hr compared to 2.6 l/hr and outside diameter of 17mm compared to 16mm for the Netafim and Eurodrip driplines respectively. Both driplines are non-pressure compensated and therefore will exhibit similar emitter flow variations with changes in pressure. After the successful replication of selected Pakistani drip irrigation system components here in Australia. These components are tested and evaluated in the laboratory.

3.4 Laboratory experimentation and measurement equipment

The initial experiments were conducted under controlled conditions at the University’s hydraulic laboratory and all the drip irrigation components purchased for use in the agricultural plot area (field test site) of University of Southern Queensland were tested and evaluated. This experimentation was completed in four trials performed on small lengths of driplines installed in the laboratory using different handmade pressure gauge attachments, fittings, vernier callipers, a stopwatch, weighing scales, catch cans and measuring cylinders. The measurement equipment was also tested and evaluated in the laboratory to finalise and select the most accurate equipment to be used at the field test site and during experimentation in Pakistan. The dripline inside and outside diameters were measured using vernier callipers and the methodology used for flow and pressure measurement in the hydraulic laboratory is provided below.

3.4.1 Pressure measurement

A pressure gauge is a mechanical device designed to measure the internal pressure of a fluid and measuring the pressure at selected points in an irrigation system is the simplest way to evaluate its performance. The pressure gauges are not normally able to measure individual emitter pressures when the emitter is integrated into the dripline. Handmade pressure gauge as shown in Figure 3.2 was constructed in the laboratory. Different pressure gauges were tested using rubbers of different thicknesses, densities and shapes with a hole in the centre. The small pieces of rubbers were glued to the Schrader valve to make a waterproof seal between the emitter outlet and the rubber hole. The Schrader valve was then connected to the air chuck on the liquid filled Bourdon pressure gauge. Plastic rubber with different shapes and thicknesses with four different pressure gauges were tested to get the most accurate and suitable fit with the dripline emitter outlets. The pressure of an individual emitter outlet along the dripline was measured by pressing and adjusting the centre of the rubber to the outlet of the emitter. These specially designed handmade pressure gauges were then used to measure the head pressure and the end pressure of the dripline in the four laboratory trials.

Figure 3.1: Specially designed handmade pressure gauge used to measure the individual emitter pressure at field test site.

Figure 3.2: Handmade fittings connected to the pressure gauge to measure the individual emitter pressure.

3.4.2 Flow measurement

The easiest, simplest and most precise way to measure, the flow rate of individual emitters in the field is to use the catch can methodology. Straight-sided cans of the same size were selected. A range of different catch cans and measuring cylinders were tested on a piece of dripline installed in the laboratory to select the most appropriate size and type for use in the field. A stop watch, catch cans (Figure 3.3) and the measuring cylinders (Figure 3.4) were used to record the time and the volume of water collected in each can for the given time. The individual emitter flow rate is also measured along the dripline installed in the laboratory.

Multi-jet and electro-magnetic flowmeters were selected and also tested in the laboratory to check their performance before installation in the field. The discharges of individual emitters were measured using catch cans and a stopwatch and trials of this process were completed before actual field measurements began.

Figure 3.3: Measuring beakers used to measure the volume of water collected in each catch can.

Figure 3.4: Catch cans used to measure the volume of water.

The pressure and flow rate measurements were used to measure the pressure loss, cumulative pressure loss, velocity, lateral flow rate, average emitter flow rate, flow rate variation and emission uniformity in the dripline. The results obtained in the four trials are provided in Section 5.2.

3.5 Methodology used for experimentation in Pakistan

To complete the experimentation in Pakistan existing drip irrigation systems were reviewed and analysed following the field experimentation at five case study sites in Punjab. Detail of the procedure and methodology used is provided below.

3.5.1 Review and analyses of already installed drip irrigation systems in Pakistan

As this project aims to investigate the factors associated with the failures of previously installed drip irrigation systems and to provide an improvement in the broad technological performance of drip irrigation systems in Punjab, these systems are comprehensively examined and discussed in terms of design, installation, monitoring and maintenance following installation. To analyse the systems already installed, a data is collected from the evidences provided by colleagues, operators, project managers, and interview with farmers. Detail of the observations and analyses completed are provided in Section 4.4 in CHAPTER 4.

3.5.2 Field experimentation at five case study sites in Punjab, Pakistan

Experimentation was performed at five selected case study sites in Punjab to examine and analyse the drip irrigation systems under actual field conditions and confirm the evidence collected from colleagues and project managers from reviews and analyses of previously installed drip irrigation systems. To complete these case studies the following methodology has been used for the measurement of pressure and flow rate.

3.5.2.1 Pressure Measurement

The driplines in these case studies are typically designed to operate between pressure ranges of 7 to 10 metres at the downstream end of the dripline. At the pump shed pressures were recorded using installed liquid filled Bourdon pressure gauges that were already installed. Three laterals were selected at the left, middle and right end of the sub main for each zone to estimate the variations in flow and pressure around the zone. To measure the individual lateral pressure in actual field conditions, the lateral pressure was recorded at the inlet and the outlet of each selected lateral by pressing the handmade pressure gauge into the inlet and the outlet of each selected lateral as shown in Figure 3.1. The number of zones were selected on the basis of the size of the field, the total number of zones, and the time available for testing at each site.

In addition, two emitters were selected from the upstream and downstream end of each selected lateral. The pressure for each selected emitter was taken using the handmade pressure gauge, by pressing the rubber fitting to the individual emitter outlet until the pressure reading became stable.

3.5.2.2 Flow measurement

The total flow rates of the drip irrigation system were measured using the flowmeters already installed at the pump shed on each site. Flow rates of the selected laterals and emitters mentioned above were measured using catch cans, measuring cylinders and a stopwatch to establish the individual emitter's flow. Water metering devices are installed on the irrigation system main supply pipe to monitor the irrigation water usage. In Pakistan flowmeters were installed at the pump shed to measure the system flow at a certain given time.

The flow rates were measured at the same emitters that were selected for pressure measurement using the catch can methodology. The catch cans were placed below the selected emitters, and water was collected for 15 minutes in each can and measured using measuring cylinders. The flow rate of each emitter was measured using the time and the amount of water measured in each catch can. Due to time constraints the readings were taken in a maximum of two zones at each selected case study sites. The results and analyses are provided in Section 4.6.1 in CHAPTER 4.

3.6 Methodology used for experimentation in Australia

The experimental design formulated to replicate the Pakistani design in Australia, is now provided to explain the setup and installation of the replicated hydraulic design at the selected site.

3.6.1 Experimental design for the field test site

Due to practical reasons this experiment was conducted outdoors, and the Agricultural Plot area of the University of Southern Queensland has been selected as the field test site for a number of reasons including the ease of achieving the desired slope for the selected length of dripline and considering the impact of water spillage. The selected design components were replicated in as true a form as possible to the Pakistani systems, while varying slope and supply pressure range have been selected to complete this particular testing. The length of the dripline was selected as 100 metres to test the performance and working process of the selected software packages and examine emitter discharges and uniformity along the dripline for the length greater than the length recommended by the manufacturer for given slope and supply pressure.

The ground slope at the Ag-plot is low and to achieve a significant slope over the 100 metres length of dripline it was necessary to elevate the dripline above the ground. A mesh wire fence at the site was chosen with sufficient length and height for the experiment. The dripline was attached to the fence at the Ag-plot using plastic ties, with the dripline running along the fence at an average slope of 2.1%. Downhill and uphill slopes were achieved in the testing by placing water supply into the highest and lowest ends of the dripline respectively. Actual elevations of the dripline were measured and replicated in the software packages and the nominal supply pressures were selected between the possible minimum and maximum pressures for eleven tests to validate the accuracy and performance of the software packages beyond the current operating field conditions.

3.6.2 Field experimentation

After setting up the experimental design the components of design system were installed at Ag-Plot field test site using the same traditional design methods as used in Pakistan and these are described in following sections.

3.6.2.1 Installation of replicated design

An electromagnetic (EM) flowmeter manufactured by ABB Instrumentation Ltd, and a multi-jet water meter made in Japan were selected, purchased and installed at the upstream end of the system as shown in Figure 3.5 and Figure 3.6 to measure the total flow of the system. They were attached to the main water supply using fittings, but the EM flowmeter stopped working due to an expired battery and the multi-jet flowmeter was used for flow calculation in all the tests performed.

Figure 3.5: Multi-jet flowmeter and filter installed at the field test site.

Figure 3.6: Electromagnetic (EM) flowmeter installed at the water supply point.

Figure 3.7: Back view of the water supply installed at the field test site.

The water used in experimentation here in Australia was potable reticulated municipal water that has been chlorinated for drinking purposes according to the Australian Drinking Water Guidelines. As the screen filters are normally used for clean water sources, therefore a screen filter was selected and installed between the flowmeters and a pressure gauging point. The pressure gauge was connected to the dripline using fittings and the Schrader valve as can be seen in Figure 3.8 and Figure 3.9. The Schrader valve was used to measure the pressure at the upstream end using a pressure gauge.

Figure 3.8: Water supply showing flowmeters, screen filter and the schrader valve installed at the field test

site (Ag-Plot).

Figure 3.9: Close view of the schrader valve installed at the supply end of the dripline.

A 6.87 m long additional section of the dripline was placed between the pressure measurement fitting and the first emitter in the 100-metre length of operating test dripline as shown in Figure 3.10. The emitters in this additional section of the dripline was sealed using duct tape to stop the emitter flow in this section and to exclude this length from the 100 metres of operating dripline.

Figure 3.10: Sealed extra dripline connecting water supply to the 100 m dripline.

The measuring tape (Figure 3.11) is used to calculate the distance, and the zip ties (Figure 3.13) and tie wires (Figure 3.14) were used to attach the dripline and the catch cans to the fence.

Figure 3.11: Measuring tape used for measuring distances and height of dripline at the field test site.

Figure 3.12: Duct tape used to block the emitters and to tie the dripline to the mesh fence.

Figure 3.13: Zip ties used to attach the dripline to the fence at the field test site.

Dripline with 16 mm outside diameter, 0.9 mm (40 mil) wall thickness and 0.4 m emitter spacing (Netafim Tiran 16009) was attached with a pressure gauge at the supply end. Small pieces of steel tie wires were used to attach the dripline to the fence as shown in Figure 3.14. Elevation is considered at each point of attachment to maintain a reasonably constant slope.

Figure 3.14: Dripline attached to the fence at agriculture plot area using steel tie wires.

At the upstream end the dripline was attached to the fence at a height of 2.35 m and followed approximately a constant slope for a length of 100 m, keeping the zero elevation at the end of the dripline as shown in Figure 3.16. The highest to the lowest height of the dripline varied from 2.35 m to 1.35 m above datum. Different test stations were selected at every tenth emitter of the dripline to take elevation, pressure and flow measurements at twenty-six tests stations along the dripline. The elevations were recorded following a methodology given in Section 3.6.2.2 using a clear tube filled with water as shown in Figure 3.15.

Figure 3.15: Clear white tube filled with water to take the elevations at selected stations in the field.

Figure 3.16: View of installed dripline on a downhill slope with water supply placed into the highest end of the dripline.

Coloured tape was used to mark every tenth emitter (every 4 m) to highlight the selected stations for the installation of the catch cans. The cans were attached to the fence below each selected emitter using tie wires. Rubber bands were tied on either side of each marked emitter to direct the water flow into the can and to stop it from running down the dripline along the slope. The volume of water collected in each catch can was measured using a measuring cylinder (Figure 3.3) and the end of the dripline was twisted and locked using plastic tie wire as shown in Figure 3.17.

Figure 3.17: End of the dripline is blocked using plastic tie wires.

The same process was repeated with water supply placed into the lowest (downstream) end of the dripline by means of a simple plastic polyethylene pipe fittings and connectors. The highest end was blocked using tie wires and the same set of readings were taken for the uphill slope.

3.6.2.2 Elevation measurement

Elevation was measured at the field test site using the principle that water always seeks its own level across the length of any field. The following procedure was adopted to obtain elevation measurements.

- A long, flexible clear tube was filled with water using a clean water from a main water supply outlet near the ag plot. The water was forced into the tube to remove the air bubbles.
- Both ends of the tube were raised and held together to check that the water level was the same in both ends. Where water bubbles or air blockages existed

in the water, the level will not remain same in both ends.

- Both ends were clamped to the ends of the mesh fence using steel wire. The water was contained by sealing both ends, and the water level was kept 50 mm to 100 mm below the end to avoid water spilling out while moving around the field. The solid concrete foundation at the base of the gate was selected as a datum i.e. a base measurement point (reference point) from which all the elevations (heights) were taken.
- The height of water and horizontal distances between stations were recorded using measuring tape by moving and clamping the end of the water tube vertically at all twenty-six tests stations.

3.6.2.2.1 Elevation measurement for downhill slope with water supply placed into the highest end of the dripline

Table 3.2 shows the measurement of slope using the water supply into the highest end of the dripline. The height on the tape from the datum was calculated by adding the height of water level from datum and height of tape from the water level. Cumulative distance was measured by adding the horizontal distances measured between any two stations and the slope was calculated, as shown in the table below.

Table 3.2: Elevation measurement using slope and placing water supply into the highest end of the dripline.

Test Position No	Length	Ht of water level from datum	Ht of tape from water level	Horizontal distance	Cumm horizontal distance	Ht of tape from datum	Slope
	m	mm	mm	mm	mm	mm	%
0	0	1648	702	0	0	2350	0
1	0.4	1648	685	400	400	2333	4.3
2	4	1625	595	3650	4050	2220	3.1
3	8	1648	446	4070	8120	2094	3.1
4	12	1559	237	4020	12140	1796	7.4
5	16	1567	43	4060	16200	1610	4.6
6	20	1593	-12	4020	20220	1581	0.7
7	24	1585	-28	4062	24282	1557	0.6
8	28	1571	-88	4074	28356	1483	1.8
9	32	1571	-170	4060	32416	1401	2.0
10	36	1528	-165	4040	36456	1363	0.9
11	40	1517	-170	4075	40531	1347	0.4
12	44	1558	-240	4020	44551	1318	0.7
13	48	1556	-287	4020	48571	1269	1.2
14	52	1534	-345	4070	52641	1189	2.0
15	56	1590	-423	4020	56661	1167	0.5
16	60	1567	-430	3960	60621	1137	0.8
17	64	1572	-532	4035	64656	1040	2.4
18	68	1552	-548	4010	68666	1004	0.9
19	72	1494	-573	3990	72656	921	2.1
20	76	1335	-676	3930	76586	659	6.7
21	80	1360	-842	3970	80556	518	3.6
22	84	1298	-878	3930	84486	420	2.5
23	88	1296	-900	4000	88486	396	0.6
24	92	1298	-933	3950	92436	365	0.8
25	96	1306	-1110	3990	96426	196	4.2
26	100	1344	-1135	3940	100366	209	-0.3

The slopes calculated were then replicated into the Hydrocalc and Eaucadi software packages to calculate the simulated individual emitter discharges for all the tests performed with water supply placed into the highest end. It can be seen from Figure 3.18 that the slope is not uniform and the actual height of the dripline was measured from the datum and the ag-plot ground was not levelled. The average slope measured in the field was 2.1% and -2.1% using the water supply into the highest and lowest end of the dripline respectively. Plots of the dripline height above the datum against the distance from the supply end were produced as shown in Figure 3.18.

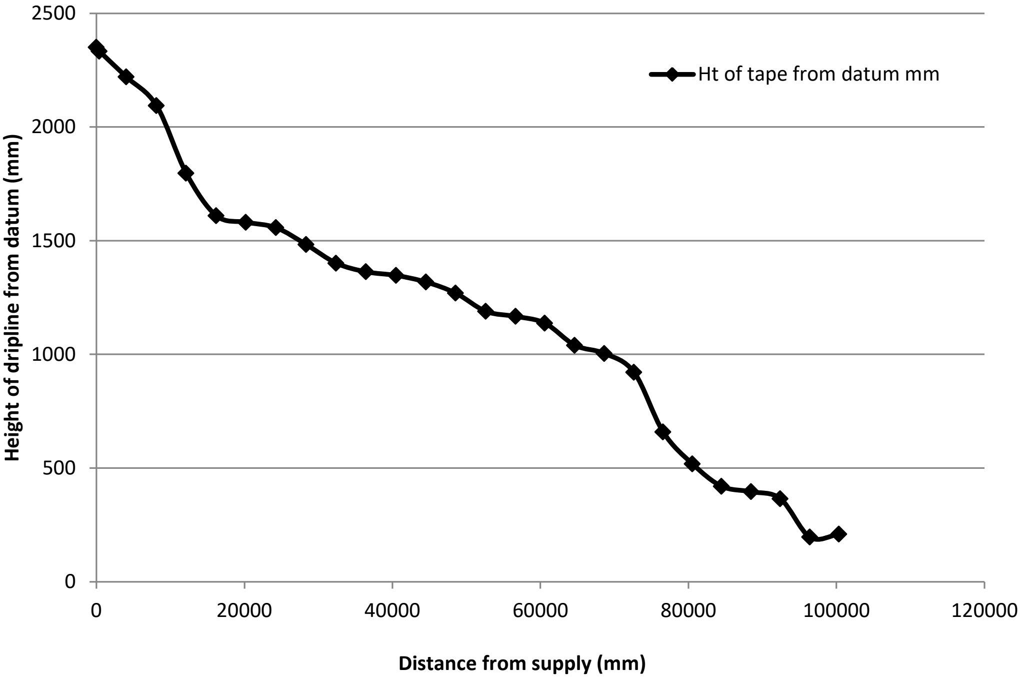


Figure 3.18: A graph of height of the dripline above the datum and the distance from the supply, placing water supply into the highest end of the dripline.

3.6.2.2.2 Elevation measurement for uphill slope with water supply placed into the lowest end of the dripline

The previously measured dripline height above the datum at each station and the horizontal distances between each station were used to calculate the slopes for all the tests performed using the water supply into the lowest end of the dripline as shown in Table 3.3.

Table 3.3: Elevation measurement using slope and placing water supply into the lowest end of the dripline.

Test Position No	Length	Ht of water level from datum	Ht of tape from water level	Horizontal distance	Cumm horizontal distance	Ht of tape from datum	Slope
	m	mm	mm	mm	mm	mm	%
0	0.4	1344	-1135	0	0	209	0.00
1	4.4	1306	-1110	3940	3940	196	0.33
2	8.4	1298	-933	3990	7930	365	-4.24
3	12.4	1296	-900	3950	11880	396	-0.78
4	16.4	1298	-878	4000	15880	420	-0.60
5	20.4	1360	-842	3930	19810	518	-2.49
6	24.4	1335	-676	3970	23780	659	-3.55
7	28.4	1494	-573	3930	27710	921	-6.67
8	32.4	1552	-548	3990	31700	1004	-2.08
9	36.4	1572	-532	4010	35710	1040	-0.90
10	40.4	1567	-430	4035	39745	1137	-2.40
11	44.4	1590	-423	3960	43705	1167	-0.76
12	48.4	1534	-345	4020	47725	1189	-0.55
13	52.4	1556	-287	4070	51795	1269	-1.97
14	56.4	1558	-240	4020	55815	1318	-1.22
15	60.4	1517	-170	4020	59835	1347	-0.72
16	64.4	1528	-165	4075	63910	1363	-0.39
17	68.4	1571	-170	4040	67950	1401	-0.94
18	72.4	1571	-88	4060	72010	1483	-2.02
19	76.4	1585	-28	4074	76084	1557	-1.82
20	80.4	1593	-12	4062	80146	1581	-0.59
21	84.4	1567	43	4020	84166	1610	-0.72
22	88.4	1559	237	4060	88226	1796	-4.58
23	92.4	1648	446	4020	92246	2094	-7.41
24	96.4	1625	595	4070	96316	2220	-3.10
25	100	1648	685	3650	99966	2333	-3.10
26	100.4	1648	702	400	100366	2350	-4.25

The slopes generated were then replicated into the Eaucadi and Hydrocalc software packages to compute the simulated individual emitter discharge for all the tests performed using water supply into the lowest end of the dripline. Plots of the dripline height above the datum against the distance from the supply end were generated and is shown in Figure 3.19.

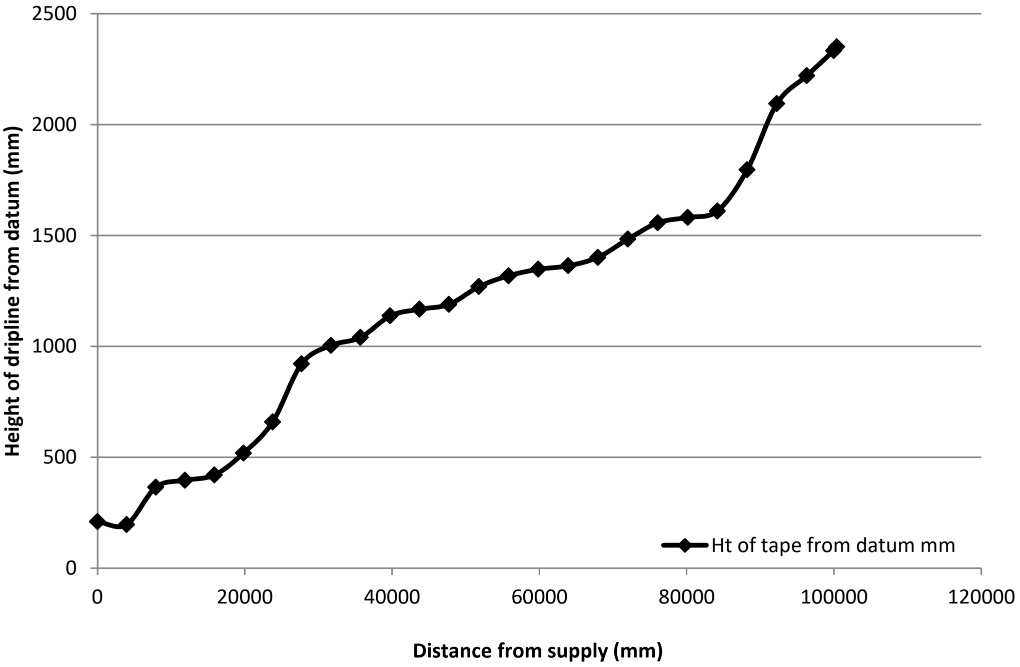


Figure 3.19: A graph of the height of the dripline from the datum and the distance from the supply placing water supply into the lowest end of the dripline.

3.6.2.3 Field testing of replicated design at the Agricultural Plot

Field tests were conducted on the drip irrigation system installed at the ag-plot area to evaluate the performance of the hydraulic system and components using different irrigation performance measures for uniformity. The following methodology was used to measure the flow and the pressure at the field test site.

3.6.2.4 Flow measurement

Two flowmeters were installed at the water supply point in the agriculture plot area to calculate the total flow of the system. As the EM flowmeter stopped working due to a failed battery, only the multi-jet flowmeter was used to calculate the total flow of the system for all of the tests performed.

The catch cans as shown in Figure 3.20, were used to measure the individual emitter flow rate. A stopwatch was used to record the time when each catch can was placed under selected emitter for all the twenty-six tests stations. Similarly, time is recorded when each catch can was removed from each station as well as the volume of water collected in each catch can. The measured time and volume of water collected in each can was used to calculate individual emitter flow rates in litres per hour. The flow at the twenty-six selected individual emitters was taken at different supply pressures with water supply placed into the highest end and then similar readings were taken with water supply placed into the lowest end of dripline.

Figure 3.20: View of water dripping down from the emitter into the catch can.

3.6.2.5 Pressure measurement

Most drip systems are designed for emitter pressures between 7 to 10 metres of water head, and the emitter flow is a function of the pressure at the emitter in the dripline. Therefore, measuring the pressure at different points is the simplest way to evaluate the hydraulic performance of the system. One pressure gauge was installed at the downstream of the flowmeters to measure the water pressure at the supply end and before recording supply pressure the system was left running until a stable supply pressure was achieved. A handmade pressure gauge as shown in Figure 3.1 was used to measure the individual emitter's pressure at all the twenty-six tests stations.. A theoretical emitter flow (Litres/hr) was measured using the manufacturer's given constant '*k*' and exponent '*x*' using the measured pressure (metres head of water) at each station. The individual emitter pressure and flow rate was recorded at all twenty-six tests stations with water supply placed into the highest end of the dripline for six tests and with the water supply placed into the lowest end of the dripline for five tests with varying supply pressure for each test.

3.6.2.6 Performance measurement

Performance and uniformity measures were measured using data collected from the flow and pressure measurements using the irrigation performance equations provided in Section 2.10 and the detailed results have been provided in Section 5.5.4.

3.7 Simulation with Eaucadi

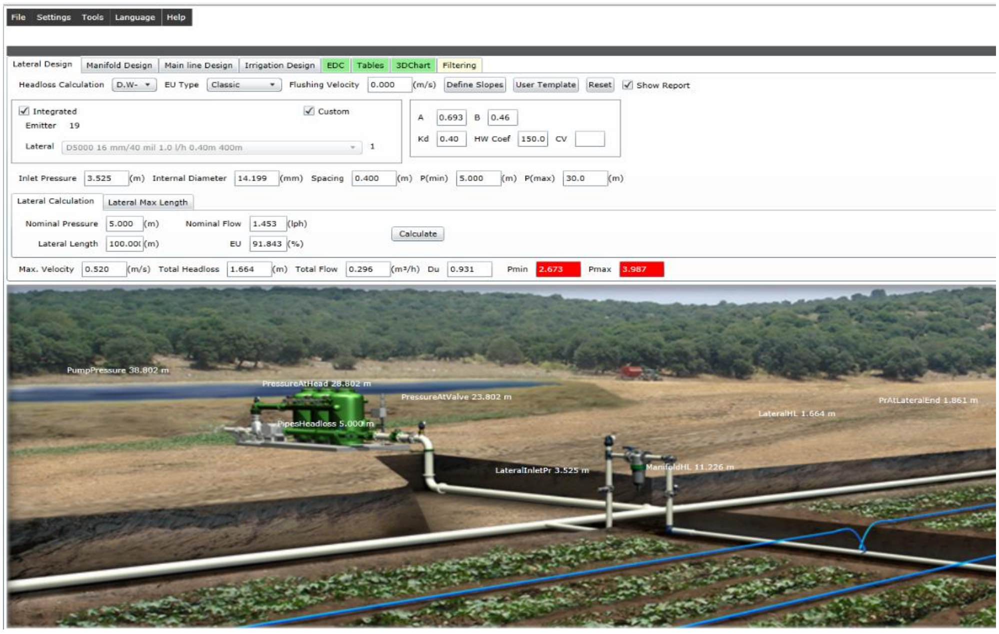
Eaucadi and Hydrocalc were selected for this research project as being most suitable for simulating the selected Punjabi drip irrigation systems. One of the main objectives of this research project is to configure the selected software packages using the characteristics of the experimental dripline and to employ a process of verifying the correct parameterisation of these packages by cross checking the simulated and field measured results. These software packages are introduced in the following sections, and the field test site configurations are replicated in these packages to confirm if the modern computer software design packages are parameterised correctly to match the hydraulic performance of drip irrigation systems in the Punjab Province of Pakistan.

3.7.1 Introduction to the Eaucadi software package

Eaucadi is one of the computers aided online software packages available for design of drip systems and is provided to authorised users by John Deere Water Company. This software package has a built-in database of John Deere Water products and the following sections will provide a systematic description of the major components of the Eaucadi.

3.7.1.1 Login into the software

Users can login to the web interface using a username and password provided by John Deere Water. After login to the software package, a new file is created and the main start up page is displayed as shown in Figure 3.21.



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☑ Show Report

☑ Integrated ☑ Custom

Emitter 19

Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1

A 0.693 B 0.46

Kd 0.40 HW Coef 150.0 CV

Inlet Pressure 3.525 (m) Internal Diameter 14.199 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.453 (lph)

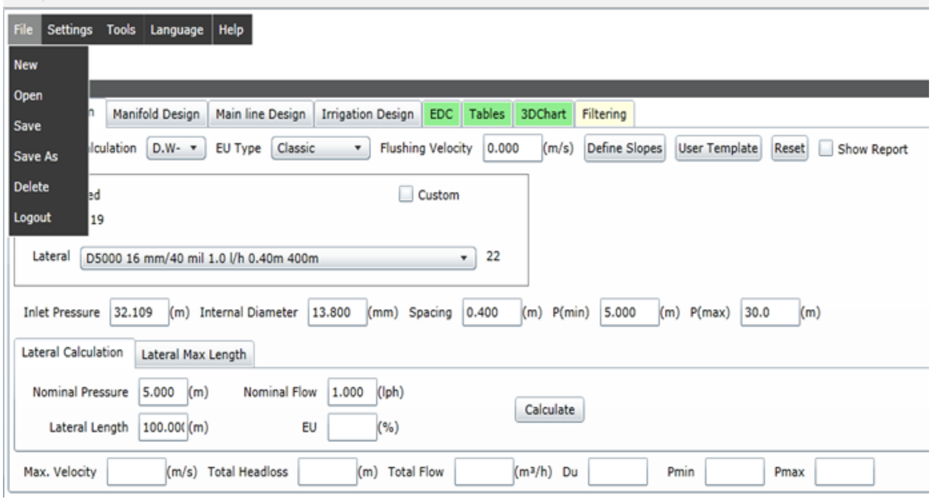
Lateral Length 100.00((m) EU 91.843 (%)

Max. Velocity 0.520 (m/s) Total Headloss 1.664 (m) Total Flow 0.296 (m³/h) Du 0.931 Pmin 2.673 Pmax 3.987

Figure 3.21: Main start-up page for Eaucadi.

3.7.1.2 Creating a new design file

The start-up page comprises of several menu items and the first five menu items are file Settings, tools, language and help as shown in Figure 3.22. The File menu helps creating a new design file, open the existing file, save or delete the already created design file. The design file is stored on the web server and is available to authorise users.



lculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☐ Show Report

ed ☐ Custom

19

Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22

Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)

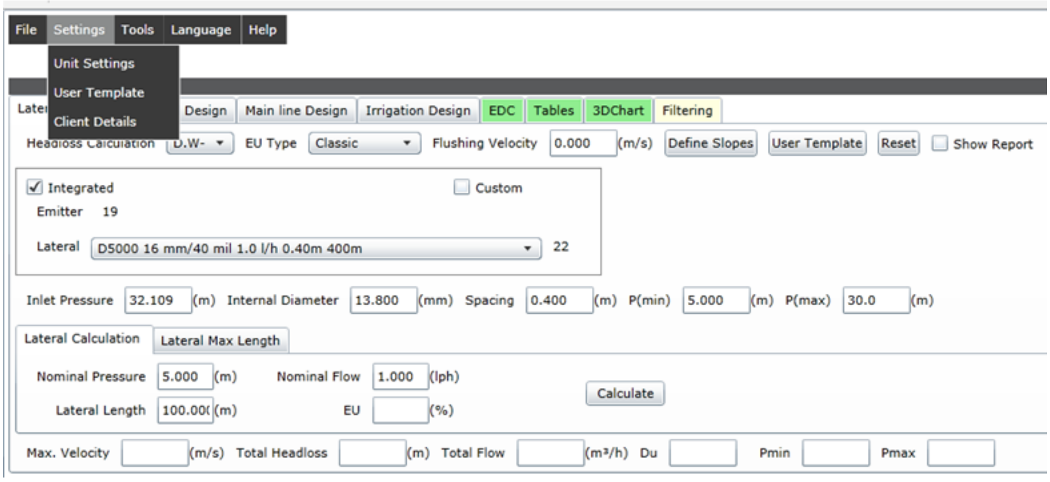
Lateral Length 100.00((m) EU (%)

Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.22: Creating a new design file in Eaucadi.

3.7.1.3 Settings

The second menu item “settings” is comprised of unit settings, user template and client details as shown in Figure 3.23.



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☐ Show Report

☑ Integrated ☐ Custom

Emitter 19

Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22

Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

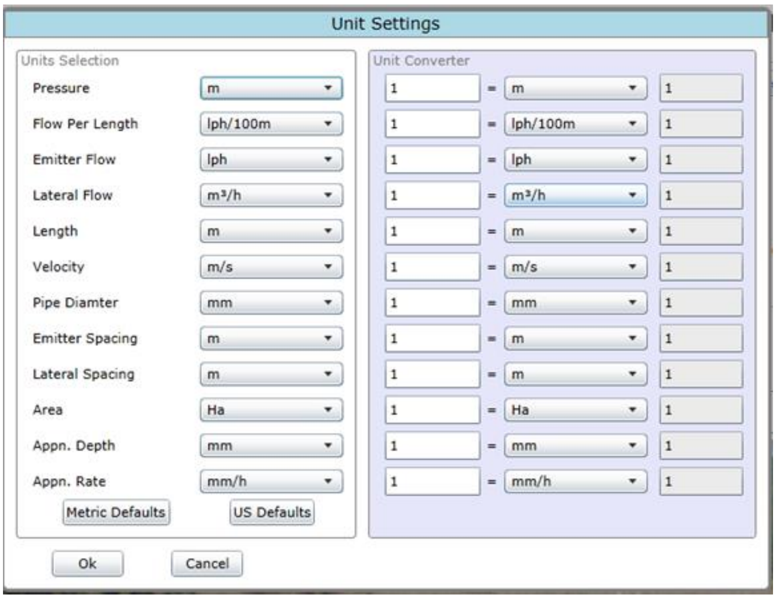
Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)

Lateral Length 100.00((m) EU (%)

Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.23: Settings tab displaying unit settings, user template and client details.

Unit settings tab gives two options of units i.e. metric units and US units as shown in Figure 3.24. Metric units have been selected for this research.



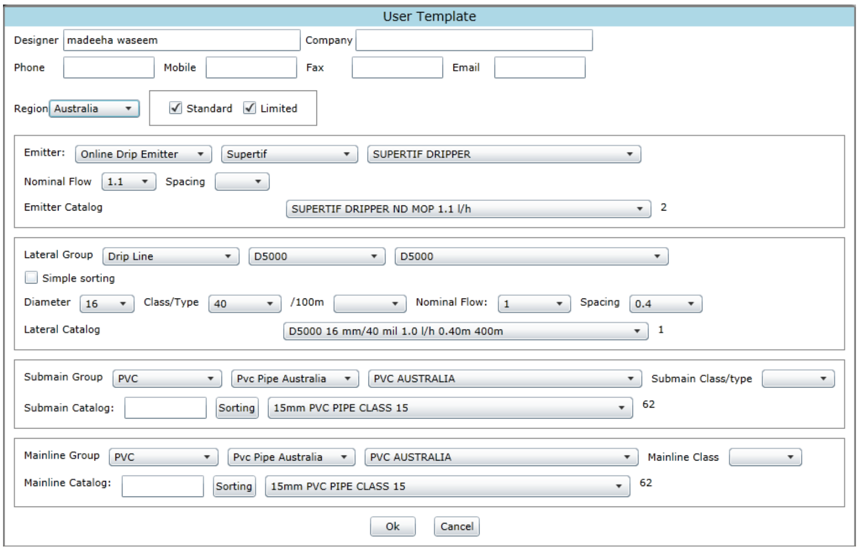
Units Selection		Unit Converter			
Pressure	m	1	=	m	1
Flow Per Length	lph/100m	1	=	lph/100m	1
Emitter Flow	lph	1	=	lph	1
Lateral Flow	m³/h	1	=	m³/h	1
Length	m	1	=	m	1
Velocity	m/s	1	=	m/s	1
Pipe Diamter	mm	1	=	mm	1
Emitter Spacing	m	1	=	m	1
Lateral Spacing	m	1	=	m	1
Area	Ha	1	=	Ha	1
Appn. Depth	mm	1	=	mm	1
Appn. Rate	mm/h	1	=	mm/h	1

Figure 3.24: Tab presenting Unit Settings as metric default and US default units.

The user template box allows the designer to add personal and company details for the design as given in Figure 3.25. There are four boxes below the first ribbon shown as Emitter, Lateral group, Submain group, and Mainline group. In the Emitter box basic details are required for online emitters, sprinklers, sprayers and foggers.

The second box in the Lateral group contains lateral type depending on material, product name, diameter, class, and flow per unit, nominal flow and spacing. In the Lateral type dropdown list there is dripline, HDPE (high-density polyethylene), LDPE (low-density polyethylene), PVC (polyvinyl chloride), flat hose and lay flat hose. The third box is the Sub-main group with different sub-main types depending on material, class and size. The Sub-main tab has a wide range of Sub mains, such as HDPE (high-density polyethylene), PVC (polyvinyl chloride), flat hose, lay flat hose and aluminium pipe.

The fourth box is the Main-line group that allows to choose between different types of main line, depending on material, class and size. The types of main-line pipes available are HDPE (high-density polyethylene), PVC (polyvinyl chloride), flat hose, lay flat hose, cast iron pipe and aluminium pipe as shown in Figure 3.25. These specifications can be changed and customised individually later in the design procedure if required.



Designer madeeha waseem Company
Phone Mobile Fax Email
Region Australia ☑ Standard ☑ Limited
Emitter: Online Drip Emitter Supertif SUPERTIF DRIPPER
Nominal Flow 1.1 Spacing
Emitter Catalog SUPERTIF DRIPPER ND MOP 1.1 l/h 2
Lateral Group Drip Line D5000 D5000
☐ Simple sorting
Diameter 16 Class/Type 40 /100m Nominal Flow: 1 Spacing 0.4
Lateral Catalog D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1
Submain Group PVC Pvc Pipe Australia PVC AUSTRALIA Submain Class/type
Submain Catalog: Sorting 15mm PVC PIPE CLASS 15 62
Mainline Group PVC Pvc Pipe Australia PVC AUSTRALIA Mainline Class
Mainline Catalog: Sorting 15mm PVC PIPE CLASS 15 62

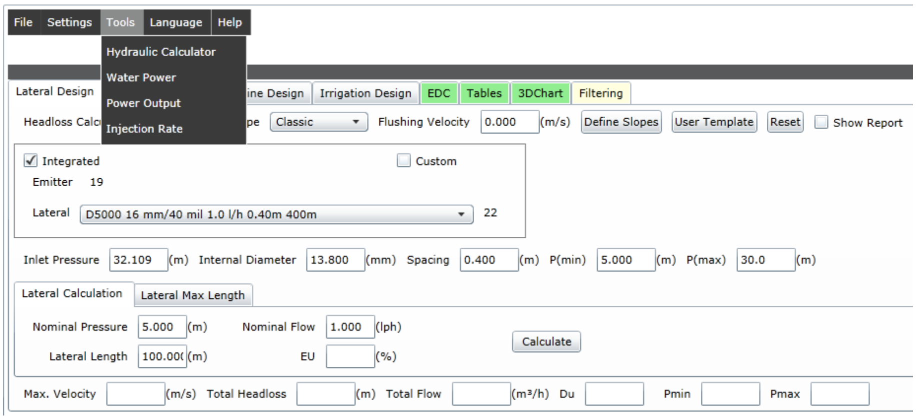
Figure 3.25: User template tab to fill in the user and basic lateral, submain and mainline specifications.

3.7.1.4 Tools tab in Eaucadi

Figure 3.26 displays the Tools tab that has four calculators as Hydraulic Calculator, Water power, Power Output and Injection Rate. The details of these are as follows.

1. Hydraulic Calculator: It is a simple calculator that helps in the measurement of pressure drop or required pipe diameter or flow or pipe length or velocity, adding into the remaining known factors.

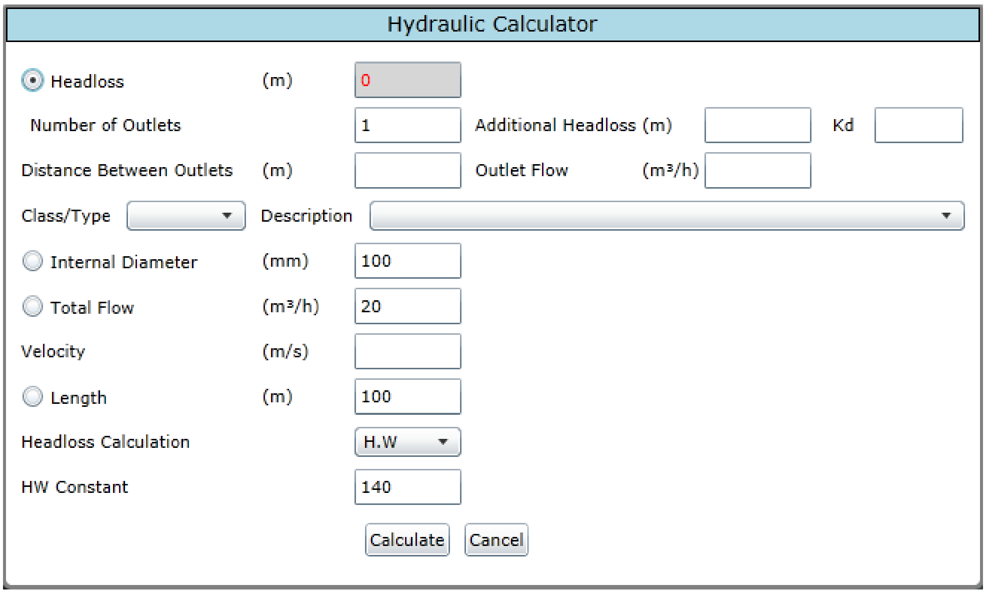
2. Water power: Water power (kiloWatts) can be used to calculate the flow rate (m^3/hr) if water head (m) and efficiency are known.
3. Power Output: Voltage (volts), power factor (%), current (Amps), efficiency (%) and power at duty point can be measured (kiloWatts) using the Power input tab after completing the design of the system.
4. Injection rate: Injection rate (L/h) can be measured using the final concentration (ppm), tank solution concentration (%), pump rate (m^3/hr); or the tank solution concentration can be measured using injection rate, pump rate and final concentration.



Classic
Flushing Velocity 0.000 (m/s)
☐ Show Report
☑ Integrated
☐ Custom
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22
Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)
Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)
Lateral Length 100.00((m) EU (%)
Max. Velocity (m/s) Total Headloss (m) Total Flow (m^3/h) Du Pmin Pmax

Figure 3.26: Tools menu displaying the hydraulic calculator, waterpower, power output and injection rate tabs.

The hydraulic calculator (Figure 3.27) allows users to calculate the pressure drop, required pipe diameter, total flow, pipe length or the velocity in the main line pipes. The calculator allows the calculations for pipes defined in the user template based on the Hazen William equation or Darcy Weisbach equation. Desired parameter is measured adding in the rest of the known parameters alternatively.



● Headloss (m) 0

Number of Outlets 1

○ Internal Diameter (mm) 100

○ Total Flow (m^3/h) 20

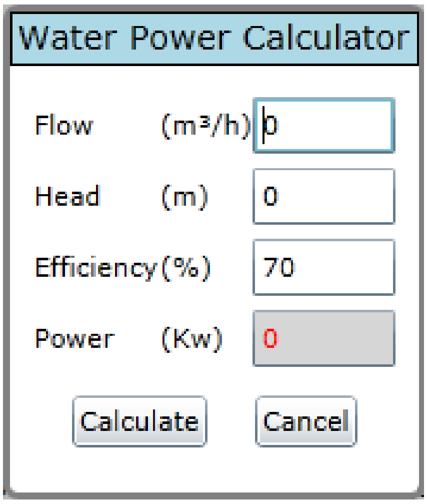
○ Length (m) 100

Headloss Calculation H.W

HW Constant 140

Figure 3.27: Hydraulic calculator to measure the head loss from given specifications of the pipe.

The water power calculator helps in calculating the power requirements for the pumping based on the required flow, pressure head and pumping efficiency as shown in Figure 3.28.



Flow (m^3/h) 0

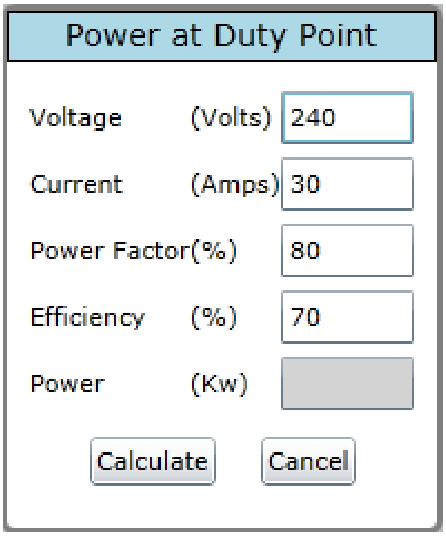
Head (m) 0

Efficiency (%) 70

Power (Kw) 0

Figure 3.28: Water power calculator to measure the required electrical power.

The required electrical power for three phase electricity can be measured if the voltage (volts), current (Amps), power factor (%) and efficiency (%) are known as shown in Figure 3.29.

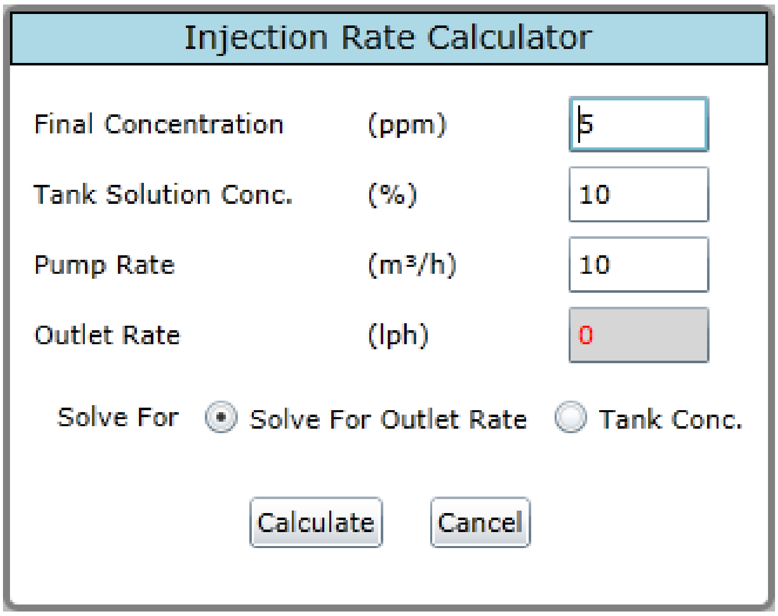


Power at Duty Point

Voltage (Volts) 240
Current (Amps) 30
Power Factor(%) 80
Efficiency (%) 70
Power (Kw)

Figure 3.29: Calculator to estimate the power at the pump duty point.

The injection rate calculator can be used to measure the tank solution concentration of fertilizer required in a fertigation tank if the field (final) concentration (ppm), application rate for the zone (pump rate) (m^3/h) and outlet rate from the fertigation tank are known. The calculator can also estimate the outlet rate from the fertigation tank are known and vice versa if other parameters are also known as shown in Figure 3.30.



Injection Rate Calculator

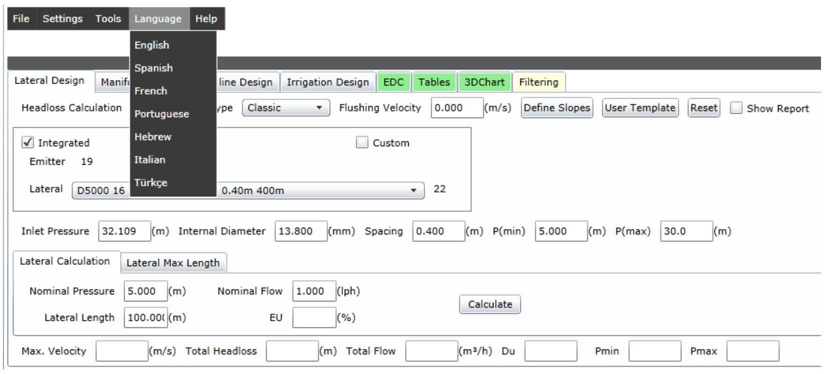
Final Concentration (ppm) 5
Tank Solution Conc. (%) 10
Pump Rate (m^3/h) 10
Outlet Rate (lph) 0

Solve For ● Solve For Outlet Rate ○ Tank Conc.

Figure 3.30: Injector rate calculator to measure the tank solution concentration rate.

3.7.1.5 Language

The language can be selected in the language tab (Figure 3.31), and English has been selected for the selected design.



Headloss Calculation ype Classic Flushing Velocity 0.000 (m/s) ☐ Show Report

☑ Integrated ☐ Custom
Emitter 19
Lateral D5000 16 0.40m 400m 22

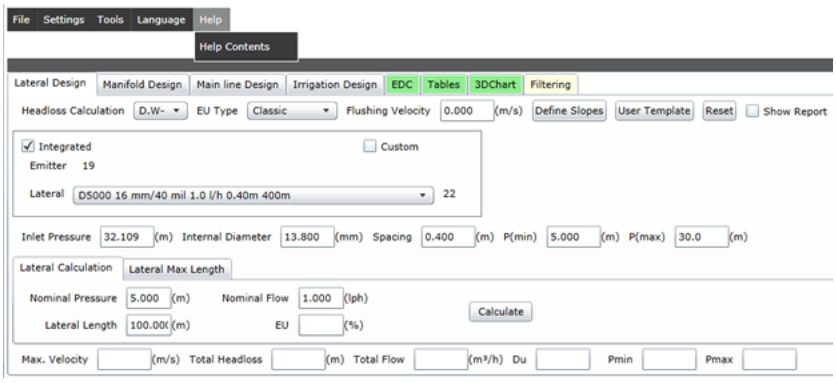
Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)
Lateral Length 100.00((m) EU (%)

Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.31: Language tab to select different languages from drop down list.

The final menu item is help contents (Figure 3.32) and it allows the users to properly understand different functions and procedures of the software and their use.



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☐ Show Report

☑ Integrated ☐ Custom
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22

Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

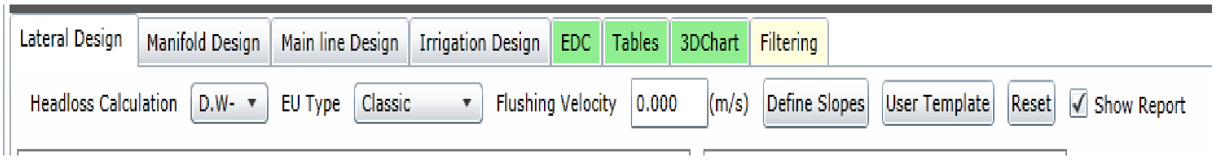
Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)
Lateral Length 100.00((m) EU (%)

Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.32: Help contents to guide the user about the usage and understanding of the software components.

3.7.1.6 Entering design details in Eaucadi

Below the main menu there are series of tabs, one for each component of the system (Figure 3.33). These tabs include lateral design, manifold design (submain design), main line design, irrigation design, EDC, Tables, 3D Chart and Filtering. These important sections will be discussed in further detail below:

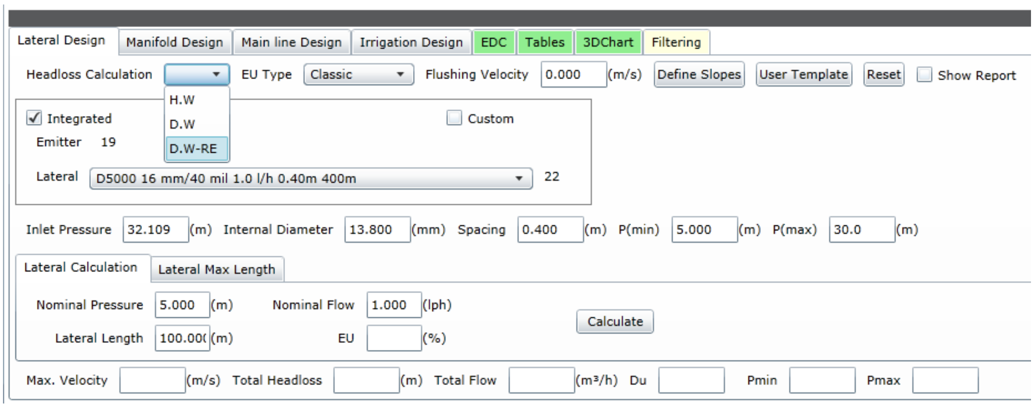


Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☑ Show Report

Figure 3.33: First menu bar for basic lateral design and tools.

The lateral design tab enables the user to specify the characteristics of the dripline (Figure 3.34). The software includes three different approaches for estimating friction: H.W (Hazen William), D.W (Darcy-Weisbach) and D.W-RE (Darcy-Weisbach Reynolds Number). The D.W-RE method has been selected for the selected design

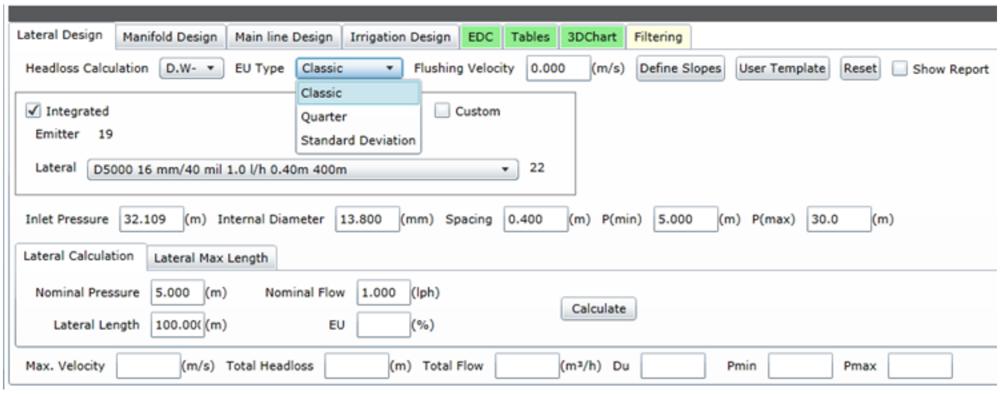
(Figure 3.34).



Headloss Calculation
EU Type Classic
Flushing Velocity 0.000 (m/s)
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22
Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)
Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)
Lateral Length 100.00((m) EU (%)
Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.34: Head loss calculation method selection.

After the selection of a head loss calculation method, the user must choose an emission uniformity calculation method; the options available include classic, quarter and standard deviation as shown in Figure 3.35.



Headloss Calculation D.W-
EU Type Classic
Flushing Velocity 0.000 (m/s)
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22
Inlet Pressure 32.109 (m) Internal Diameter 13.800 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)
Nominal Pressure 5.000 (m) Nominal Flow 1.000 (lph)
Lateral Length 100.00((m) EU (%)
Max. Velocity (m/s) Total Headloss (m) Total Flow (m³/h) Du Pmin Pmax

Figure 3.35: Emission uniformity type tab to select a method of emission uniformity measurement.

The lateral slope can be added in to the “define slopes” for each length of dripline (m) i.e. the distance from the inlet and the slope percentage at the same distance from the inlet. The direction of slope can be selected as uphill and downhill according to the field slope as shown in Figure 3.36. This software package allows an unlimited number of slope entries in terms of pipe length, percentage and direction of slope.

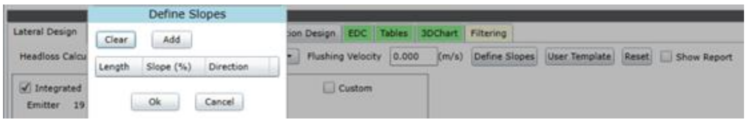
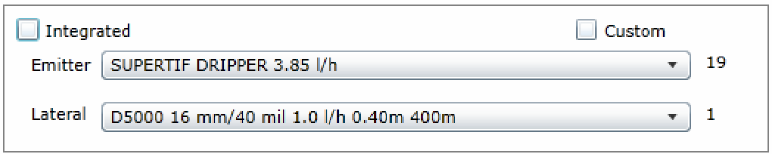


Figure 3.36: Slope entries as per length, percentage and direction of slope.

3.7.1.7 Selection and configuration of lateral

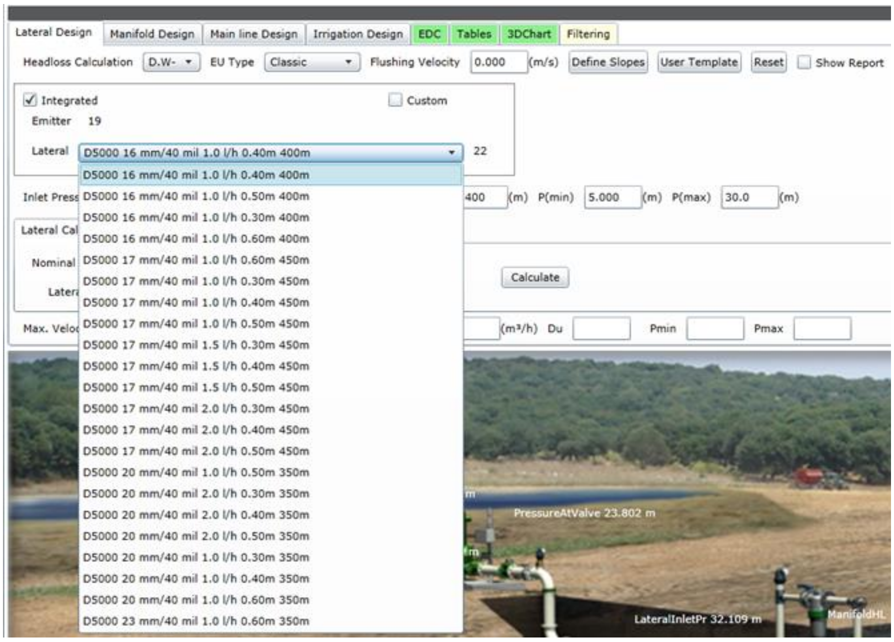
Before choosing a lateral, the user must select the type of emitter. Two types of emitters are available i.e. integrated dripline and online emitter as shown in Figure 3.37.



☐ Integrated ☐ Custom
Emitter SUPERTIF DRIPPER 3.85 l/h 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1

Figure 3.37: Tab for the selection of a lateral and emitter specifications as per requirement.

The software covers a large variety of dripline types in terms of model number, size, lateral spacing and emitter flow rates as shown in Figure 3.38. These are already available in the database provided by John Deere Water.

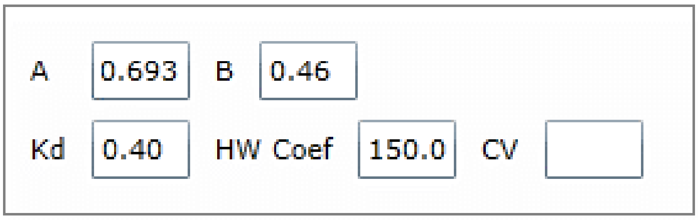


Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☐ Show Report
☑ Integrated ☐ Custom
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 22
Inlet Press 400 (m) P(min) 5.000 (m) P(max) 30.0 (m)
(m³/h) Du Pmin Pmax

D5000 16 mm/40 mil 1.0 l/h 0.40m 400m
D5000 16 mm/40 mil 1.0 l/h 0.50m 400m
D5000 16 mm/40 mil 1.0 l/h 0.30m 400m
D5000 16 mm/40 mil 1.0 l/h 0.60m 400m
D5000 17 mm/40 mil 1.0 l/h 0.60m 450m
D5000 17 mm/40 mil 1.0 l/h 0.30m 450m
D5000 17 mm/40 mil 1.0 l/h 0.40m 450m
D5000 17 mm/40 mil 1.0 l/h 0.50m 450m
D5000 17 mm/40 mil 1.5 l/h 0.30m 450m
D5000 17 mm/40 mil 1.5 l/h 0.40m 450m
D5000 17 mm/40 mil 1.5 l/h 0.50m 450m
D5000 17 mm/40 mil 2.0 l/h 0.30m 450m
D5000 17 mm/40 mil 2.0 l/h 0.40m 450m
D5000 17 mm/40 mil 2.0 l/h 0.50m 450m
D5000 20 mm/40 mil 1.0 l/h 0.50m 350m
D5000 20 mm/40 mil 2.0 l/h 0.30m 350m
D5000 20 mm/40 mil 2.0 l/h 0.40m 350m
D5000 20 mm/40 mil 2.0 l/h 0.50m 350m
D5000 20 mm/40 mil 1.0 l/h 0.30m 350m
D5000 20 mm/40 mil 1.0 l/h 0.40m 350m
D5000 20 mm/40 mil 1.0 l/h 0.60m 350m
D5000 23 mm/40 mil 1.0 l/h 0.60m 350m

Figure 3.38: Dripline types in a drop-down list to select the lateral specifications.

All models come with a predefined hydraulic configuration, but the parameters can be manually adjusted. To get the desired flow rate, the emitter parameters can be customized by changing A (emitter exponent), B (constant *k)*, and *Kd* (Flow disturbance factor) as shown in Figure 3.39.



A 0.693
B 0.46
Kd 0.40
HW Coef 150.0
CV

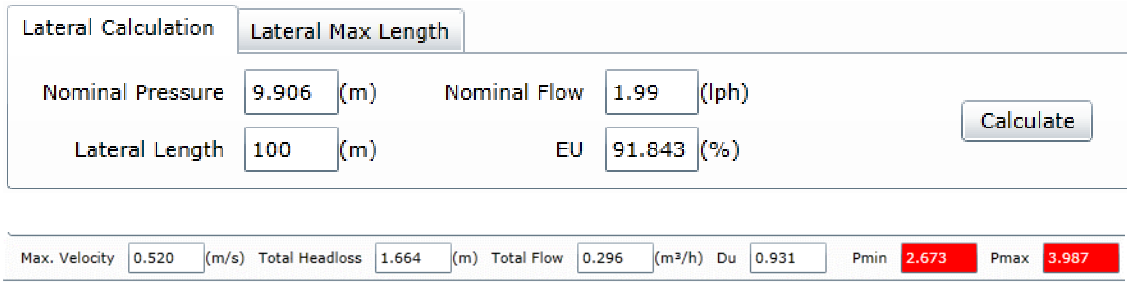
Figure 3.39: Custom tab to select the emitter specifications as per requirement.

Once the lateral has been configured, the inlet pressure, internal diameter, spacing, minimum, and maximum pressures can be changed for the design requirements in the lateral design section as shown in Figure 3.40.

Inlet Pressure 3.525 (m)
Internal Diameter 14.199 (mm)
Spacing 0.400 (m)
P(min) 5.000 (m)
P(max) 30.0 (m)

Figure 3.40: Menu bar to select the inlet pressure, internal diameter, spacing, minimum and maximum pressure for the lateral.

The final selection in the lateral configuration allows the user to calculate the supply pressure and flow for a given length, or a maximum lateral length, for a given supply pressure (Figure 3.41). Results shown also provides emission uniformity (%), maximum velocity (m/sec), total head loss (m), total flow (m^3/h), distribution uniformity, minimum pressure (m) and maximum pressure (m) in results.



Nominal Pressure 9.906 (m)
Lateral Length 100 (m)
Nominal Flow 1.99 (lph)
EU 91.843 (%)

Max. Velocity 0.520 (m/s)
Total Headloss 1.664 (m)
Total Flow 0.296 (m³/h)
Du 0.931
Pmin 2.673
Pmax 3.987

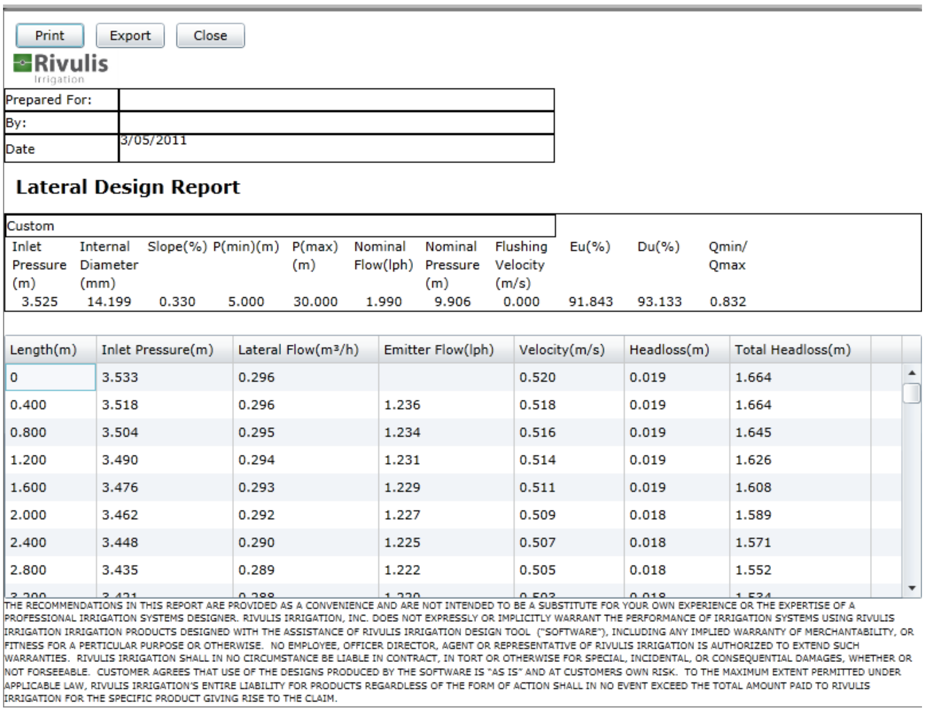
Figure 3.41: Maximum velocity, total head loss, total flow, distribution uniformity, and maximum and minimum pressure obtained from lateral calculation results.

3.7.1.8 Design Layout

The design layout at the lateral (dripline) design page shows the pressure and head loss in different components and locations of the system as shown in Figure 3.42.

Figure 3.42: Design layout showing the lateral, submain (manifold) and mainline configuration and specifications.

The lateral design report (Figure 3.43) can be printed or exported and this report produces the sheet providing the inlet pressure (m), lateral flow (m^3/ h), emitter flow (L/h), velocity (m/sec), head loss (m) and total head loss at each emitter along the length of lateral.



Prepared For:	
By:	
Date	3/05/2011

Lateral Design Report

Custom

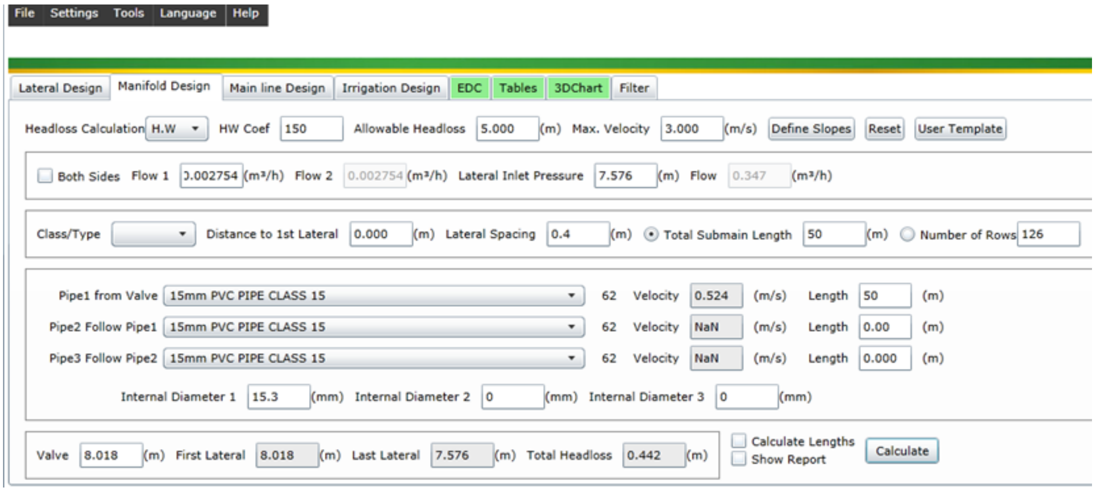
Inlet Pressure (m)	Internal Diameter (mm)	Slope(%)	P(min)(m)	P(max) (m)	Nominal Flow(lph)	Nominal Pressure (m)	Flushing Velocity (m/s)	Eu(%)	Du(%)	Qmin/ Qmax
3.525	14.199	0.330	5.000	30.000	1.990	9.906	0.000	91.843	93.133	0.832

Length(m)	Inlet Pressure(m)	Lateral Flow(m³/h)	Emitter Flow(lph)	Velocity(m/s)	Headloss(m)	Total Headloss(m)
0	3.533	0.296		0.520	0.019	1.664
0.400	3.518	0.296	1.236	0.518	0.019	1.664
0.800	3.504	0.295	1.234	0.516	0.019	1.645
1.200	3.490	0.294	1.231	0.514	0.019	1.626
1.600	3.476	0.293	1.229	0.511	0.019	1.608
2.000	3.462	0.292	1.227	0.509	0.018	1.589
2.400	3.448	0.290	1.225	0.507	0.018	1.571
2.800	3.435	0.289	1.222	0.505	0.018	1.552

Figure 3.43: Lateral design final report, providing individual emitter distance from the lateral head, inlet pressure, lateral flow rate, emitter flow rate, velocity, head loss and total head loss.

3.7.1.9 Manifold Design (Submain Design)

After defining allowable head loss, maximum velocity, class/ type of sub main, distance to 1st lateral and lateral spacing, submain total length, the number of lateral rows can be generated. Adding the slope into Eaucadi will present the relevant pipe combination that fits the given maximum velocity and the hydraulic data as shown in Figure 3.44. Length and hydraulic data can be changed according to the desired conditions until the green coloured velocity and pressure is achieved that is acceptable to ensure optimum operation.



Headloss Calculation H.W HW Coef 150 Allowable Headloss 5.000 (m) Max. Velocity 3.000 (m/s)

☐ Both Sides Flow 1 ɔ.002754 (m³/h) Flow 2 0.002754 (m³/h) Lateral Inlet Pressure 7.576 (m) Flow 0.347 (m³/h)

Class/Type Distance to 1st Lateral 0.000 (m) Lateral Spacing 0.4 (m) ● Total Submain Length 50 (m) ○ Number of Rows 126

Pipe1 from Valve 15mm PVC PIPE CLASS 15 62 Velocity 0.524 (m/s) Length 50 (m)

Pipe2 Follow Pipe1 15mm PVC PIPE CLASS 15 62 Velocity NaN (m/s) Length 0.00 (m)

Pipe3 Follow Pipe2 15mm PVC PIPE CLASS 15 62 Velocity NaN (m/s) Length 0.000 (m)

Internal Diameter 1 15.3 (mm) Internal Diameter 2 0 (mm) Internal Diameter 3 0 (mm)

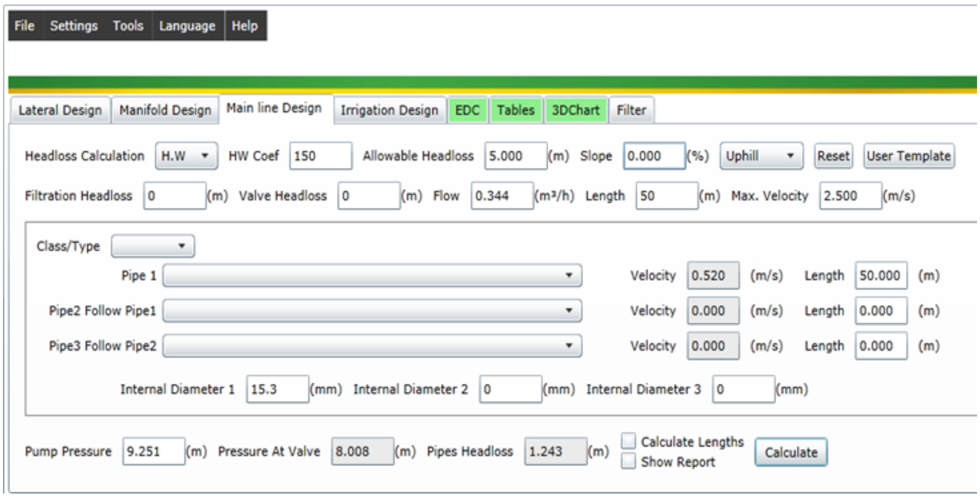
Valve 8.018 (m) First Lateral 8.018 (m) Last Lateral 7.576 (m) Total Headloss 0.442 (m)

☐ Calculate Lengths
☐ Show Report

Figure 3.44: Submain data input tab to design submain line.

3.7.1.10 Mainline Design

Defining allowable head loss, maximum velocity, class/type of pipes, main line length, uphill/downhill slope, allows Eaucadi to generate relevant pipe combinations that fits to the given maximum velocity and acceptable hydraulic data. As shown in Figure 3.45. The length of mainline and the hydraulic data can be altered to get the desired green coloured velocity and pressure results. The report window will generate the full updated report.



Headloss Calculation H.W HW Coef 150 Allowable Headloss 5.000 (m) Slope 0.000 (%) Uphill

Filtration Headloss 0 (m) Valve Headloss 0 (m) Flow 0.344 (m³/h) Length 50 (m) Max. Velocity 2.500 (m/s)

Class/Type

Pipe 1 Velocity 0.520 (m/s) Length 50.000 (m)

Pipe2 Follow Pipe1 Velocity 0.000 (m/s) Length 0.000 (m)

Pipe3 Follow Pipe2 Velocity 0.000 (m/s) Length 0.000 (m)

Internal Diameter 1 15.3 (mm) Internal Diameter 2 0 (mm) Internal Diameter 3 0 (mm)

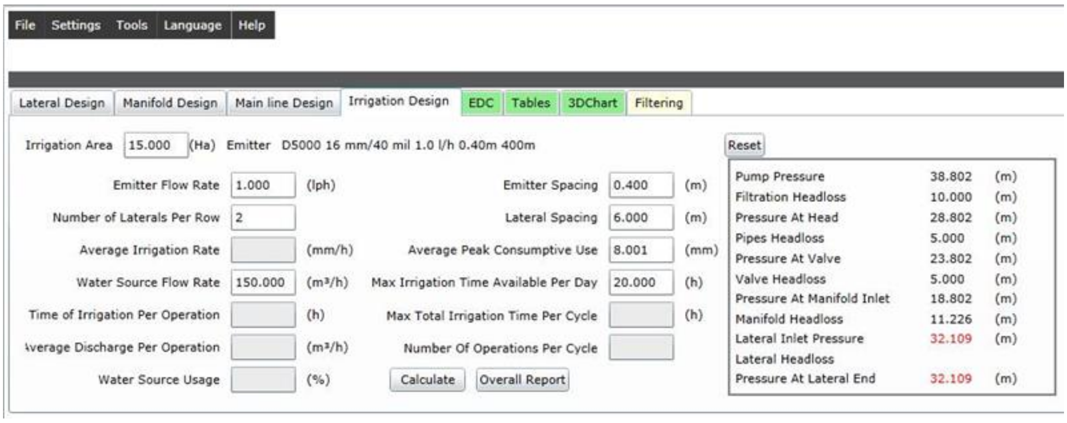
Pump Pressure 9.251 (m) Pressure At Valve 8.008 (m) Pipes Headloss 1.243 (m)

☐ Calculate Lengths
☐ Show Report

Figure 3.45: Main line data input tab to design the main line.

3.7.1.11 Irrigation design

The next important component of the design layout is the irrigation design, which helps in the calculation of the parameters that are required for irrigation scheduling of the system as shown in Figure 3.46. In the irrigation design tab, the emitter spacing, emitter flow rate and lateral spacing are imported from the previous design stages. Defining the average peak consumptive use, maximum irrigation time available per day, the number of laterals per row and the water source flow rate provides information to calculate the average irrigation rate, time of irrigation per operation, average discharge per operation, water source usage, maximum total irrigation time per cycle, and number of operations per cycle. The overall report gives the full project data table of the design.



Irrigation Area 15.000 (Ha) Emitter D5000 16 mm/40 mil 1.0 l/h 0.40m 400m

Emitter Flow Rate 1.000 (lph)
Number of Laterals Per Row 2
Average Irrigation Rate (mm/h)
Water Source Flow Rate 150.000 (m³/h)
Time of Irrigation Per Operation (h)
Average Discharge Per Operation (m³/h)
Water Source Usage (%)

Emitter Spacing 0.400 (m)
Lateral Spacing 6.000 (m)
Average Peak Consumptive Use 8.001 (mm)
Max Irrigation Time Available Per Day 20.000 (h)
Max Total Irrigation Time Per Cycle (h)
Number Of Operations Per Cycle

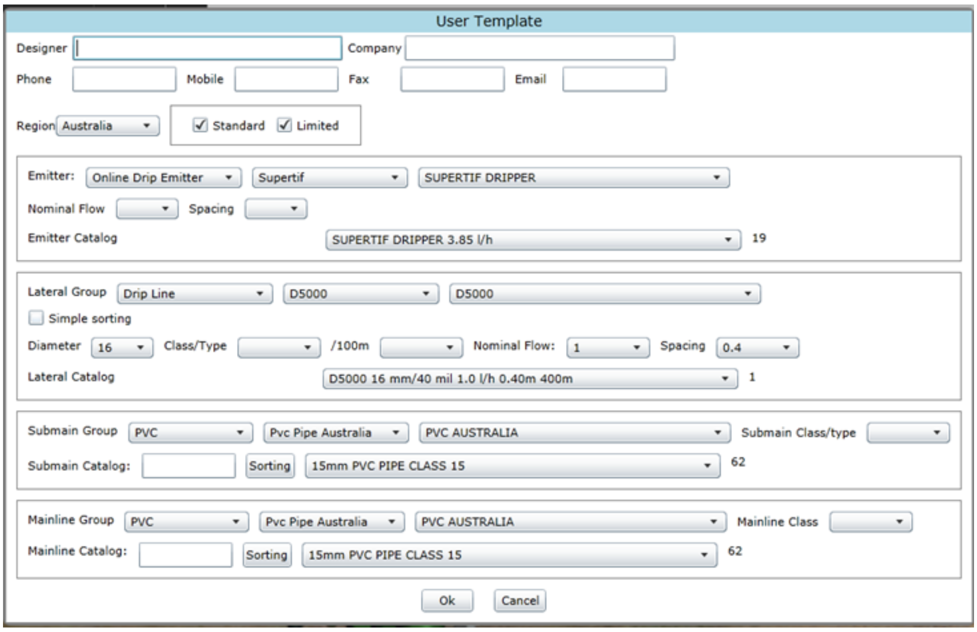
Pump Pressure	38.802	(m)
Filtration Headloss	10.000	(m)
Pressure At Head	28.802	(m)
Pipes Headloss	5.000	(m)
Pressure At Valve	23.802	(m)
Valve Headloss	5.000	(m)
Pressure At Manifold Inlet	18.802	(m)
Manifold Headloss	11.226	(m)
Lateral Inlet Pressure	32.109	(m)
Lateral Headloss		
Pressure At Lateral End	32.109	(m)

Figure 3.46: Irrigation design tab to calculate the hydraulic parameters and irrigation scheduling for the design.

3.7.2 Replication of measured field configuration in the Eaucadi with water supply placed into the highest end

The configuration for the field test site for six tests with water supply placed into the highest end of the dripline are shown below.

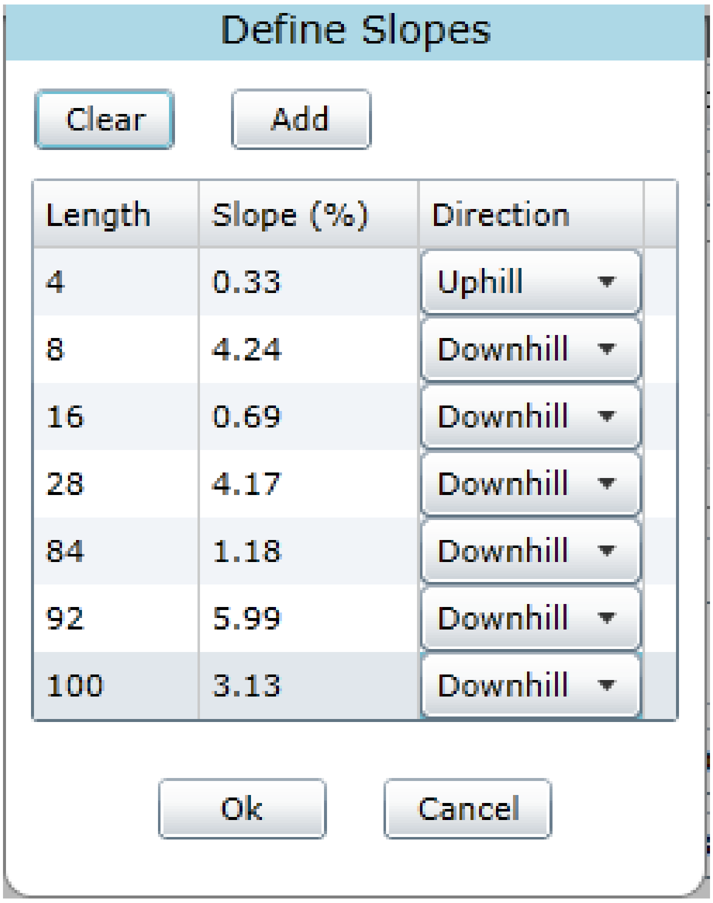
To replicate the emitter and dripline specification of the field test site, the following specifications were selected for the Dripline: “D5000 16 mm (40 mil) 1.0 l/h, 0.4 m 400 m”, where the outside diameter is 16mm with 1mm (40 mil) wall thickness, with a 1.0 L/h flow rate, and an emitter spacing of 0.4 m as shown below in Figure 3.47.



Designer
Company
Phone
Mobile
Fax
Email
Region Australia
☑ Standard ☑ Limited
Emitter: Online Drip Emitter | Supertif | SUPERTIF DRIPPER
Nominal Flow
Spacing
Emitter Catalog SUPERTIF DRIPPER 3.85 l/h 19
Lateral Group Drip Line | D5000 | D5000
☐ Simple sorting
Diameter 16
Class/Type
/100m
Nominal Flow: 1
Spacing 0.4
Lateral Catalog D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1
Submain Group PVC | Pvc Pipe Australia | PVC AUSTRALIA
Submain Class/type
Submain Catalog: Sorting 15mm PVC PIPE CLASS 15 62
Mainline Group PVC | Pvc Pipe Australia | PVC AUSTRALIA
Mainline Class
Mainline Catalog: Sorting 15mm PVC PIPE CLASS 15 62

Figure 3.47: User template to select the basic specifications of lateral submain and mainline.

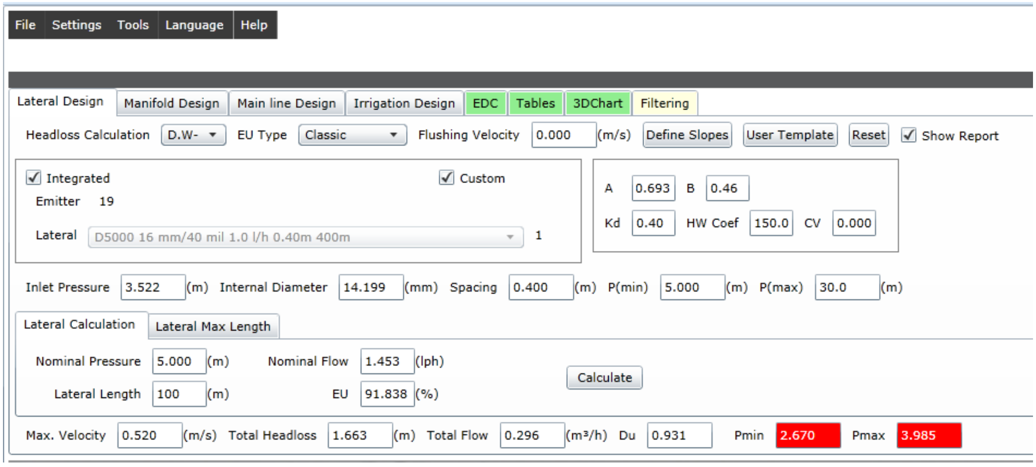
The slopes calculated from the measured field test site as detailed in Section 3.6.2.2 have been added as the length of pipe (m) i.e. from the inlet, the slope percentage over this same distance from the inlet, and the direction of slope, as shown in Figure 3.48.



Length	Slope (%)	Direction
4	0.33	Uphill
8	4.24	Downhill
16	0.69	Downhill
28	4.17	Downhill
84	1.18	Downhill
92	5.99	Downhill
100	3.13	Downhill

Figure 3.48: Slope entries per dripline length, slope percentage, and direction of slope using water supply into the highest end of the dripline.

As shown in Figure 3.49 the emitter specifications have been customized to replicate the design parameters for Test No. 1 with the type of emitter as: “Integrated”, and the emitter has been customized with “A” (exponent *x*) as 0.693, “B” (constant *k*) as 0.46, “*Kd”* as 0.40, and HW Coefficient as 150, to get the desired flow. “Classic” EU Type emission uniformity has been selected for this design.



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☑ Show Report

☑ Integrated ☑ Custom

Emitter 19

Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1

A 0.693 B 0.46

Kd 0.40 HW Coef 150.0 CV 0.000

Inlet Pressure 3.522 (m) Internal Diameter 14.199 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.453 (lph)

Lateral Length 100 (m) EU 91.838 (%)

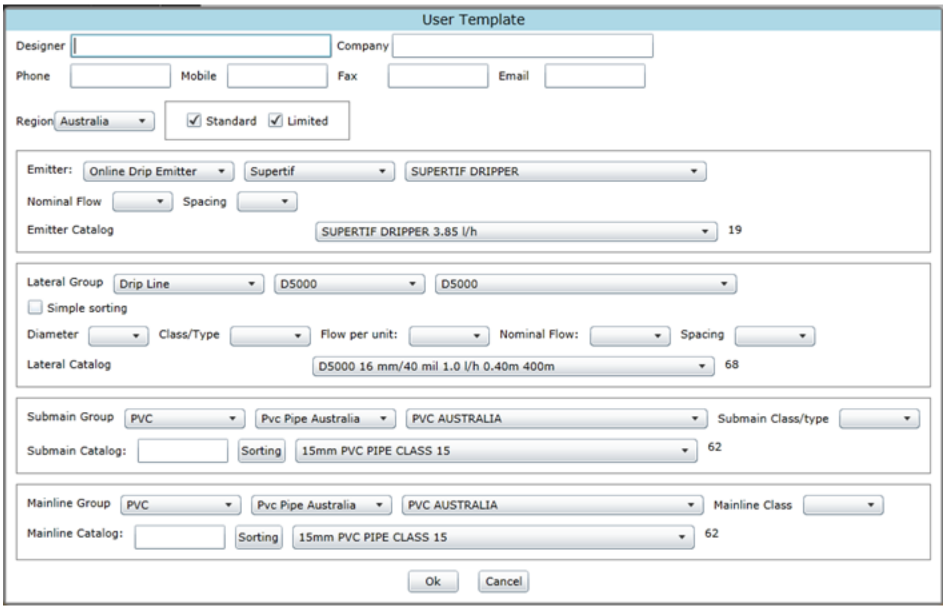
Max. Velocity 0.520 (m/s) Total Headloss 1.663 (m) Total Flow 0.296 (m³/h) Du 0.931 Pmin 2.670 Pmax 3.985

Figure 3.49: Lateral design tab showing all the specifications and design parameters selected to replicate Test No. 1.

From the “Head -Loss Calculation” drop-down menu, the Darcy-Weisbach-RE method has been selected for the calculation of head loss. The lateral was selected from lateral drop-down list with the specifications as: LDPE 16 mm with wall thickness of 1 mm (40 mil), a flowrate of 1 L/h, and an emitter spacing of 0.4 m. Other specifications have been selected with the internal diameter as 14.199 mm, and an inlet pressure of 3.522 m to get the desired pressure of 3.515 m at the first emitter with the selected lateral length of 100 metres. Minimum and maximum pressures were selected as 5 m and 30 m respectively, as shown in Figure 3.49. The results obtained are provided and discussed in Section 5.4.1 of CHAPTER 5.

3.7.3 Replication of measured field configurations in the Eaucadi with water supply placed into the lowest end of the dripline

The process described in Section 3.7.2 was repeated for the test system with water supply placed into the lowest end of the slope. As shown in Figure 3.50, the required specifications of dripline have been added as: Dripline: D5000 16 mm (40 mil) 1.0 l/h, 0.4 m 400 m”, where the outside diameter is 16 mm with a 1 mm (40 mil) wall thickness, with a 1.0 L/h flow rate, and an emitter spacing of 0.4 m.


User Template

Designer
Company
Phone
Mobile
Fax
Email

Region: Australia
☑ Standard ☑ Limited

Emitter: Online Drip Emitter | Supertif | SUPERTIF DRIPPER
Nominal Flow
Spacing
Emitter Catalog: SUPERTIF DRIPPER 3.85 l/h 19

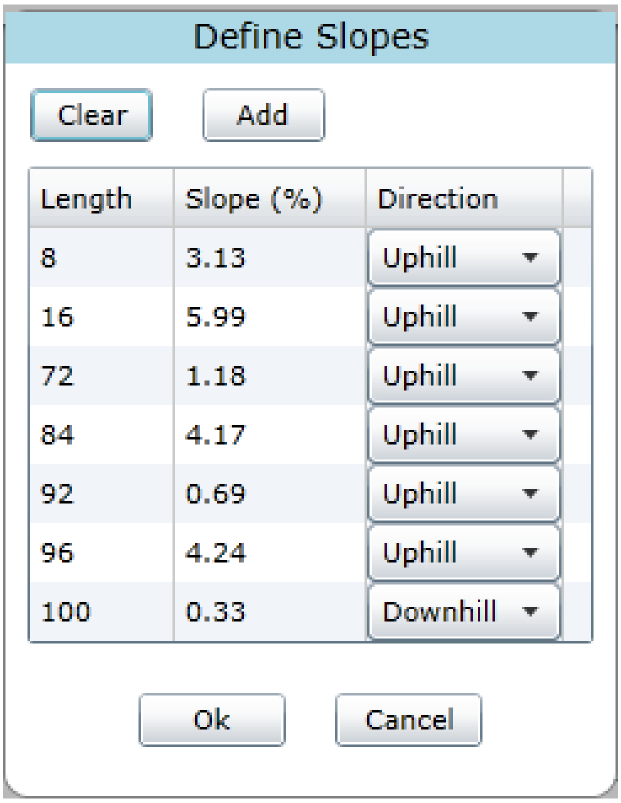
Lateral Group: Drip Line | D5000 | D5000
☐ Simple sorting
Diameter
Class/Type
Flow per unit:
Nominal Flow:
Spacing
Lateral Catalog: D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 68

Submain Group: PVC | Pvc Pipe Australia | PVC AUSTRALIA
Submain Class/type
Submain Catalog: Sorting 15mm PVC PIPE CLASS 15 62

Mainline Group: PVC | Pvc Pipe Australia | PVC AUSTRALIA
Mainline Class
Mainline Catalog: Sorting 15mm PVC PIPE CLASS 15 62

Figure 3.50: User template to select the basic lateral, submain and mainline specifications.

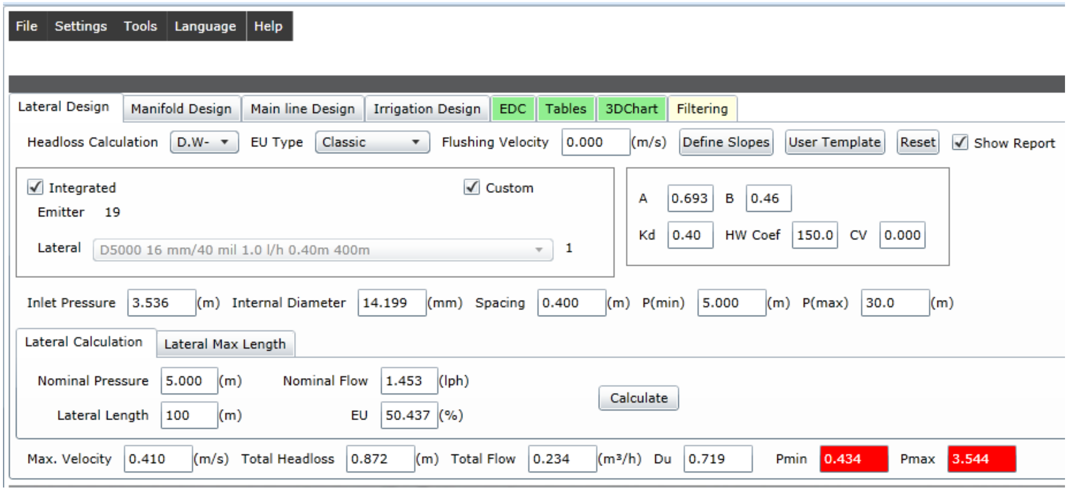
The slope measured and calculated from the field test site has been added as the length of pipe (m) over the distance from the inlet, the slope percentage over that the same distance from the inlet and the direction of the slope as uphill or downhill, as shown in Figure 3.51.



Length	Slope (%)	Direction
8	3.13	Uphill
16	5.99	Uphill
72	1.18	Uphill
84	4.17	Uphill
92	0.69	Uphill
96	4.24	Uphill
100	0.33	Downhill

Figure 3.51: Slope entries as per length, slope percentage and direction of slope using water supply into the lowest end of dripline.

As shown in Figure 3.52, the emitter specifications have been customized to replicate the design parameters for Test No. 7 using the type of emitter as" Integrated", while the emitter characteristics have been customized with "A" (exponent *x*) as 0.693, "B" (constant *k*): 0.46, *Kd*: as 0.40, and HW Coefficient as 150, to get the desired emitter flow rate. From the drop-down menu for EU Type, "Classic" emission uniformity has been selected for this design case.



Headloss Calculation D.W-
EU Type Classic
Flushing Velocity 0.000 (m/s)
☑ Show Report
☑ Integrated
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1
☑ Custom
A 0.693 B 0.46
Kd 0.40 HW Coef 150.0 CV 0.000
Inlet Pressure 3.536 (m) Internal Diameter 14.199 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)
Nominal Pressure 5.000 (m) Nominal Flow 1.453 (lph)
Lateral Length 100 (m) EU 50.437 (%)
Max. Velocity 0.410 (m/s) Total Headloss 0.872 (m) Total Flow 0.234 (m³/h) Du 0.719 Pmin 0.434 Pmax 3.544

Figure 3.52: Lateral design tab showing all the specifications and design parameters selected to replicate Test No. 7.

The “Darcy- Weisbach-RE” option was selected from the “Head loss Calculation” drop-down for the calculation of head loss. The lateral type was selected from the lateral drop-down list with the specifications of LDPE 16 mm with wall thickness of 1 mm (40 mil), flowrate of 1 L/h, emitter spacing of 0.4 m. Other specifications have been with an internal diameter of 14.199 mm, inlet pressure of 3.536 m, to get the desired pressure of 3.515 m at the first emitter. A lateral length of 100 m and minimum and maximum pressures were selected as 5 m and 30 m respectively and the results obtained are explained in Section 5.4.2 in CHAPTER 5.

3.8 Simulation with Hydrocalc

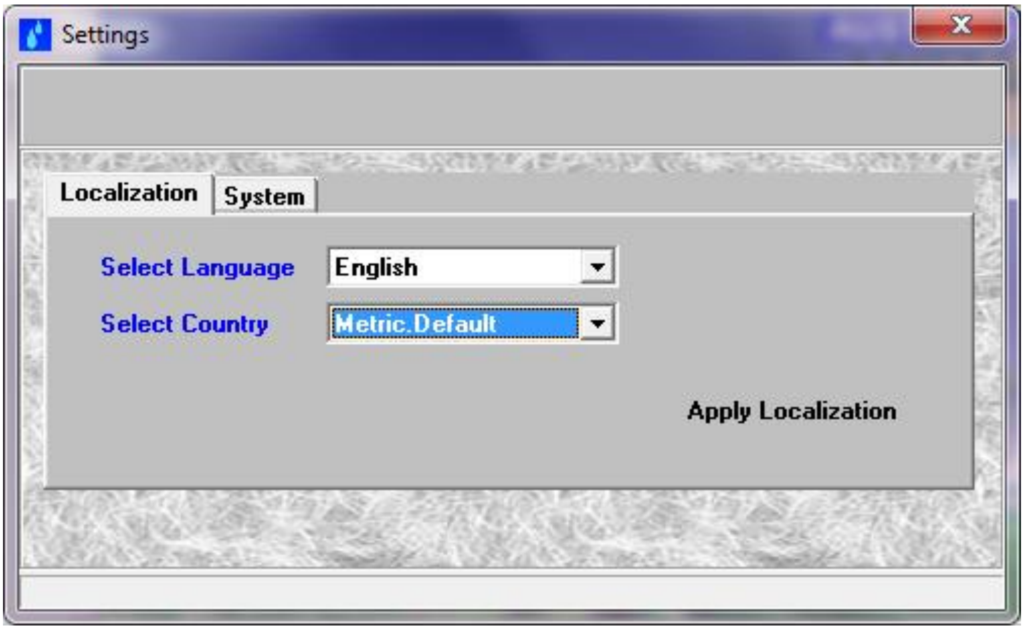
3.8.1 Introduction to the Hydrocalc software package

Hydrocalc is another online software tool available from Netafim, an Israeli based company, which pioneered the concept of drip irrigation with the new concept of low-volume irrigation. Netafim offers the innovative irrigation system design software, Hydrocalc. It is a user-friendly design tool for carrying out simple hydraulic calculations. Hydrocalc enables designers, dealers and end users to evaluate the irrigation performance of in-field components such as drip laterals and micro-sprinklers, sub mains, main lines (e.g. PVC, PE), and valves.

3.8.1.1 Login to the software

The software language and country can be selected in the localization tab as shown in

Figure 3.53. For this design case “English” language and “metric default” options have been selected.



Select Language: English

Select Country: Metric.Default

Figure 3.53: Localization tab to select language and units.

After applying these settings, the Hydrocalc software displays the main window (Figure 3.54), which includes different design tabs such as Emitters, Shape Wizard, Submain, Main Pipe, Collector, Valves, Shifts, Energy, and Settings along with Help tab.

- “Emitters” tab program allows calculations of the cumulative pressure loss, average flow rate, water flow velocity, and can be altered to suit the particular design requirements.
- “Submain” tab calculates the cumulative pressure loss, water flow velocity in the submain. It can also be changed according to user’s requirements.
- “Main pipe” program also calculates the cumulative pressure loss and water flow velocity in the main line and can be modified as per requirement.

Figure 3.54: Mainline tab with all design sections and settings.

The details of these major components on each of the separate tabs or buttons of the Hydrocalc home page are explained in the following sections.

3.8.1.2 Emitters (emitter line data input)

In the first section of the emitter line data input, topography can be selected as fixed or changing. In “fixed” slope conditions we need to provide the average slope (Figure 3.56), while in the case of the changing slope, the slope can be entered for a maximum of ten positions, giving the distance from the inlet (m) and the heights (m) at respective positions, as we can see in Figure 3.55.

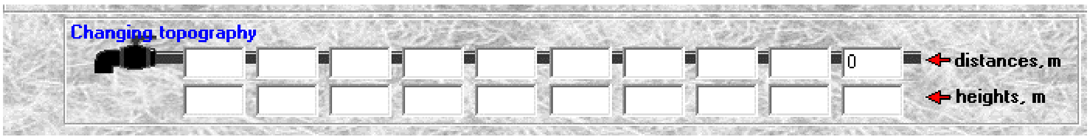


Figure 3.55: Changing topography bar to enter the distances (m) and heights (m).

Different types of irrigation systems can be selected from the "emitter” dropdown list as "dripline”, "online”, "sprinklers” and “micro-sprinklers”. The other parameters include the emitter spacing (m), and flushing velocity (m/s), as shown in Figure 3.56.

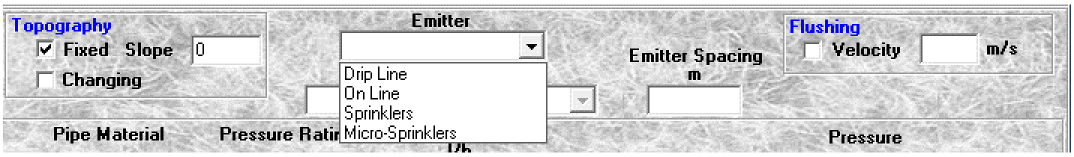


Figure 3.56: Emitter line data input first menu bar to select the type of lateral with emitter type.

In the case of "dripline” option, the specifications are entered to obtain the results by providing the type of dripline, emitter spacing (m), flow rate (L/h), end pressure (m), segment length (m), and calculation method, as shown in Figure 3.57.

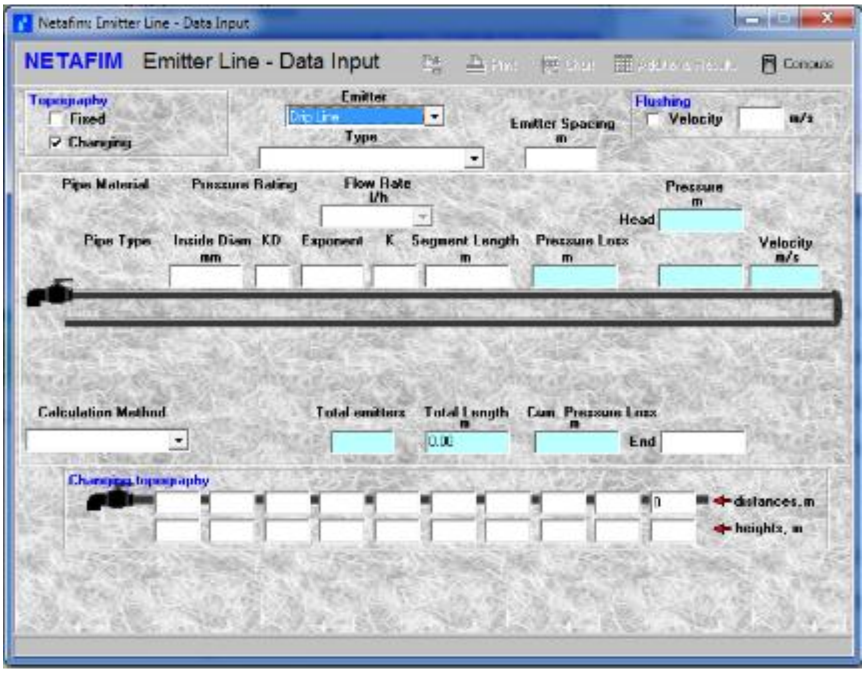


Figure 3.57: Emitter line data input tab to enter all the specifications to compute the results.

The different types of driplines can be selected from the "dripline” type dropdown list, as shown in Figure 3.58.

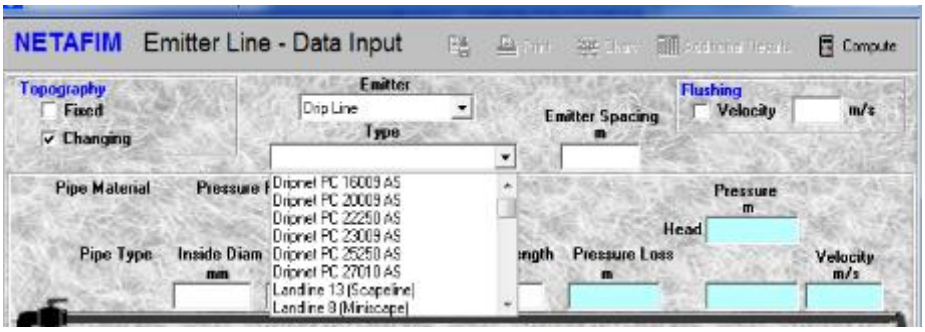


Figure 3.58: Different types of driplines available in the Hydrocalc.

Four types of calculation methods can be used to design the system, and these are “Emitter Line Length”, “Pressure Range”, "Flow Rate Variation” and “Emission

Uniformity", as can be seen in Figure 3.59.

1. In the "Emitter Line Length" method, calculation will be executed for the given drip-line length.
2. In the "Pressure Range" method, the minimum to maximum pressure range is selected to design the system with-in that selected pressure range. The segment length is not required in this method.
3. The "Flow Rate Variation" method performs the calculation for the requested flow variation and will produce the maximum lateral length permissible with in the flow variation percentage.
4. The "Emission Uniformity" method will perform the calculation for the desired emission uniformity provided and will generate the maximum lateral length possible for the selected emission uniformity.

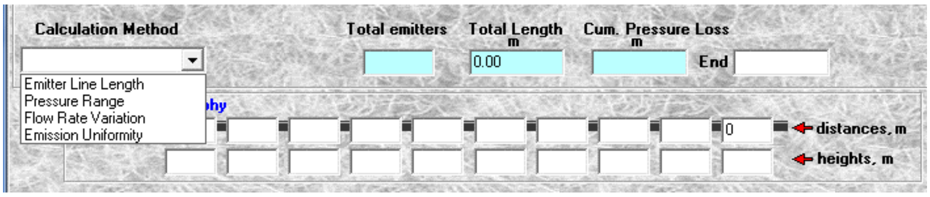


Figure 3.59: Calculation method selection in the Hydrocalc.

3.8.1.3 Calculations and results

The "compute" button will give the results after the selection of the desired emitter line parameters. The design results and charts can be saved and printed, and the result sheet will generate the spreadsheet providing the detail emitter line results and additional results as shown in Figure 3.60.

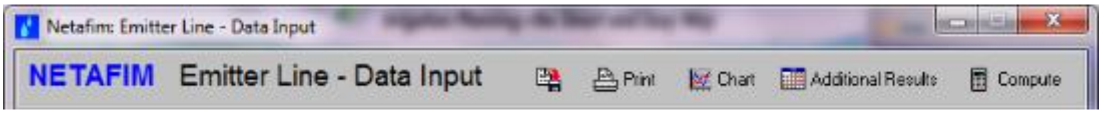
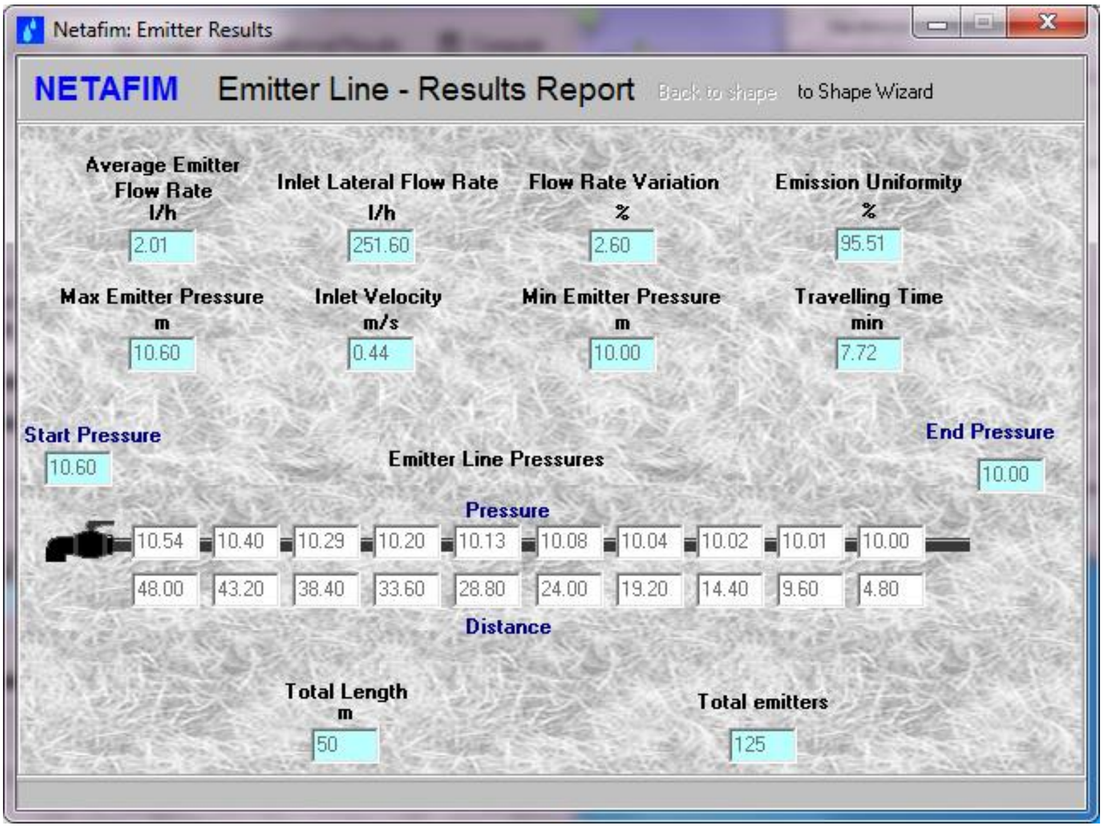


Figure 3.60: Emitter line data input bar showing save, print, chart, additional results and compute button.

3.8.1.4 “Additional Results” tab

As shown in Figure 3.61, the “additional results” report generates average emitter flow rate (L/h), inlet lateral flow rate (L/h), flow rate variation (%) (difference in percentage between maximum and minimum emitter discharges), emission uniformity (%), min./max. emitter pressures, inlet velocity (m/sec), total length of dripline (m), total number of emitters, emitter line pressures and end pressure (m head). This report also generates the table showing pressures in ten different emitters equally spaced along the dripline with the distance from the inlet (m). It is important to note that only ten pressures will be given regardless of the actual number of emitters in the line.



Average Emitter Flow Rate l/h: 2.01
Inlet Lateral Flow Rate l/h: 251.60
Flow Rate Variation %: 2.60
Emission Uniformity %: 95.51
Max Emitter Pressure m: 10.60
Inlet Velocity m/s: 0.44
Min Emitter Pressure m: 10.00
Travelling Time min: 7.72
Start Pressure: 10.60
End Pressure: 10.00

Emitter Line Pressures

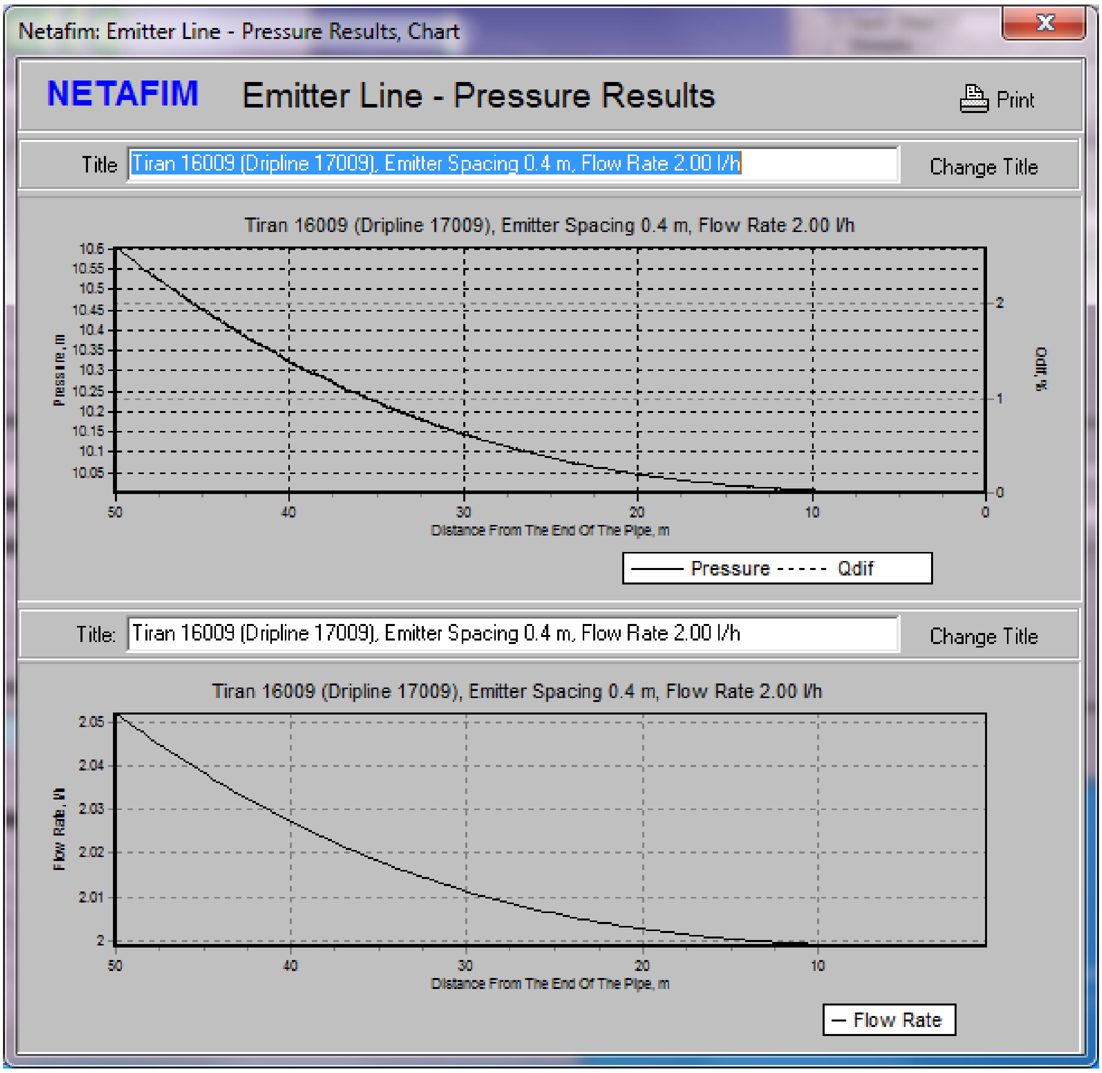
Pressure	10.54	10.40	10.29	10.20	10.13	10.08	10.04	10.02	10.01	10.00
Distance	48.00	43.20	38.40	33.60	28.80	24.00	19.20	14.40	9.60	4.80

Total Length m: 50
Total emitters: 125

Figure 3.61: Additional results tab generated from the emitter line data input.

3.8.1.5 Chart window

The chart window (Figure 3.62) shows the plots of emitter pressure (m) and emitter flow rate (L/h) against the distance from the end of the pipe (m). There does not appear to be any way of changing the formatting of these graphs apart from altering the title. The chart shows the changes of the pressure and flow rate variation along the line. If the inlet supply pressure will be less than 0.1 m and more than 50 m for non-regulated emitters the calculations will be stopped, and results will not be displayed.



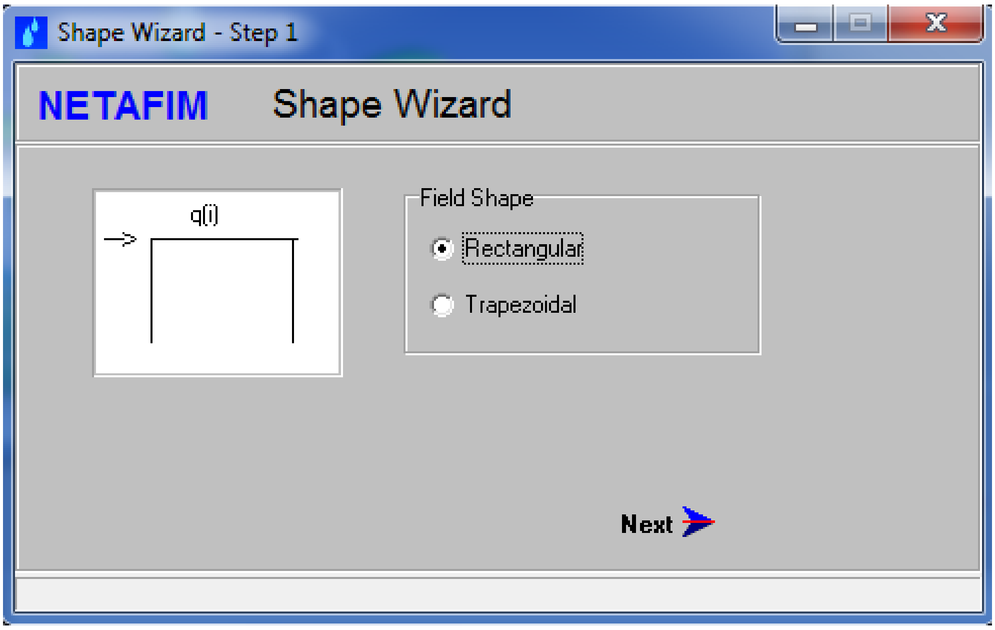
Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Figure 3.62: Results showing plots of emitter pressure (m) and flow rate (L/h) against the distance from the end of the pipe (m).

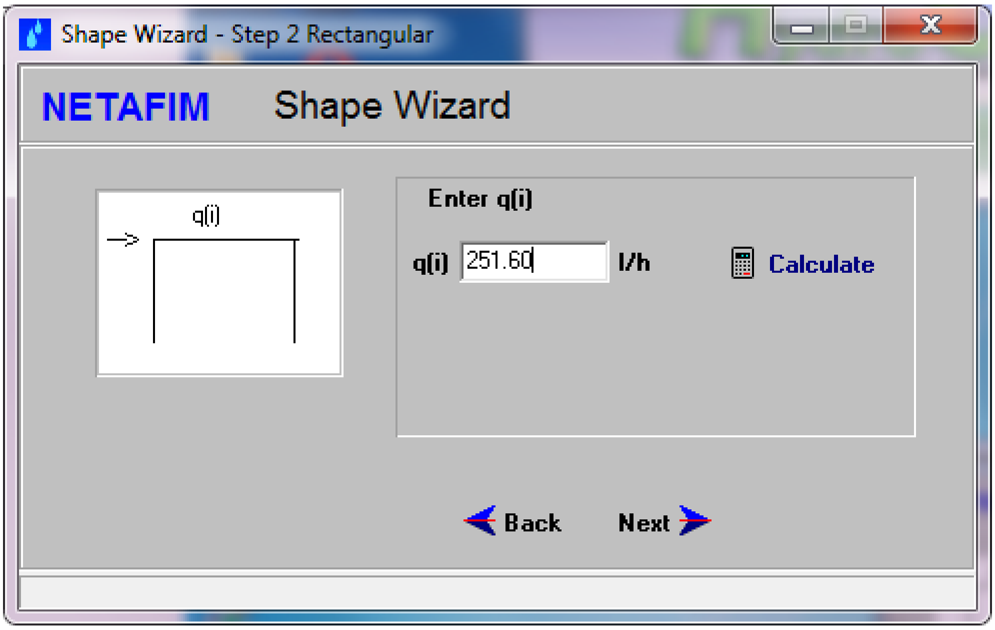
3.8.1.6 Shape Wizard tab

The “shape wizard” tab (Figure 3.63) is designed to assist in determining the irrigation rate and number of shifts needed for the selected design. It transfers the required system parameters from “emitter line” to the “submain” program directly. The field shape can be selected as rectangular or trapezoidal, and after entering the field shape inlet lateral, the flow rate from the first lateral is entered or can be automatically calculated from the emitter data provided and shown in Figure 3.63 and Figure 3.64 . The flow rate for the last lateral and head pressures for both laterals are automatically transferred to the submain design panel.



Field Shape
● Rectangular
○ Trapezoidal

Figure 3.63: Shape wizard to select the field shape.



q(i) 251.60 l/h

Figure 3.64: Shape wizard to enter the lateral flow rate (L/h).

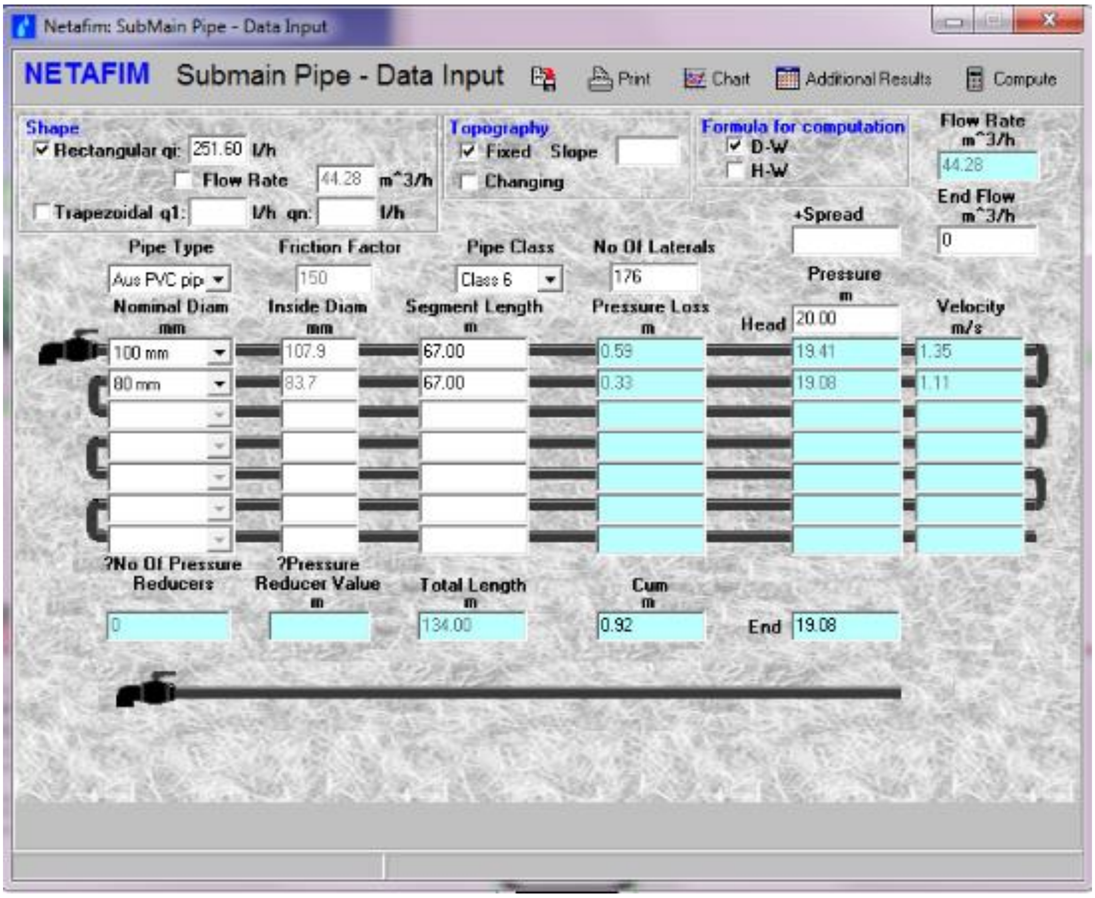
3.8.1.7 Submain design tab

The submain design tab calculates the cumulative pressure loss and water flow velocity in the submain. This component is shown in Figure 3.65, and has the following sections:

- Pipe material can be selected as PE pipe, PVC pipe, lay flat, or aluminium.
- Pipe class can be selected after the selection of the pipe material.

- Formula for computation of head-loss can be selected as Hazen-Williams or Darcy-Weisbach.
- Topography can be selected as fixed or changing, just like emitter line data input.
- Nominal diameter (m), segment length (m), number of laterals, end flow of submain (m^3/h), and head pressure (m), are selected to get the pressure loss (m), head loss (m), and velocity in each pipe along with the cumulative pressure loss (m).
- The friction factor and inside diameter of the sub mains are already provided in the database from the manufacturer.

In a similar manner to the “emitters” tab, the shape of the field is selected in the shape wizard as rectangular (in the case of all laterals being the same length), or trapezoidal (in the case of unequal lengths of laterals), and lateral flow rate (L/h), and are added for the first and last lateral.



Shape
☑ Rectangular qi: 251.60 l/h
☐ Flow Rate 44.28 m^3/h
☐ Trapezoidal q1: l/h qn: l/h

Topography
☑ Fixed Slope
☐ Changing

Formula for computation
☑ D-W
☐ H-W

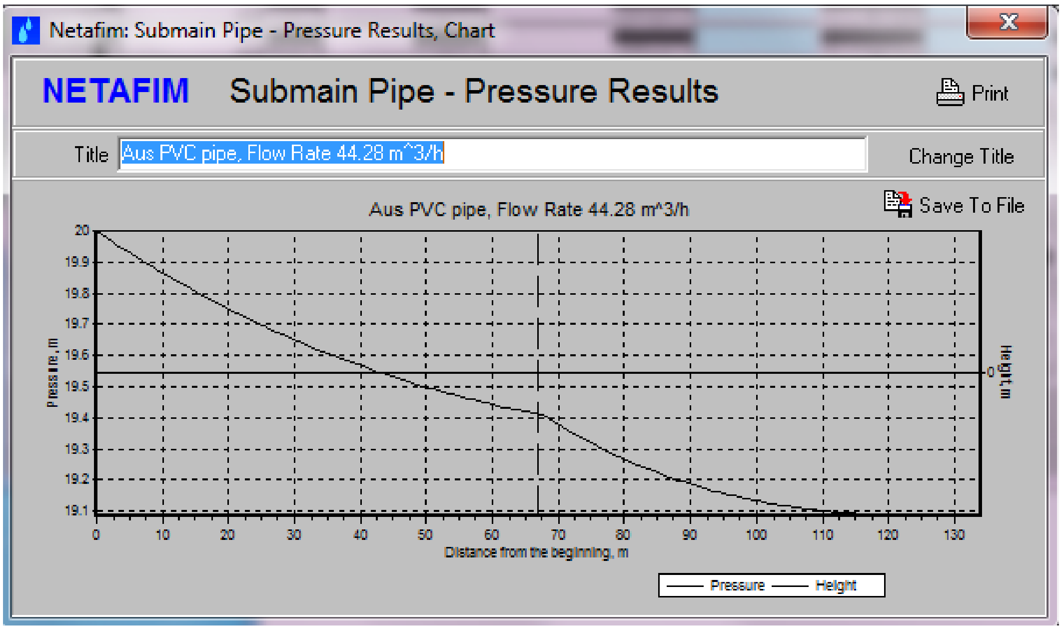
Flow Rate m^3/h: 44.28
End Flow m^3/h: 0
+Spread:
Pipe Type: Aus PVC pip
Friction Factor: 150
Pipe Class: Class 6
No Of Laterals: 176
Pressure m Head: 20.00

Nominal Diam mm	Inside Diam mm	Segment Length m	Pressure Loss m	Pressure m	Velocity m/s
100 mm	107.9	67.00	0.59	19.41	1.35
80 mm	83.7	67.00	0.33	19.08	1.11

?No Of Pressure Reducers: 0
?Pressure Reducer Value m:
Total Length m: 134.00
Cum m: 0.92
End: 19.08

Figure 3.65: Submain tab showing pipe data input to design the submain.

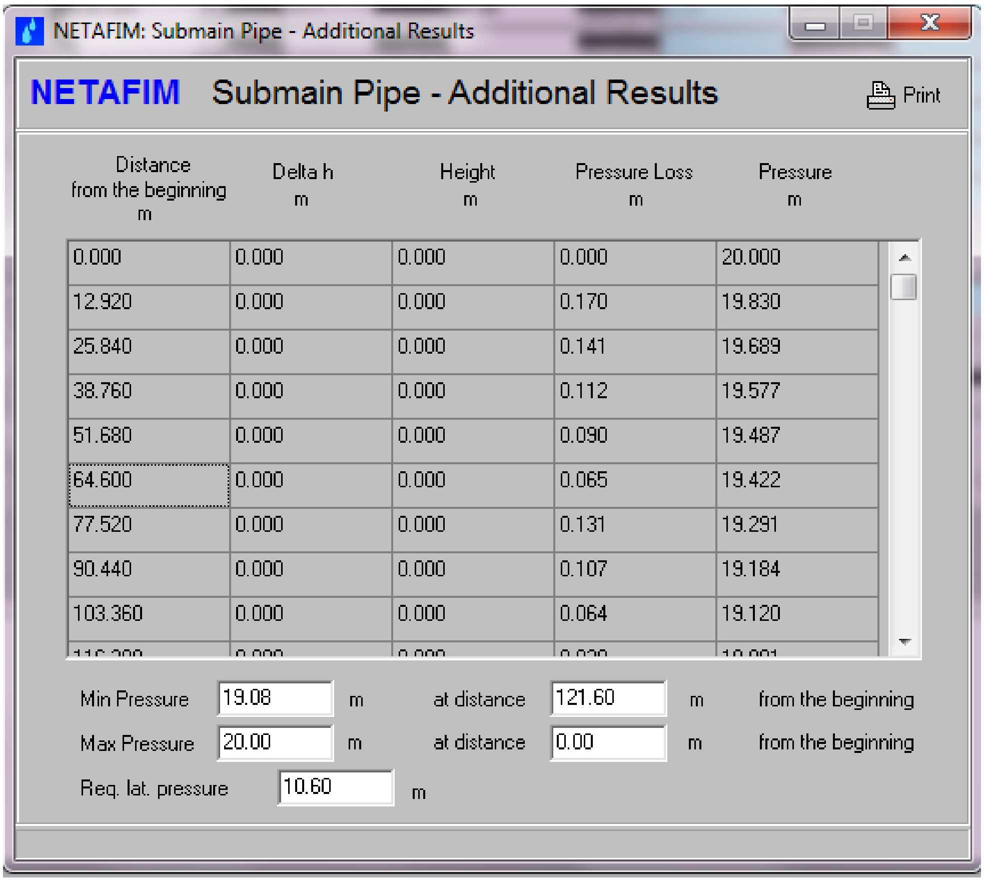
After adding all the parameters into the data screen, the Hydrocalc can calculate the system pressures and display them in a graphical form as shown in Figure 3.66.



Title: Aus PVC pipe, Flow Rate 44.28 m^3/h

Figure 3.66: Submain pipe pressure results.

To view more detailed results, the user can access the “additional results” tab, which shows the minimum and maximum pressures along the line, and the distance from the beginning of the line at which pressures are calculated, as shown in Figure 3.67. It also contains pressure, pressure loss, height and difference in heights at ten different points, located at equal distances along the line. These values do not refer to the distances entered into the software for the topography along the dripline, as shown in Figure 3.67.



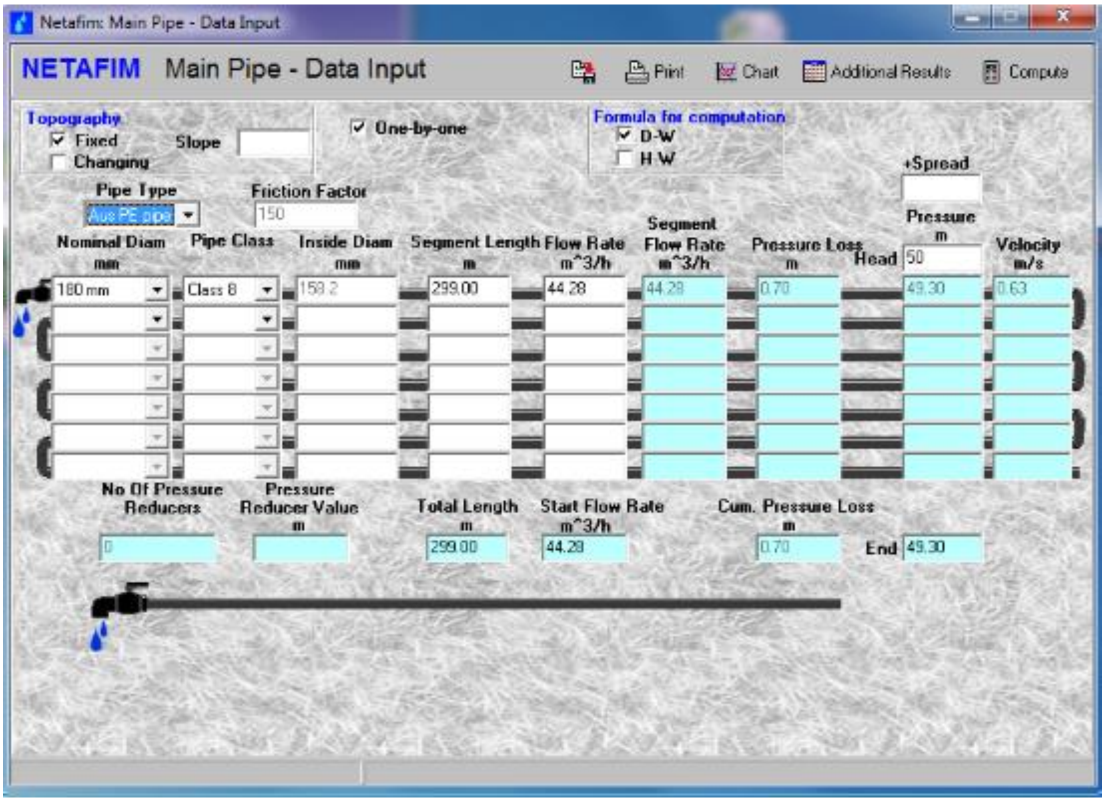
Distance from the beginning m	Delta h m	Height m	Pressure Loss m	Pressure m
0.000	0.000	0.000	0.000	20.000
12.920	0.000	0.000	0.170	19.830
25.840	0.000	0.000	0.141	19.689
38.760	0.000	0.000	0.112	19.577
51.680	0.000	0.000	0.090	19.487
64.600	0.000	0.000	0.065	19.422
77.520	0.000	0.000	0.131	19.291
90.440	0.000	0.000	0.107	19.184
103.360	0.000	0.000	0.064	19.120

Min Pressure 19.08 m at distance 121.60 m from the beginning
Max Pressure 20.00 m at distance 0.00 m from the beginning
Req. lat. pressure 10.60 m

Figure 3.67: Additional results tab for submain pipe data input.

3.8.1.8 Main Pipe calculation tab

The specifications for the main line pipe can be entered in the ”Main Pipe” tab data input window to enable calculation of the cumulative pressure loss (m) and water flow velocity (m/sec) in the main line, as shown in Figure 3.68.



Topography
☑ Fixed
☐ Changing
Slope

☑ One-by-one

Formula for computation
☑ D-W
☐ H W

+Spread

Pipe Type: Aus PE pipe
Friction Factor: 150

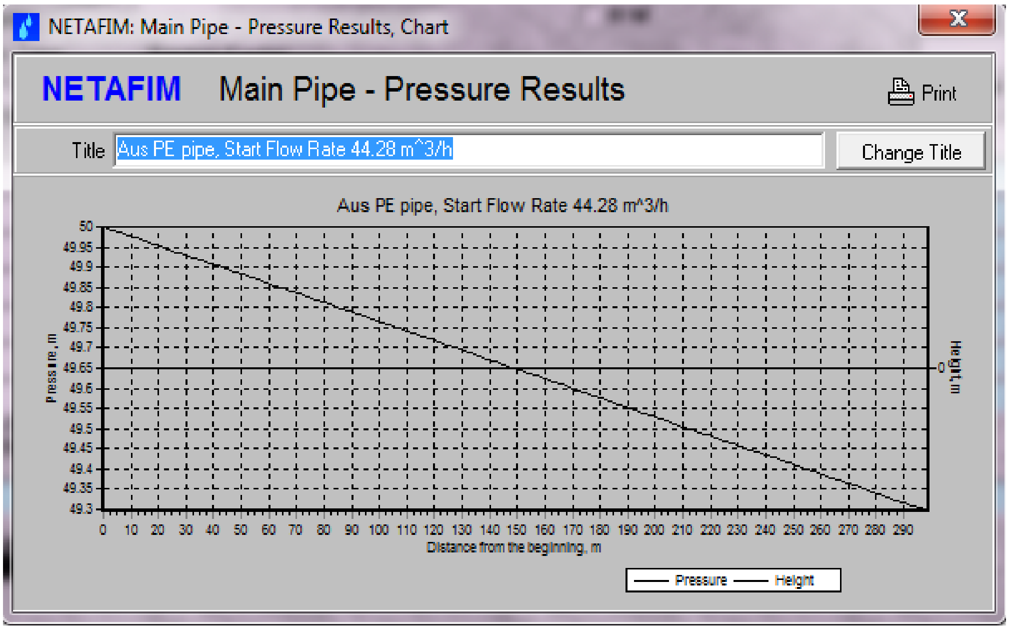
Pressure m Head: 50

Nominal Diam mm	Pipe Class	Inside Diam mm	Segment Length m	Flow Rate m^3/h	Segment Flow Rate m^3/h	Pressure Loss m	Pressure m	Velocity m/s
180 mm	Class 8	158.2	299.00	44.28	44.28	0.70	49.30	0.63

No Of Pressure Reducers	Pressure Reducer Value m	Total Length m	Start Flow Rate m^3/h	Cum. Pressure Loss m	End
0		299.00	44.28	0.70	49.30

Figure 3.68: Main Pipe data input program in the Hydrocalc.

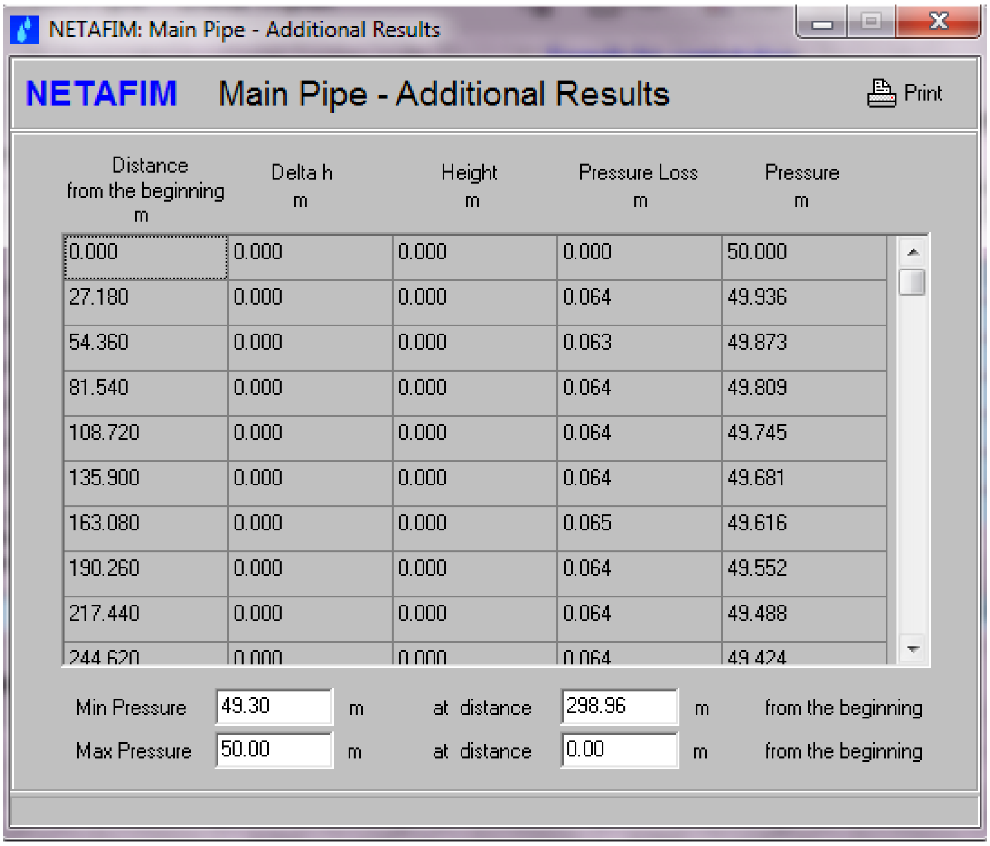
The main pipe pressure results (Figure 3.69) show the plots of main line pressure (m) against the distance from the upstream end in metres.



Title: Aus PE pipe, Start Flow Rate 44.28 m^3/h

Figure 3.69: Main pipe pressure head results.

The "additional results" tab outputs in Figure 3.70 displays the minimum and maximum pressures along the main line and the distance from the beginning of the line at which the pressures are calculated.



Distance from the beginning m	Delta h m	Height m	Pressure Loss m	Pressure m
0.000	0.000	0.000	0.000	50.000
27.180	0.000	0.000	0.064	49.936
54.360	0.000	0.000	0.063	49.873
81.540	0.000	0.000	0.064	49.809
108.720	0.000	0.000	0.064	49.745
135.900	0.000	0.000	0.064	49.681
163.080	0.000	0.000	0.065	49.616
190.260	0.000	0.000	0.064	49.552
217.440	0.000	0.000	0.064	49.488
244.620	0.000	0.000	0.064	49.424

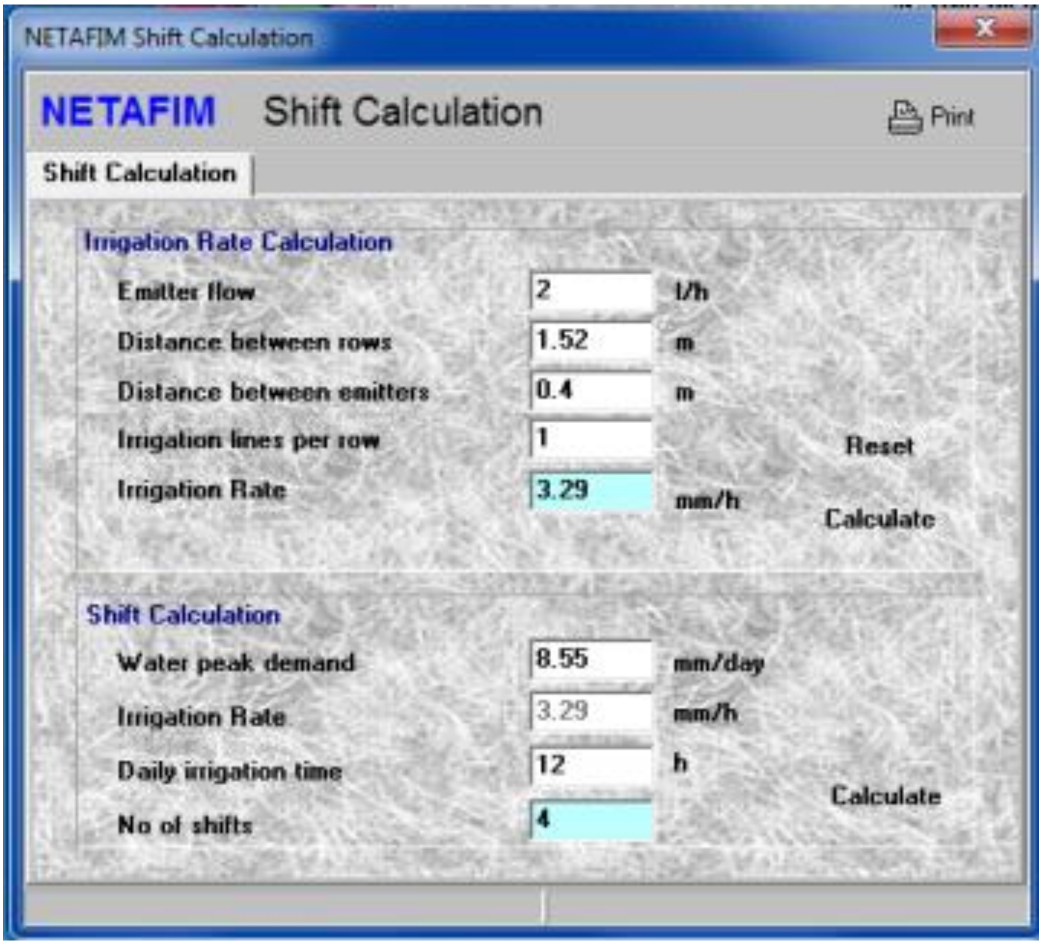
Min Pressure 49.30 m at distance 298.96 m from the beginning

Max Pressure 50.00 m at distance 0.00 m from the beginning

Figure 3.70: Main pipe additional results.

3.8.1.9 Shifts tab calculation panel

The “shifts” tab window Figure 3.71 calculates the irrigation rate and number of shifts needed, according to the parameters input. The emitter flow rate (L/h), distance between rows (m), the distance between emitters (m), and irrigation lines per row are entered to calculate the irrigation rate (mm/h). The number of shifts is measured based on the irrigation rate calculated previously (mm/h), water peak demand (mm/day) and daily irrigation time (h).



Emitter flow 2 l/h

Distance between rows 1.52 m

Distance between emitters 0.4 m

Irrigation lines per row 1

Irrigation Rate 3.29 mm/h

Water peak demand 8.55 mm/day

Irrigation Rate 3.29 mm/h

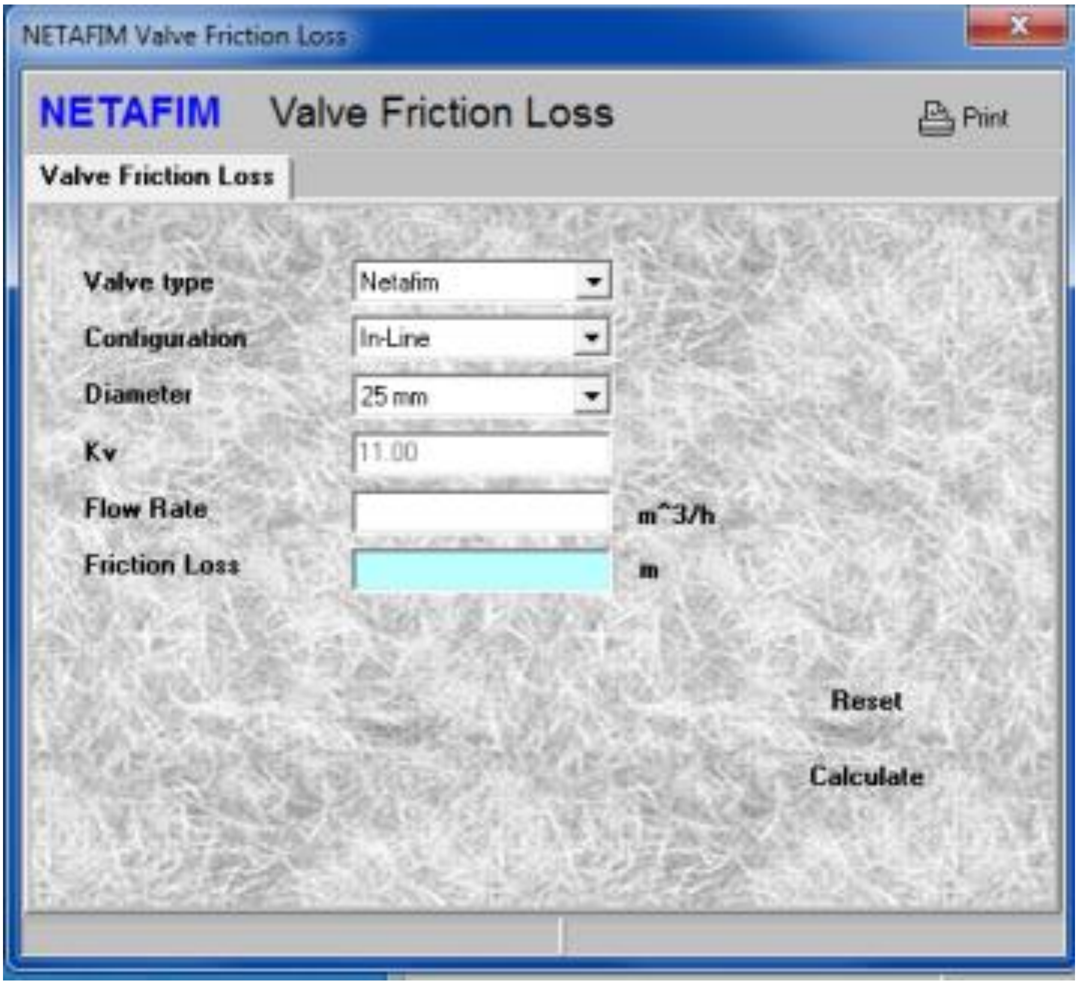
Daily irrigation time 12 h

No of shifts 4

Figure 3.71: Shifts tab calculation inputs.

3.8.1.10 Valve friction loss Valve head loss from “Valves” tab

The” valves” tab window as shown in Figure 3.72 enables calculation of the valve head loss according to given parameters. Selecting a valve type, the configuration of the valve, diameter (mm) and a desired flow rate gives the head loss across the valve, from the valve parameters provided in the database.



Valve type: Netafim

Configuration: In-Line

Diameter: 25 mm

Kv: 11.00

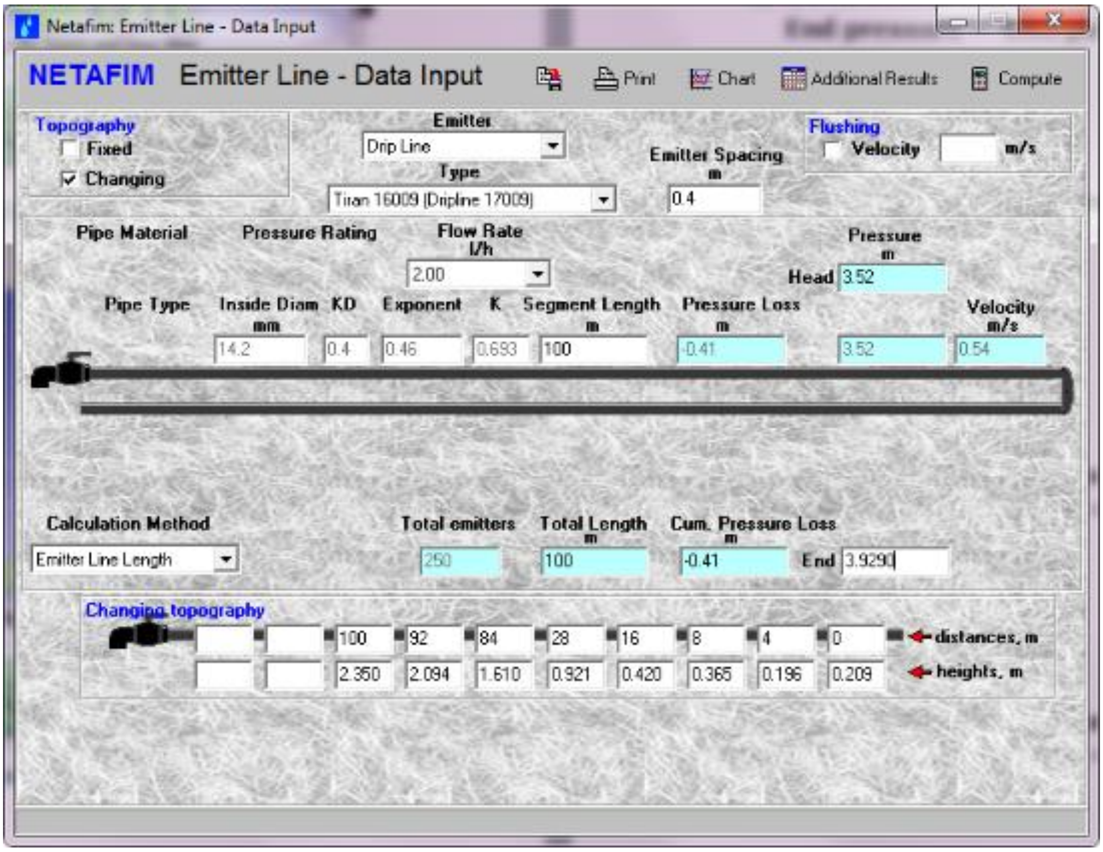
Flow Rate: m^3/h

Friction Loss: m

Figure 3.72: Valve head loss calculation input on the "Valves" tab.

3.8.2 Replication of measured field configurations in the Hydrocalc with water supply placed into the highest end of the dripline

The dripline installed in the field at the Ag-Plot (field test site) is available in the Hydrocalc database, as it was purchased from Netafim, and is shown in Figure 3.73.



Topography
☐ Fixed
☑ Changing

Emitter: Drip Line
Type: Tiran 16009 (Dripline 17009)
Emitter Spacing m: 0.4

Flushing
☐ Velocity m/s

Pipe Material
Pressure Rating
Flow Rate l/h: 2.00
Pressure m Head: 3.52

Pipe Type	Inside Diam mm	KD	Exponent	K	Segment Length m	Pressure Loss m		Velocity m/s
	14.2	0.4	0.46	0.693	100	-0.41	3.52	0.54

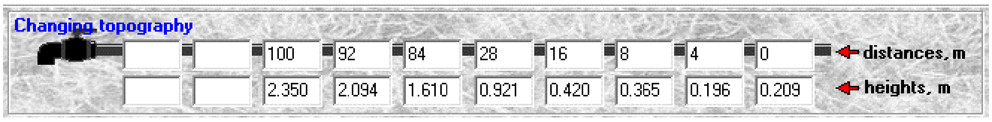
Calculation Method: Emitter Line Length
Total emitters: 250
Total Length m: 100
Cum. Pressure Loss m: -0.41
End: 3.9290

Changing topography

		100	92	84	28	16	8	4	0	← distances, m
		2.350	2.094	1.610	0.921	0.420	0.365	0.196	0.209	← heights, m

Figure 3.73: Emitter line data input tab to fill in the emitter and dripline specifications.

The slope at eight different positions along the length of the dripline was added into the input panels as the distance (m) from the inlet and heights (m) above a datum at these same positions as shown in Figure 3.74.



Changing topography

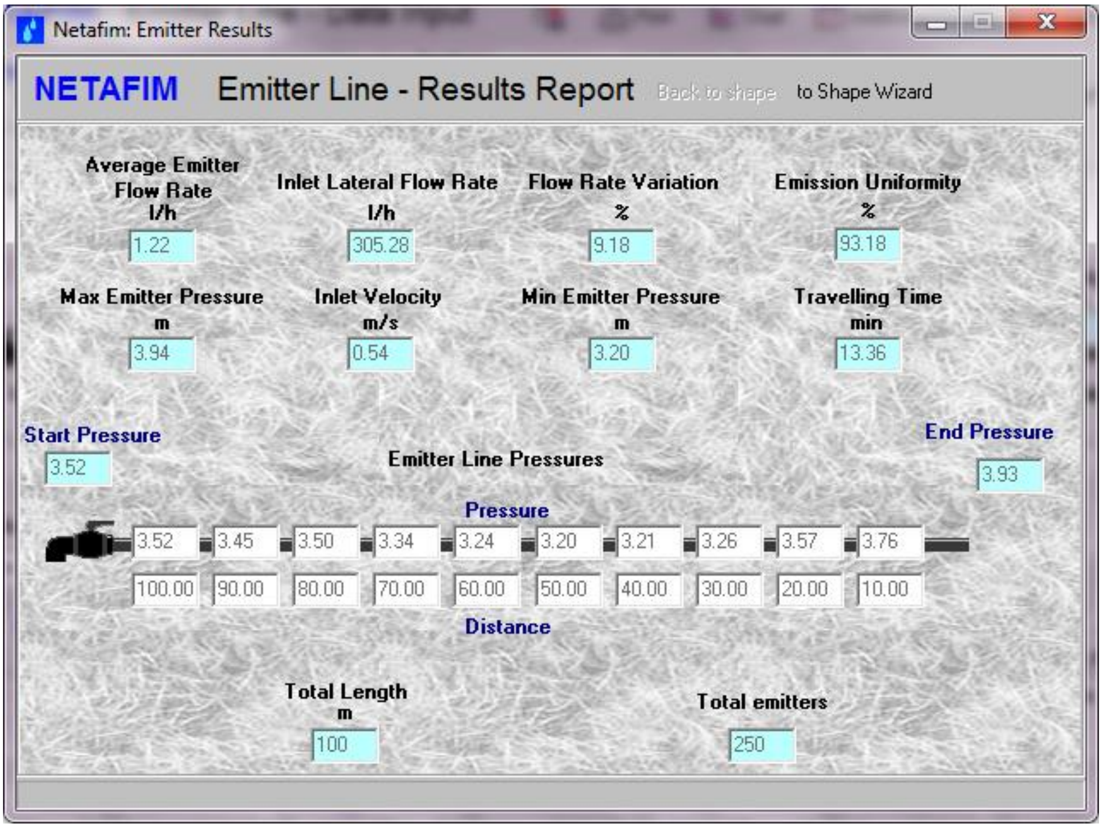
		100	92	84	28	16	8	4	0	← distances, m
		2.350	2.094	1.610	0.921	0.420	0.365	0.196	0.209	← heights, m

Figure 3.74: Changing topography tab showing the distances (m) from the inlet and the height of dripline (m).

The lateral specifications were entered for the Emitter and Dripline as follows:

- Type: Tiran 16009
- Flow rate: 2 L/hr
- Emitter spacing: 0.4 m
- Segment length: 100 m
- Calculation method: Emitter line method

The downstream end pressure was set as 3.93 m as shown in Figure 3.75 to achieve the pressure of 3.515 m at the first emitter and replicate the same input pressure measured in the field test.



Emitter Line - Results Report

Average Emitter Flow Rate l/h: 1.22
Inlet Lateral Flow Rate l/h: 305.28
Flow Rate Variation %: 9.18
Emission Uniformity %: 93.18
Max Emitter Pressure m: 3.94
Inlet Velocity m/s: 0.54
Min Emitter Pressure m: 3.20
Travelling Time min: 13.36
Start Pressure: 3.52
End Pressure: 3.93

Emitter Line Pressures

Pressure	3.52	3.45	3.50	3.34	3.24	3.20	3.21	3.26	3.57	3.76
Distance	100.00	90.00	80.00	70.00	60.00	50.00	40.00	30.00	20.00	10.00

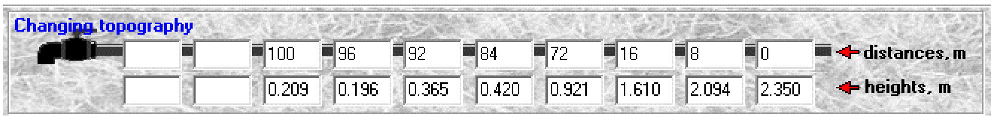
Total Length m: 100
Total emitters: 250

Figure 3.75: Emitter line result report showing all the results obtained.

The results obtained as shown in Figure 3.75, using Hydrocalc software package are explained in Section 5.4.3 in CHAPTER 5.

3.8.3 Replication of measured field configurations in the Hydrocalc with water supply placed into the lowest end of the dripline

The Hydrocalc simulation described in Section 3.8.2 was modified by reversing the elevation data in the topography section of the data input screen as shown in Figure 3.76. The dripline specifications have been selected same as selected when the water supply was into the highest end. Selecting the changing topography, slope has been added at 8 different positions along the length of the dripline, as the distance (m) from the inlet and heights (m) at the corresponding positions using the water supply into the lowest end of the dripline as shown in Figure 3.76.



		100	96	92	84	72	16	8	0	distances, m
		0.209	0.196	0.365	0.420	0.921	1.610	2.094	2.350	heights, m

Figure 3.76: Changing topography tab showing the distances (m) from the inlet and the height of dripline (m).

The dripline specifications remain same as for the previous tests described in Section 3.8.2. The end pressure was set at 0.52 m to get the pressure of 3.515 m at the first emitter to replicate the same pressure as measured in Test No. 7. The results for this example are provided and explained in a Section 5.4.4 in CHAPTER 5.

3.9 Measurement and instrument errors

It is very important to also address any measurement and instrument errors to ensure the accuracy and precision of results. The measurement errors can be divided into human errors and instrument errors. Human errors include the errors in taking readings from the instrument or improper data input such as incorrect placement of slope in software or the difference in the assessment of the given slope by different software packages that have been trialled. Human errors can also come about as a result of inexperience in trying to make a specific measurement. Two terms commonly associated with errors are precision and accuracy. Precision reflects the reproducibility of a measurement, while accuracy is a measure of closeness to the true value.

Instrument errors are the errors that occur exclusively from lack of accuracy in an instrument, such as broken measuring device. Another significant error that needs to be addressed in this project is sampling error. Sampling error refers to the difference between the sample size and actual size of the dataset. Increasing sample size will reduce this type of error. The maximum sampling error is the ± figure associated with results such as ± 4% at the 95% confidence level, which means the chances are 95 in 100 that the results you get are within 4 percentage points higher or lower than the true percentage for the actual data set.

Comparison of results with other data sets helps in noticing the measurement and instrumental errors. Comparison of measured field results with the simulated results using software packages will identify some of the errors in this project.

3.10 Conclusions

After the selection of a typical Pakistani drip irrigation system purchase of the components was made to replicate these in Australia. These components have been tested and verified in the laboratory in terms of their operation and hydraulic performance. Laboratory testing has also been performed to assess the measurement methodology and equipment. Field experimentation was conducted after the installation of the system at a field test site. Measurements of flow and pressure were conducted at this site using specially designed and handmade equipment. This same selected drip irrigation design was successfully replicated in the selected software packages, Hydrocalc and Eaucadi. A similar field test methodology was used in Pakistan at five case study sites. In CHAPTER 4 these measured field and simulated results have been compared and analysed while in CHAPTER 5 these results are discussed.

CHAPTER 4 RESULTS FROM EXPERIMENTATION IN PAKISTAN

4.1 Introduction

Experimentation performed in Pakistan is divided into four major sections:

i. Review and analysis of Indus Basin irrigation system
ii. Need for improved irrigation performance in Pakistan
iii. Review and analyses of drip irrigation systems in Pakistan
   - Need for the promotion and adoption of drip systems
   - Constraints in adaptability of pressurised irrigation systems
   - Need for the evaluation of hydraulic design and performance evaluation
iv. Field experimentation at five case study sites in Punjab, Pakistan

4.2 Review and analysis of Indus Basin irrigation system

Indus basin irrigation system have been reviewed and inefficiencies have not only been noticed in on farm administration but also at the structural and management level of Indus Basin irrigation system. The prospective recommendations made from the observations and research analysis of Indus basin irrigation system in Section 2.5 are given below:

- Researchers and government need to interconnect and link the conventionally separate sectors such as agriculture, irrigation, energy, environment and the social divisions to improve the coordination and to achieve the mutual management and correct decision making.

- Although, additional research is required to determine the nature and extent of interdependencies between these sectors.
- Effective drainage interventions and institutional reforms needs to be introduced to make the managing organizations more involved and approachable.
- Water and agriculture policies need to be formulated with the objective of extending the role of agricultural institutions, users and the private sector in delivery of services to farmers.
- Active participation of all water related stakeholders at all stages of implementation is essential to ensure the successful execution of drip irrigation systems. Their engagement and connection will build and improve the interaction.
- Similarly, water storage and water reservoirs need to be expanded and upgraded in terms of capacity and can be used for additional electricity generation.
- Canals needs to be lined to prevent conveyance losses.
- A strategic system needs to be developed, governing and manage issues relevant to the management and operation of irrigation system and agriculture.
- Separate strategies need to be formulated for large commercial and small farmers because of small farmer’s dependency on only available groundwater resources.
- Technical as wells as scientific and political tools need to be formulated and implemented to preserve groundwater resources and their quality.
- Additional procedures need to be applied to improve the allocation security

and equity of access for water buyers.

- Current water pricing needs to be evaluated and revised pricing needs to be applied.
- New laws and orders need to be developed and applied to prevent canal water breaches and water theft.
- More budget and investment need to be allocated to the maintenance and operation of Indus basin irrigation and drainage system, as well as on conjunctive water management and research and development.
- A wide-ranging research and data collection are required to evaluate the current available groundwater resources, its quality, withdrawal and impacts on agriculture, irrigation and energy sources.
- Spatial sampling and surveys need to be designed and conducted to gather and link water data at canal command, district and aquifer level.
- These analyses will also help understanding individual farmer’s needs and precise management of collective (surface and ground) water resources for varying crops, seasons and cultivation practices in different regions of Pakistan.
- Extensive research is required on available energy sources and consumption in different divisions, in addition to the energy consumption in groundwater pumping and crop production to evaluate the accurate current and future energy needs and making informed decisions accordingly.
- Due to huge power crisis and rising electricity prices alternative energy sources need to be considered and these alternative energy sources needs to be evaluated in terms of feasibility and suitability with the advance irrigation technologies.

- Power failures, extended load shedding, poor electricity supply and high fuel prices are putting pressure on ground water resources and in turn increasing tube well prices.
- Latest irrigation technologies and advanced software packages need to be introduced to improve the on-farm water efficiency and farmers need to be trained about adoption of advanced irrigation technologies like drip irrigation.
- Farmers need education regarding the state and quality of current available water resources and their practical management to grow suitable crops, so the water can be efficiently applied without disturbing the natural hydrological balance between surface and ground water resources.
- Prevailing cropping patterns need to be reviewed in Pakistan, especially in the areas with insufficient ground water resources to support the intensive future agriculture needs.
- Moreover, the rainfed areas require more attention to increase the crop production by efficient water management.

Implementing above-mentioned suggestions and observations cannot only assist with enhancing drip irrigation performance on farm but will also improve the performance of entire Indus basin irrigation system. Threatened water resources will be preserved due to the improvement in water use efficiency. The performance and interaction of conventionally separated sectors in Pakistan such as agriculture, energy, irrigation and social divisions will be enhanced, and a strategic system can be developed to control and monitor the water usage through improved interaction and engagement. Analysing and studying the current groundwater resources and prevailing cropping patterns will help in educating farmers and precise management of surface and groundwater resources and their quality.

4.3 Need for improved irrigation performance in Pakistan

Agriculture is the backbone of Pakistan's economy and contribute to 21.4% of national GDP and it is using 98% of freshwater resources for agriculture (Iqbal & Iqbal, 2015). Moreover, Pakistan has already fallen below water stress threshold (Briscoe & Qamar, 2006) and it has the potential to be a water famine country in coming ten years (Iqbal & Iqbal, 2015). Therefore, per capita water availability is estimated to reach 915 m^3/capita by 2020. As Pakistan is the world's sixth most populous country and 50% of the population and have been already characterised as food insecure and 28% severely food insecure (Ahmad et al., 2014).

Moreover, farmers are not receiving enough water supplies to fulfil the crop water requirement. Also, the cropping intensity have increased to 150% from 67% due to increase in food and fibre requirements (Kamal, 2009) and out of 6.9 million MegaLitres of water only 3.2 million MegaLitres reaches to the farm gate due to heavy losses in canals and water courses (Eleazar, 2018).

Likewise, there will be an estimated shortfall of 20 billion m^3 gross water supply for agriculture due to the declining Indus basin water availability (Hussain et al., 2011) and despite the increase in storage capacity of Indus Basin Irrigation system it cannot accommodate the changing water demands (Bhutta & Smedema, 2007).

Although around million tube wells have been installed to overcome the surface water shortages, but due to the heavy groundwater exploitation the groundwater levels have also reduced drastically (Basharat et al., 2014) and because the small farmers are the majority, the small net water savings may not be reused on farm. Instead, water savings could allow only large and medium farmers to get more safe and substantial water supply (Ahmad et al., 2007). Further, poor irrigation management practices on farm resulted into inefficient water application (Watto & Mugera, 2015).

Therefore, it is analysed that performance of canal irrigation system as well as the on farm water productivity and water application efficincy has to be improved to fullfil the current and future agriculture needs of ever growing population in Pakistan.

The following suggestions are proposed from the research analysis provided in

Section 2.6 to improve the irrigation performance in Pakistan:

- Consumer participation and support must be encouraged and improved in the planning and organisation of irrigation system.
- Appropriate canal system maintenance needs to be implemented.
- Additional research and study need to be conducted on precise measurement and analysis of consumptive crop water requirements for different crops grown all around the country.
- Misuse of ground water resources needs to be monitored and rectified with the efficient water management.
- Water need to be used wisely to produce more crop per drop of water.
- More systematic measurements are required to analyse and study the water balance components at a farm to whole irrigation system scale using hydrological modelling.
- It is very important to have a full understanding of the impacts of surface and ground water use on salinity and water logging to ensure proper conjunctive water management.
- Small farmers need to provide with incentives and subsidies and ground water use restrictions need to be applied for medium and large farmers.
- It is essential to improve the performance of canal water supply systems and promote the evaporation reducing technologies in Punjab.
- Water productivity must be improved with efficient water application because the extensive increase in population will eventually demand increase food production which will either demand increase water availability or efficient water use.
- It has been highly suggested to use high efficiency irrigation systems to

conserve the remaining assets. Such as drip irrigation and sprinkler irrigation systems can efficiently save water and increase water use efficiency.

- Although more investigation is required on data collection, evaluation and monitoring of water productivity using resource conservation technologies at all scales from field to canal system and basin level.
- Additional research is required on the consumptive crop water requirement in different areas of the country for varying crops using different irrigation application practices and technologies.
- Other ways that can be used to improve irrigation efficiency and productivity includes repairing and maintenance of water delivery systems, land levelling, improved and equitable distribution of water system, developing plans and policies for surface and ground water management.

4.4 Review and analyses of drip irrigation systems in Pakistan.

The observations made from the review and analyses of already installed drip irrigation systems in Pakistan are given below:

4.4.1 Potential and need for the promotion and adoption of drip systems in Pakistan

Due to the current water scenario, low water productivity and low performance of traditional irrigation methods in Pakistan have impelled number of locals, irrigation industries as well as multinational companies to get interested and involved in the irrigation facilities and services to the farmers (Mangrio et al., 2013). Hence, the researchers, private and government bodies are highly interested in the promotion and implementation of drip irrigation systems. The major reasons and motivations behind the promotion and adaptability of drip irrigation systems are given below:

- Crop productivity, yield and quality needs to be enhanced to meet the food requirements of the ever-growing population in Pakistan, which will require enormous increase in agriculture production.
- Canal water shortages, energy crisis along with the lack of knowledge and training regarding fertilizer application are resulting into low water productivity.
- Massive increase in the agriculture production and area under cultivation in Punjab is putting pressure on scarce water resources.
- Moreover, Pakistan has the lowest yield per unit of water around the world.
- The crop water productivity can only be improved either by increasing the crop yields or by minimising the water losses or managing both.
- Conventional surface irrigation methods have shown low efficiency of around 50%, due to lack of management, poor farm design, misuse of water resources and water losses (Director General Agriculture, 2011).
- Significant reduction has been observed in the rice production due to the water shortage and low efficiency conventional irrigation methods, whereas Punjab and Sindh has a potential to increase the export up to $4 billion annually if the water resources are precisely managed (Iqbal & Iqbal, 2015).
- Farm water productivity needs to be improved with efficient water management using high efficiency irrigation systems such as sprinkler and drip irrigation instead of surface irrigation.
- Drip irrigation can not only increase the rice production but also uses 70% less water than traditional paddy rice with highly reduced methane emissions and arsenic uptake (Netafim Ltd, 2020).
- Appreciable water savings and increased crop yields and farm productivity are

observed using drip irrigation, due to the effective and timely application of water, fertilizer and nutrients as per the plant's requirement at various stages of its growth.

- The drip irrigation system has shown 57% of water saving in case of sugarcane, while 50% for both citrus and potato crops against conventional irrigation methods.
- 34%, 39% and 105% of yield increase has been recorded using drip irrigation for potato, sugarcane and citrus respectively (Ashraff & Yasin, 2012).
- Reduced time for water application and improved product quality is observed using drip irrigation along with the sapling's survival rate of 97%, which was 60% on flood irrigation (Bank, 2014).
- 26% increase in yield is recorded for sunflower crop using drip irrigation over furrow irrigation method, due to precise irrigation management and effective utilization of fertigation in drip irrigation (Qureshi et al., 2015).
- Drip irrigation is also financially practical irrigation method for vegetables and it can increase water use efficiency (60-200%), saves water (20-60%), reduces fertilization requirement (20-33%) through fertigation, improve crop quality and yield (7-25%) (Arya et al., 2017).
- Irrigation efficiencies calculated for drip irrigation, perforated pipe irrigation and flood irrigation were 95- 98%, 65-76% and 50-59% respectively in field experimentation on wheat (Bakhsh et al., 2015).
- 1.2 ML of precious ground water and 1365 kWh of energy can be saved for each hectare using drip irrigation system with a potential to achieve efficiency as high as 95% as compared to the traditional flood and furrow irrigation. (Reddy & Satyanarayana, 2010).

- Drip irrigation has also shown increase in water use efficiency by 50% and yield from 35-100%, with reduced mortality rate of the plants. It also gives the ease of efficient nutrient distribution with the reduction of labour work by about 20%" (Bank, 2014).
- It has also shown the potential of about 56% water savings with increase of 26% in sunflower yield over furrow irrigation (Qureshi et al., 2015).
- Drip irrigation has increased the net sown area, net irrigated area and thereby has helped in achieving higher cropping and irrigation intensity.
- It has also shown significant reduction in cost of cultivation, with increase in crop yield and farm profitability. It can be effectively promoted in the regions where shift towards crops like coconut, banana and grapes are common.
- The major factors contributing to the adoption of water conservation technologies in Pakistan are increase in crop yield, area under cultivation and farm productivity with reduced energy and labour cost (mainly for the large and medium farmers).
- Higher yield of vegetables with the higher water use efficiency and considerable water savings is recorded with the use of drip irrigation system. Surface irrigation system's efficiency can be improved with improve design and maintenance, but the efficiency will not be higher than drip irrigation system (Ahmad et al., 2014).
- The country's edible oil production is only 24% of the total demand and the remaining 76% is imported. There is a potential to increase the cultivation of sunflower up to 535560 ha with the production up to 1659762 tons with the implementation of drip irrigation method (Qureshi et al., 2015).
- Likewise, ground water is saline in Sindh province and these technologies can

contribute to real water savings and sustainable food production by reducing the recharge to ground water.

- Similarly, developments in manufacturing technology have also considerably decreased the initial cost of pressurised irrigation systems that was a major deterrent for adoption these technologies (Pakistan Agriculture Research Centre, 2010).
- Furthermore, serious water shortages and a trend towards growing higher value crops has motivated farmers in other countries with similar growing conditions to invest in pressurised irrigation systems.
- The availability of latest and new drip products has also reduced the cost of system.

Water saving technologies like drip irrigation has been highly recommended by World bank and other researchers (Muhammad et al., 2010) as both the crop yields and water losses can be effectively managed using drip irrigation (Mangrio et al., 2013). Hence, to secure the future of agriculture in Pakistan advance high efficiency drip irrigation technology needs to be introduced to promote the crop diversification and improve water use efficiency. which will not only enhance the crop yield and quality but will also promote the development and growth of high value crops and energy saving.

4.4.2 Constraints in adaptability and successful implementation of drip irrigation systems in Pakistan

Although the pressurised irrigation systems have been effectively used all over the world and has shown appreciable water savings with improved production and quality of agricultural products, but most of the drip irrigation systems installed in Pakistan have been abandoned due to low operational performance. The main constraints observed in the adoption of pressurised irrigation systems in Pakistan, from the past research analyses and personal observations are as follows:

- The ground water abstraction has a lack of control, regulation authority and policies therefore, unregulated abstraction has resulted into the disruption of natural water balance at farm, system and basin levels (Ahmad et al., 2014).
- Another major constraint is the rotational water supply system of Pakistan known as "*Warabandi*". Therefore drip irrigation systems require an on farm storage of water which involves additional expenses (Kahlown et al., 2007).
- The farmer receives water supply for a duration relative to the size of the field and land holding and delivery of irrigation water to farmers is supply based therefore, crop water requirements are not met timely which negatively affect the agricultural production.
- Imbalance between supply and demand of water supplies.
- Discriminatory and inequitable water distribution.
- The farmers has a lack of opportunity to sell or store water as they receive only fixed allocation of canal water per week, so they try to utilize whole allocation each week (Ahmad et al., 2014).
- From last 4 -5 years farmers are not receiving their fixed share of canal water due to the unreliability and unpredictability of surface water availability (Ahmad et al., 2007).
- According to 75% of the farmers, the reasons for the poor performance of the irrigation system are low discharge rates, farm location in terms of the distance from the canal or water course head, poor maintenance, water theft, reduced time allocation and conveyance losses (Ahmad et al., 2007).
- Another biggest limitation in adoption of the drip irrigation system is the high initial cost and low availability and high prices of energy.
- Another challenge is that the majority of the farmers have small land holdings

(less than 5 ha) and lack enough investment and technical knowledge about the technology (Bakhsh et al., 2015)

- Farming of close growing crops (Bakhsh et al., 2015).
- Another constraint is the lack of awareness and knowledge regarding the advantages associated with drip irrigation technique.
- The prevailing efficient irrigation methods have not been evaluated in terms of suitability, economic viability, payback period and benefit cost ratios (Bakhsh et al., 2015).
- The lack of quality check and control may have compromised the results in terms of suboptimal materials, poor design and services and farmers also completely lack knowledge and technical guidance and depends only on the service providers.
- The evapotranspiration at the farm level is higher under drip irrigation as compared to the surface irrigation. Increase adoption of this technology will increase the water depletion at farm to catchment levels, reduce groundwater recharge, and will reduce the flows to the users at the tail end. Therefore, in such areas water application and depletion limits need to be implemented to maintain the water balance (Masih et al., 2014).
- These systems also require careful study and inclusion of all the relevant factors like land topography, soil, water, crop and agro-climatic conditions and suitability of drip irrigation system and its components are vital in its design and performance.
- In lighter soils, subsurface drip may be unable to wet the soil surface for germination, so in lighter soils, careful consideration of the installation depth is required. The main purpose of drip irrigation is to reduce the water

consumption by reducing the leaching factor.

- Another technical challenge with this system is that the sun can affect the tubes used for drip irrigation, shortening their usable life and solution for this can be wheat or rice straw that should cover the pipes to prevent the direct striking of sun rays on pipes.
- Farmers should be made aware of the fact that if water is not properly filtered and the equipment not properly maintained, it can result in clogging.
- Farmers lack experience and training regarding the time required for water application with drip irrigation system This may lead to the farmer either applying too much water (low efficiency) or an insufficient amount of water and this is particularly common where the operators are not well experienced and trained.
- Additional research is required on the evaluation of subsurface drip systems installed for irrigating different crops as the irrigator cannot see the water that is applied.
- Farmers and operators also need training regarding proper installation of drip irrigation systems as it can lead to the waste of water, time and harvest, if not installed properly.
- Occasional flood irrigation will be required to leach the salts down the soil in arid and semi-arid regions where water is of high salinity or alkalinity. Because using drip irrigation in these areas will rise the soil salinity due to the poor soil infiltration and will turn the land barren due to inadequate rainfall.
- The lack of experience with the drip irrigation technology is the hinderance in its effective adoption and implementation.
- Increased petroleum prices and constant unscheduled electricity outages is

another constraint in its adaptability.

- The other constraints and limitations are extensive maintenance requirement of system components like emitter due to clogging, damage to the pipes due to rodents and insects causing leakages, salinity hazards due to reverse pressure gradient in saline areas.
- Technical limitations observed are high skill requirements, lack of local manufacturing facilities and lack of expertise in sensitive technical areas regarding design, installation, maintenance and troubleshooting.
- Low availability of drip irrigation spare parts and components are root causes for the abandonment of schemes in Pakistan.
- The current inefficient water policies, depletion of ground water due to over exploitation, imbalance between supply and demand and inequitable water distribution has also created hindrance in adoption of these technologies.
- Moreover, extensive research is required on the irrigation application time and scheduling using drip irrigation systems for different crops these systems can show low performance and yield if not carefully designed and installed.
- Another potential hazard is increase in salinity due to reverse pressure gradient in saline areas with the use of drip irrigation systems.
- Famers are mostly inexperienced and needs training regarding operation and maintenance of the drip irrigation.
- They also need support and training regarding the irrigation scheduling and fertigation using drip irrigation systems.
- The biggest and most crucial concern is the lack of updated, efficient and technically suitable design available for drip irrigation systems.
- The current farmer friendly systems are designed by third party sales

representatives, though technical professionals are required to design these systems (Bakhsh et al., 2015).

- Therefore, designers also need training and knowledge regarding optimal designing and installation of the systems.

Assessing and resolving above mentioned constraints in adaptability of drip irrigation systems will promote the implementation and suitability of these systems in Punjab. Adopting water saving techniques like pressurized irrigation methods are preferred over traditional surface irrigation to improve the water use efficiency, however government’s financial and technical support is required to make this technology workable and affordable in Pakistan.

4.4.3 Need for the evaluation of hydraulic design and performance of Pakistani drip irrigation systems

As most of the drip systems installed under numerous projects as mentioned in Section 2.8 have met failure and have been abandoned due to their poor performance, which proves that implementing high efficiency irrigation systems does not always deliver high productivity if it is not properly designed, installed and maintained.

- According to the current scenario in already installed drip irrigation systems in Punjab, the system efficiencies have been improved approximately 25% to 30% in terms of operational performance only and no evaluation has been made on hydraulic design performance in terms of uniformity and emission measures (Khan, 2019).
- The impacts of water conservation technologies need to be well understood and documented beyond the field level as the real water savings can be much lower because of water recycling and the conjunctive use of surface and groundwater in many areas in Pakistan (Ahmad et al., 2007).

- Multi-disciplinary analysis and further research and development efforts are required in order to determine the adoption process and impacts of water saving technologies on food production and evaluating the real water savings at field, farm and higher three-dimensional levels (Ahmad et al., 2014).
- It is important to have a clear understanding of the different water balance components along with the knowledge of how certain interventions (e.g. drip irrigation systems) influence them in given field conditions (Ahmad et al., 2014).
- Additional studies are required to see the performance and suitability of drip irrigation in term of economics, material cost, payoff and constant management on different soils at different locations (Qureshi et al., 2015).
- According to Asif et al., (2015), the performance of these systems needs to be evaluated, tested and standardized. Because the drip irrigation systems can only apply water efficiently if they are well designed.
- Furthermore, the performance evaluation of drip irrigation systems already installed under both public and private schemes will improve the adequacy, efficiency and reliability of this technology by enhancing the performance that will help achieving sustainable irrigated agriculture in Pakistan.

As it is observed that no updated, efficient and technically suitable design for drip irrigation systems is available in Pakistan (Bakhsh et al., 2015). Which shows that besides the right selection of technology and irrigation method, the most vital element to achieve desired water productivity is the effective and optimal design and constant management of the system in terms of installation, and monitoring. However, the precise management can only be accomplished with the evaluation of drip systems in terms of their hydraulic design and performance at regular intervals. These systems can be further tested with alternative energy sources to make them feasible and affordable in Pakistan.

Moreover, with the substantial advancements in computer-assisted design tools, better simulations, and analysis techniques, a reliable and optimal design can be achieved. Likewise already installed drip irrigation systems can be assessed in detail not only in terms of design procedure (including data collection, hydraulic design, installation and monitoring) but water application efficiency and uniformity can be evaluated using advanced software packages to improve the design procedure, performance and suitability of these systems in Punjab, Pakistan.

4.5 Outcomes and observations made from the review of previously abandoned and failed drip irrigation systems in Punjab, Pakistan

After the review of previously installed drip irrigation systems in Punjab a lot of inconsistencies have been observed not only in data collection and integration but also in design procedure, installation and maintenance after installation.

4.5.1 Collection and integration of field data to design the drip irrigation systems

The first step in design practice is to survey the field and gather the data regarding field, crop and land topography.

- Meteorological data (temperature, rainfall, humidity etc.) has been taken from some fixed stations located in large cities, although it varies from position to position across the country. Meteorological data scarcity is always an issue and the possibility of a network of weather stations should be investigated.
- Estimated values of soil and water characteristics were used instead of measuring the actual soil and water characteristics of certain site. Soil type is important for the lateral spacing as in sandy soils a closer spacing will be required while wider lateral spacing is possible for heavier soil as wetting patterns and water movement is greater in heavier soils.

Meteorological data, soil and water characteristics reports needs to be updated and drip irrigation designs should incorporate the actual environmental, soil and water characteristics for each site. It is also suggested that the imported parts and equipment needs standardization.

4.5.2 Design practice of pressurized drip irrigation systems in Punjab, Pakistan

There is a lack of adequate technical expertise for design procedure, monitoring, field-testing and evaluation of pressurized irrigation systems as per approved designed. The following problems were observed from previous experience working in the design office in Pakistan.

- Both the industry and the projects require qualified and skilled manpower.
- There is a lack of updated, efficient and technically suitable design for drip irrigation systems.
- Instead of experienced professional these systems are mostly designed by in experienced designers and third party sales representatives.
- In design of specific land, the specific preferences and requirements of landowner/farmer are not kept in consideration particularly, regarding crops (Orchard/vegetables) to be grown in different seasons of the year. The farmers intend to grow different crops in summer and winter season, which will have different water requirements as most of the systems are designed for single crop for whole land that might not be suitable for other crops intended to be grown. Different crops may also have different requirements in terms of lateral and emitter selection and spacing.
- The same estimated values of crop data (crop kc, wetted area, evapotranspiration, etc.) are used for most of the crops. This will have an impact on the system capacity.

- Water and soil characteristics used in the design procedure are mostly taken from adjacent main cities, although soil and water characteristics vary significantly from one place to other place across the country.
- Emitter selection and spacing is not chosen based on soil type, only on available components, which greatly influences the soil wetting patterns of the soil in relation to crop root size and extent root depth/width, which is the most important component to ensure adequate system capacity.
- Systems are designed for average daily water requirement neglecting the daily peak and seasonal crop water requirements. This will severely impact the ability of the system to cope with periods of hot dry weather.
- Water losses through evaporation and seepage needs to be considered at the stage of design procedure and irrigation management of the system.
- Provision of a single design for drip systems is not suitable for all locations. The design should be adaptable to meet the requirements of a specific region taking in consideration the field size, climatic data, soil conditions, type of crop, water source, crop water requirements. Use of these single designs resulted in low average performance as land conditions in Pakistan are highly varied from region to region.
- Power is measured at the ideal efficiencies of diesel engines and pumps, which are not practically available. Therefore, all power requirements will be underestimated.
- In some designs laterals of wall thickness of about 0.45 mm is used to decrease the overall cost of the system that reduces the life of the system by up to a year due to the high temperatures in summer. The average high temperature in summers is 41°C.

- In most of the designs, the sub main has been designed to be placed in the centre of the field. That creates a hurdle for cultivation activities especially for future crop rotation.
- The famers also suggested that the design should be discussed and finalized with the mutual consent of the farmer and the designer, particularly in regard to zoning of the land, pipe sizes, pipe direction and alignment of laterals.
- It has been mentioned that the design of the system does not consider the position and direction of the sun, which is very important in selecting the direction of lateral rows, as some of the crops need direct sunlight.
- The farmers were not satisfied with the sizing of the zones in designs as they were concerned with the labour involved to run each zone.
- No performance measurement, field-testing and evaluation of pressurized irrigation systems has been undertaken to check the approved designs pre and post installation.
- One grower advised to have one row spare after each row that can be blocked or connected with drip tube according to the type of crop to be grown in future in different seasons. This practice will have a significant impact on the design of the pumping infrastructure.
- Most of the installed drip irrigation systems were found inadequate in terms fulfilling the crop water requirements.

  Which points towards the inadequacy of the design procedure and requires performance evaluation in terms of uniformity to maintain the quality and productivity of the crop.

Bakhsh et al., (2015) also agrees that each site should be studied individually in terms of soil type, topography, crops to be grown, water quality and source and most importantly farmer’s commitment and skill to improve crop water productivity and irrigation efficiency. Then irrigation techniques and technological package has to be selected accordingly.

It has been found that most of the drip irrigation systems were designed and installed without the mutual consent of the farmers and considering their specific requirements, particularly regarding future crop rotation, land zoning, lateral sizing and alignment. Daily peak and seasonal water requirements, water losses through evaporation and seepage along with soil wetting patterns needs to be considered at the design stage. Moreover, provision of single design for drip irrigation systems based on estimated values of crop data, soil and water characteristics along with lack of performance evaluation will not be able to ensure system adequacy and acceptable performance. The selection of drip irrigation systems is based on availability rather than detailed system requirements. Performance evaluation, field-testing and evaluation of already installed system would be the key factor to improve the cycle of efficiency and adoptability to ensure the system adequacy.

4.5.3 Installation, monitoring and performance evaluation of the installed drip irrigation systems

Investigating the factors, which have contributed to the failures of previously installed drip irrigation gives the following outcomes:

- The farmers have drip systems installed on a subsidized rate from government agencies, but are not satisfied with the installation practices, as most of the systems are installed by hiring a local mechanic or plumber that does not have expertise or training in drip irrigation installation.
- Farmers and operators need to be trained by professionals regarding the operation and maintenance of the systems before the installation of the systems.
- Although drip irrigation is the most efficient technique but it requires technical knowledge as well as intensive training for its successful operation

(Bakhsh et al., 2015).

- There is a lack of capacity building of the manufacturers, suppliers, installers, and local technicians. Therefore, they lack expertise and technical knowledge in monitoring, maintenance and troubleshooting of installed systems after installation.
- Service providers and farmers also required support and assistance with irrigation scheduling and fertigation scheme for improving crop productivity.
- Therefore, it is suggested that an agronomist, engineer or expert is required that can resolve the technical problems, particularly with water and fertigation scheduling for different crops at different growth stages, so that the system can be successful in varying field conditions.
- Excessive time is required for the operation & maintenance of system components and troubleshooting such as clogging of emitters, damage to pipes due to rodents and insects causing leakages, which involves additional expenses and training.
- The farmers have issues with the length of the lateral selected either very short length is hindrance in intercultural activates and very long length is difficult to clean. One farmer suggested a maximum length of 60.96 m (200 ft) for vegetable drip irrigation design.
- The farmers were more interested in drip tube instead of dripline, as it is easier to roll and store.
- There is an absence of awareness regarding selection and application of environmentally and crop friendly fertilizers and chemicals. Chemicals are used for chlorination to flush and clean the driplines to prevent clogging. The suitable fertilizers and chemicals are not easily available in the market.

- There should be guidance regarding high value crops agronomies so that the cost benefit ratio of the drip irrigation systems can be justified and make it suitable and feasible for Pakistan.
- Follow up, back up support and assistance should be provided to keep the system operative and timely maintenance of drip systems and its components. Which is one of the reasons for the abandonment of the system.
- There is big deficiency of performance evaluation in design practice to evaluate the factors resulting in low system efficiency and adequacy in Punjab to ensure the fulfilment of crop needs.

Poor management of the drip irrigation systems and its components is witnessed in the field post installation in Punjab. There is a lack of technical expertise in installation practices, maintenance and trouble shooting. Training and equipment should be provided to the farmers and operators regarding system maintenance, trouble shooting, and water and fertigation scheduling. Absence of follow up assistance and a complete technological package including crop establishment methods, fertilizer requirements, plant protection techniques and other agronomic practices results in low performance of these systems. The observations made by analysis of already existing drip irrigation systems in Punjab also demonstrate that the transfer of traditional irrigation methods to pressurised irrigation methods is not a simple solution for the improvement of performance and efficiency of existing irrigation practices and productivity. Further involvement of third-party agencies in the monitoring and evaluation of micro irrigation systems installed will encourage the adoption of micro irrigation systems.

4.5.4 Other technical complications observed

The review of past experience in Pakistan uncovered several technical issues in addition to what is discussed above:

- Due to the water shortage Pakistan is dealing with a huge power crisis with the increase in electricity prices. The surface water needs to be used wisely and judiciously Iqbal & Iqbal, (2015).

- Further decreasing ground water resources are increasing tube well prices and making it an unreliable source to be used in future.
- The other issues reported by farmers are canal water shortages, poor groundwater quality, and issues regarding fertilizer, seed, energy, and low soil fertility and financial constraints (Bakhsh et al., 2015).
- One major constraint is the fluctuation of voltage in the electricity supply that results in a change of pressure and flow in the field and there is no appropriate arrangement for alternative electricity resources available to control this issue. As a result, many farmers in Pakistan use diesel engines to supply power for their irrigation systems due to shortage and irregular supply of electricity. This adds to the cost of the system upfront capital.
- Also, there is an inequitable distribution of water between canals, watercourses and downstream users. The current water policies and difference between supply and demand creates an inequitable water distribution. This creates a hindrance in adoption of these technologies due to system failure.
- Non-availability and poor management of components in case of damage to the installed components of the system is also a problem that has been faced by growers. As there is a lack of local manufacturing facilities.
- The quality of drip components provided by service provider companies is poor. Electric motors, filters, emitters, main and sub main pipes and other complementary components are substandard. The efficiency of the electric motors declines over time and results into the loss of pressure in the field.
- Further, automation needs to be introduced and adopt in drip irrigation.
- High value fruits and vegetables should be promoted and processed to increase

the promotion and adoption of drip irrigation in Pakistan.

Economic and technical limitations is another significant reason of rejection of these systems by farmers. Uncertain electricity and intermittent water supply are two of the major obstacles in the success of the existing installed drip irrigations systems is Pakistan. Poor quality and non-availability of drip irrigation components in case of damage are other causes of failure of the systems installed in Punjab. Therefore, drip components and spare parts need standardization and quality check before installation. The observations made by analysis of these systems also show that the transfer of traditional irrigation methods to advanced irrigation methods are not the solution for the improved performance and productivity of existing irrigation systems. The success of any type of irrigation system entirely depends on the management and operation of the whole irrigation structure and system and its components.

4.6 Field experimentation at five case study sites in Punjab, Pakistan

Field experimentation is performed at five case study sites in Punjab as Site No. 1, 2, 3, 4 and 5 in actual field conditions to confirm the observations made in this research and evidences provided by colleagues, farmers and project managers regarding failure of previously installed drip systems in Punjab, Pakistan.

4.6.1 Introduction to the case studies performed in Pakistan

A series of farm site visits to farms with drip irrigation systems were completed to assess installations. Five sites have been selected from different regions of Punjab, Pakistan. These sites were selected on the basis that the drip systems represented common design installed in Pakistan. The measured equipment developed as described in Section 3.5.2 were used to measure the emitter flow rates and pressures in the selected sites. Farmers at each site were interviewed in regard to their satisfaction and the performance of the drip irrigation systems installed. The problems and constraints in operation and maintenance on a case by case basis were also noted. A maximum of two zones have been selected at each site due to limitations associated with travel and time issues. The tests were performed on the site require that the zone of interest is being irrigated at that time. It has been observed that the mainline was the pipe connecting pump shed to the centre of submain of each zone and submain was further connected to the driplines at all sites. The slope was measured in the direction of dripline using dumpy level at all selected sites. A dumpy level is an optical instrument used to establish and verify points in the same horizontal plane. The results of the interviews and tests that have been carried out on their farms are provided in the following sections:

4.6.2 Site No. 1 and test results

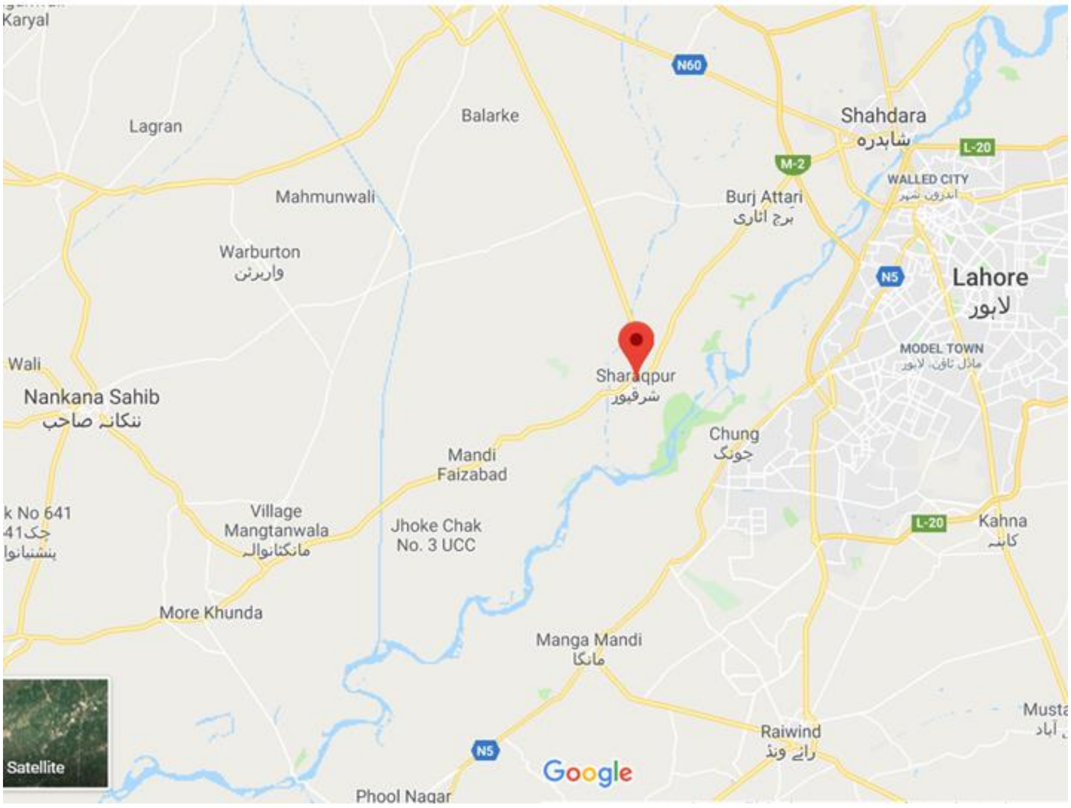


Figure 4.1: Map of Sharaqpur city in Punjab province of Pakistan

Figure 4.1 shows the map of the first site visited, owned by Mr Gohar Butt and is situated near Sharaqpur City in the Punjab Province. The system was designed by a Dadex Eternit Limited from Karachi. The land is a medium-textured soil, and the water source is from a canal and a tube well; the depth to the water table from the ground surface was 18.3 m.

The drip irrigation system was installed on 6.07 hectares of land used for growing vegetables (capsicums, tomatoes and cucumbers) as shown in Figure 4.2. The total area was divided into seven equal zones, each zone being 0.87 ha. The lateral and emitter spacing that had been selected was 1.22 m and 0.3 m, respectively. A dripline with a nominal dripper flow rate of 1.6 litres per hour was selected for this design. The main PVC pipes of 4 inches in diameter, and the sub mains of 2.5 inches and 2 inches diameter were used in the field.

Figure 4.2: View of drip irrigation system installed on the field.

The mainline was connected from pump shed to the centre of submain in each zone. The length of submain line was 35 m for each zone while, the length of main line from the pump shed to the centre of submain was approximately 150 m and 179 m for Zone No. 2 and 4 respectively. The submain was connected to the centre of each zone with the lateral lengths of 61 m and 36.6 m for Zone No. 2 and 4 respectively as shown in Figure 4.4

The slope measured in the field was approximately 0.074 m / 200 m (0.037%). The gravel filter, disc filter, venturi injector, flowmeter, electric motor and pump are installed at the pump shed as shown in Figure 4.3.

Figure 4.3: Pump shed including gravel filter, disc filter, flowmeter, venturi injector and pressure gauges installed on field.

Figure 4.4: View of submain valve to operate the zone water flow.

Testing was performed on zones No. 2 and 4, which are numbered from supply to end. Testing was only performed on these zones because these were the only operating (irrigating) zones at the time of testing at this site. The submains of 2.5 inches were selected in the selected zones. The following tests were performed on different components of the drip irrigation system.

1. Pressure measurement through the pump and filtration unit

The pressures were recorded at the pump shed using the bourdon pressure gauges already installed at pump discharge, outlet of sand media filter and disc filter. The following results were obtained:

- Pressure at pump discharge: 44.88 m
- Pressure at outlet of sand media filter: 42.84 m
- Pressure at outlet of disc filter: 40.80 m

A reasonable pressure drop of 4.08 m was observed through the sand media and disc filter.

2. Pressure measurement at the inlet and outlet of three laterals in each zone

Three laterals were selected at the left, middle and right end of the sub main in each zone to estimate the variations in flow and pressure throughout the zone. Lateral 1, 2 and 3 were selected at the left, middle and right end of the sub main respectively in each zone. The pressure was measured at the inlet and outlet of the laterals using portable handmade pressure gauges using the method described in Section 3.5.2.1 with the results as shown in Table 4.1.

Table 4.1: Pressure measured at the inlet and the end of the laterals selected in Zone No. 2 and 4 at Site No. 1.

Results	Lateral Length (m)	Inlet Pressure (m)	End Pressure (m)	Pressure Loss (m)
Zone No	2			
Lateral 1	61	28.56	17.34	11.22
Lateral 2	61	28.56	16.32	12.24
Lateral 3	61	27.54	10.20	17.34
Zone No	4			
Lateral 1	36.6	22.44	19.38	3.06
Lateral 2	36.6	22.44	19.38	3.06
Lateral 3	36.6	22.44	19.38	3.06

3. Pressure measurements at two emitters at upstream and downstream end of the laterals.

The pressure was measured at two emitters at upstream and downstream end of each selected laterals using portable pressure gauge with the results shown in Table 4.2.

Table 4.2: Pressure measured at the emitters at upstream and downstream end of the laterals selected in Zone No. 2 and 4.

Results	Lateral Length (m)	Emitter at upstream end (m)	Emitter at downstream end (m)	Pressure Loss (m)
Zone No	2			
Lateral 1	61	25.50	16.32	9.18
Lateral 2	61	25.50	15.30	10.2
Lateral 3	61	22.45	9.18	13.27
Zone No	4			
Lateral 1	36.6	20.40	17.34	3.06
Lateral 2	36.6	20.40	17.34	3.06
Lateral 3	36.6	20.40	16.32	4.08

Similarly, extensive losses were noticed through emitter from upstream to the downstream end of the lateral in Zone No. 1.

1. Flow rate measurement at the same emitters

The flow rate was measured using the catch can methodology described in Section 3.4.2. Cans and a stopwatch were used to take the flow and time measurement to estimate the flow rate of individual emitters. The average flow rate of the emitter in this zone was 1.59 litres per hour. The sub-main and main flow rates could not be measured as they were buried underground.

This site was considered as the best operating site of the area in terms of performance and operation. The farmer appointed an agronomist as manager of the farm to look after its operation and management. At this site the operators were taking pressures at the end of the laterals only to check the working of the system. No measurements have ever been taken in terms of flow measurement in the main, sub main or laterals.

4.6.3 Site No. 2 and test results

Figure 4.5: Mandi Bahauddin city map in Punjab province of Pakistan

The second site visited owned by Mr Ijaz Cheema is situated near Mandi Bahaudin City (Figure 4.5) in the Punjab Province. The system was designed by Jaffer Brother Pvt. Limited from Karachi. The land is a medium textured soil and the water source is a tube well, where the depth to the water table from the ground surface normally is 6 m. The farm's power source was a diesel engine.

The drip irrigation system was designed for 1.58 hectares of sugar cane, but at the time of testing a muskmelon crop was being irrigated by the system. The total area was divided into four equal zones (each zone being 0.39 ha). The lateral and emitter spacing were selected as 1.22 m and 0.4 m respectively. Two crop rows were being irrigated by one dripline with a nominal dripper flow rate of 2.4 litres per hour. The main PVC pipes of 3 inches in diameter and the sub mains of 2.5 inches and 2 inches diameter were used. The mainline was connected from pump shed to the centre of submain in each zone. The distance of main line from the pump shed to the centre of submain was approximately 117 metres and 185 metres for Zone No. 2 and 4 respectively. The submain was connected to the centre of each zone with the lateral length 58 m on both sides of submain.

The slope in the field was 0.04 m / 100 m (0.04%). The screen filter, disc filter, venturi assembly, fertigation manifold, flowmeter, electric motor and diesel engine were installed at the pump shed as shown in Figure 4.6 to Figure 4.12.

Figure 4.6: Pump shed showing installed venturi assembly and pressure gauges.

Figure 4.7: View of a screen filter, disc filter and flow meter installed at the pump shed.

Figure 4.8: Water pump with electric motor installed at the pump shed.

Figure 4.9: View of diesel engine installed at the pump shed.

Figure 4.10: Screen media filter and pressure gauge installed at the pump shed.

Figure 4.11: Close view of flow meter installed at the pump shed.

Figure 4.12: View of a pump shed with installed filters, flow meter, electric motor and venturi assembly.

Testing was only performed on Zone No. 2 and 4 numbered from supply to end. The following tests were performed on different components of the drip irrigation system:

1. Pressure measurement through the pump and filtration unit

The pressures were recorded at the head unit using the existing bourdon pressure gauges installed at the site. The following results were obtained:

- Pressure at pump discharge: 25.50 m
- Pressure at outlet of disc filter: 14.28 m

A significant pressure drop of 11.22 m has been observed between pressure at pump discharge and disc filter.

2. Pressure measurement at the inlet and outlet of the three laterals in two zones.

Three laterals were selected at the left, middle and right end of the sub main in each zone to estimate the variations in flow and pressure throughout the zone. The submain of 2.5 inches were used in Zone No. 2 and 4. The pressure was measured at the inlet and outlet of the selected laterals using portable pressure gauge with the following results:

Table 4.3: Pressure measured at the inlet and end of the laterals selected in Zone No. 2 and 4 at Site No. 2.

Results	Lateral Length (m)	Inlet Pressure (m)	End Pressure (m)	Pressure Loss (m)
Zone No	2			
Lateral 1	58	14.28	12.24	2.04
Lateral 2	58	14.28	12.24	2.04
Lateral 3	58	13.26	12.24	1.02
Zone No	4			
Lateral 1	58	15.30	11.22	4.08
Lateral 2	58	15.30	11.22	4.08
Lateral 3	58	13.26	10.20	3.06

The Table 4.3 shows the pressure loss resulted due to the friction and minor losses encountered through the main, sub-main pipes and lateral in the zone.

2. Pressure measurement at two emitters at upstream and downstream end of the selected laterals.

Pressures at individual emitter could not be measured, as the pressure range was higher than the maximum capacity of portable pressure gauge.

Figure 4.13: Water flow measurement using catch can and stopwatch.

3. Flow rate measurement at the same emitters

At the time of measurement, three laterals were closed. The flow rate was measured using the catch can methodology. Catch can methodology was used to calculate the flow rate of individual emitters as shown in Figure 4.13. The average flow rate over the zone was 2.8 litres per hour. The sub-main or main flow rates could not be measured as these pipes were buried underground.

The farmer tried to contact the company, who supplied the drip system components to resolve some of the issues observed in the field, but the company did not respond. After installation of the system, the operators were told to increase the pressure of the system to increase the number of zones irrigated at one time. As already mentioned, the system was designed for a sugar cane crop, but at the time of testing musk melons were being grown and three laterals were closed in each zone.

4.6.4 Site No. 3 and test results

Figure 4.14: Village Rasheed Pur map near Saraye Alamgir, Punjab Pakistan.

The third site visited owned by Mian Iftikhar is situated in Rasheed Pur village near Saraye Alamgir in the Punjab Province. The map of the city can be seen in Figure 4.14 and this system was designed by the Royal Construction Company from Islamabad. The land is a sandy loam soil and the only water source is from a tube well, where the water table depth was 17 m below the ground level. The slope measured was 0.1 m / 200 m (0.05%). Different components of pump shed including filters, flowmeter, pressure gauges, electric motor have been shown in Figure 4.15, Figure 4.16, Figure 4.17, and Figure 4.18.

Figure 4.15: View of pump shed with filters installed along with pressure gauges and reservoir.

Figure 4.16: Back view of pump shed along with filters and reservoir.

Figure 4.17: View of bourdon pressure gauge installed at pump shed.

Figure 4.18: Disc and screen filter installed at pump shed.

Figure 4.19: View of dripline installed along the field at site No. 3 for cucumbers and strawberries.

Figure 4.20: Close view of dripline installed at the field for strawberries and cucumbers.

The drip and sprinkler irrigation systems were installed on an area of 4.25 hectares, growing rice, wheat, strawberries and cucumbers. The area under drip irrigation was 1.62 hectares (4 acres) divided into two equal zones (each zone being 0.81 ha) for strawberries and cucumbers as can be seen in Figure 4.20. The lateral and emitter spacing selected were 1.52 m and 0.3 m, respectively as shown in Figure 4.19. The system was designed for growing cucumbers. A dripline with a nominal dripper flow rate of 2 litres per hour was selected for this design. Testing was performed only on one Zone No. 1 operating at the time of testing at the site. The length of main line and submain line in each zone was 70 m and 35 m respectively. The distance of main line from the pump shed to the centre of submain was approximately 62 metres for Zone No. 1. The main PVC pipes of 3 inches in diameter and the sub mains of 2 inches diameter were installed at the site.

The mainline was connected from pump shed to the centre of submain in each zone. The submain was led in the centre of each zone given the laterals of 35 m length on both sides of submain. The sand media filter, disc filter, venturi assembly, fertigation manifold, flowmeter, centrifugal pump and diesel engine were installed at the pump shed as shown in Figure 4.15 and Figure 4.16. The following tests were performed on different components of the drip irrigation system.

1. Pressure measurement thorough the pump and filtration unit

Pressure has been recorded at head unit from existing pressure gauges installed at head unit. The following results were obtained:

- pressure at pump discharge: 40.80 m
- pressure at outlet of sand media filter: 35.70 m
- pressure at outlet of disc filter: 30.60 m

A significant pressure drop of 10.2 m was observed through the sand media and disc filter.

Figure 4.21: Measuring pressures at the end of dripline using pressure gauge.

2. Pressure measurement at the inlet and outlet of three laterals in Zone No. 1

Three laterals from the start, middle and end were selected in each zone to estimate the variations in flow and pressure throughout the zone. Lateral No. 1, 2 and 3 were selected at the left, middle and right end of the sub main respectively. The pressure was measured at the inlet and outlet of the laterals using pressure gauges as shown in Figure 4.21 with the following results:

Table 4.4: Pressure measured at the emitter at upstream and downstream end of the laterals selected in Zone No. 1.

Results	Lateral Length (m)	Inlet Pressure (m)	End Pressure (m)	Pressure Loss (m)
Zone No	1			
Lateral 1	35	30.60	26.52	4.08
Lateral 2	35	30.60	26.42	4.18
Lateral 3	35	30.60	24.48	6.12

3. Pressure measurement at two emitters at upstream and downstream end of the selected laterals.

Pressures at individual emitter could not be measured, as the pressure range was higher than the maximum capacity of portable pressure gauge.

4. Flow rate measurement at the same emitters

The flow rate was measured using the catch can methodology. The average flow rate across the zone was 2.8 litres per hour. The sub-main or main flow rates could not be measured as they were buried underground.

The system was designed for a cucumber crop, but at the time of testing and taking the field measurements, strawberries were being irrigated by the system. Only one zone was operating at that time. The farmer was very progressive and seemed interested in these systems; he was experimenting on growing different crops at the same time using drip and surface irrigation.

4.6.5 Site No. 4 and test results

Figure 4.22: Sheikhupura city map located in Punjab.

As shown in the figure above Figure 4.22, the fourth site visited is owned by Mr.

Azhar Ahmed, is situated near City Sheikhupura in the Punjab Province. The system was designed by Jaffer Brothers Pvt Ltd from Islamabad. The land is a loamy soil, and the water source is from canal and a tube well, while the depth to the water table depth from the ground surface is 20 m.

The drip irrigation system was installed on 6.07 hectares of land used for growing vegetables (capsicums, tomatoes and cucumbers). The total area was divided into equal seven zones (each zone of 0.87 ha) with lateral and emitter spacing had been selected as 1.25 m and 0.4 m, respectively. A dripline with nominal dripper flow rate of 2 litres per hour and the main PVC pipes of 4 inches in diameter and the sub mains of 2.5 inches and 2 inches diameter were selected for the design. The average slope of the field measured was 0.05 m / 100 m (0.05%).

The length of main line and submain line was 214 m and 50 m respectively. The mainline was connected from pump shed to the centre of submain in each zone. The submain was led in the centre of each zone. The distance of main line from the pump shed was approximately 158 and 220 metres from the centre of submain for Zone No. 1 and 4 respectively. Length of the lateral selected for all zones was 62.3 m. The screen filter, disc filter, venturi assembly, flowmeter, pump and electric motor were installed at the pump shed as shown in Figure 4.24 and Figure 4.25. The reservoir installed is shown in Figure 4.23.

Figure 4.23: Reservoir constructed at the drip system site to store the water.

Figure 4.24: View of a disc filter installed at the pump shed.

Figure 4.25: View of a screen filter installed at the pump shed along with venturi injector, flowmeter and pressure gauges.

Testing was performed on zones 1 and 4 numbered from supply to end. The following tests were performed on different components of the drip irrigation system,

1. Pressure measurement through the pump and filtration unit

The pressure was recorded at the head unit using bourdon pressure gauges. The following results were obtained:

- Pressure at pump discharge: 30.60 m.
- Pressure at outlet of sand media filter: 30.60 m.
- Pressure at outlet of disc filter: 22.44 m.

A reasonable pressure drop of 8.16 m was observed through the sand media and disc filter.

2. Pressure measurement at the inlet and outlet of three laterals in one zone.

Two laterals, instead of three, were selected from the start and the end of each zone, due to a shortage of time available to irrigate that zone. Lateral 1, and 2 were selected at the left and right end of the sub main respectively. The pressure was measured at the inlet and outlet of the laterals using pressure gauges to estimate the variation of flow and pressure throughout the zone, with the following results:

Table 4.5: Pressure measured at the inlet and end of the laterals selected in Zone No. 1 and 4.

Results	Lateral Length (m)	Inlet Pressure (m)	End Pressure (m)	Pressure Loss (m)
Zone No	1			
Lateral 1	62.3	18.36	11.22	7.14
Lateral 2	62.3	18.36	11.22	7.14
Zone No	4			
Lateral 1	62.3	20.40	16.32	4.08
Lateral 2	62.3	20.40	15.81	4.59

3. Pressure measurement at two emitters at upstream and downstream end of the selected laterals

The pressures were measured at two emitters at the upstream and downstream end of each selected laterals using portable pressure gauge.

Table 4.6: Pressure measured at the emitter at upstream, centre and downstream end of the selected laterals in Zone No. 1 and 4.

Results	Lateral Length (m)	Emitter at upstream end (m)	Emitter at downstream end (m)	Pressure Loss (m)
Zone No	1			
Lateral 1	62.3	12.65	11.22	1.43
Lateral 2	62.3	12.24	11.22	1.02
Zone No	4			
Lateral 1	62.3	20.40	15.81	4.59
Lateral 2	62.3	20.40	15.81	4.59

4. Flow rate measurement at the same emitters

The flow rate was measured using the catch can methodology. The average flow rate across the zone was 1.75 litres per hour.

The biggest issue observed on the site was the limited availability of electricity to run the system. The pump installed was only diesel operated. At the time of visit, the electricity and diesel both were unavailable. While, only a small quantity of diesel was kept on the site for the backup motor.

4.6.6 Site No. 5 and test results

Figure 4.26: View of city Mandiali situated in Punjab province.

The fifth site visited is situated near city Mandiali as shown in Figure 4.26 in Punjab Province of Pakistan. On the first visit, the electricity was not available and on the second visit the control panel was not working. It clearly reveals the negligence of farmer, system's supplier and system operator. The farm was poorly managed and only one zone was in operating condition at the time of visit.

4.7 Discussion of results

4.7.1 Pressure measurement through the pump and filtration unit

The pressures were recorded at the pump shed using the bourdon pressure gauges already installed at pump discharge, outlet of sand media filter and disc filter, while portable handmade pressure gauges were used for the pressure measurement in laterals and emitters. There may be slight difference in the accuracy of already installed and portable pressure gauges. Regardless of the design, drip filter systems always involve a moderate head loss. Any head loss represents an additional energy cost to the farmer. Large head losses may be caused by either undersized or partially blocked filter systems. Following a general rule of thumb, as mentioned in Section 2.11 a reasonable pressure drop across the filter system in the systems tested was considered as having a total head loss of less than 10 m that will limit the outflow variation to 10% to get the desired uniformity in the field. Following this rule of thumb, a reasonable pressure drop has been observed through pump and disc filter at Site No. 1, and 4, while a significant pressure drop was recorded at Site No. 2 and 3.

4.7.2 Supply pressures compared to recommended pressure

The supply pressures at the upstream end of the drip laterals matched well with the recommended pressures at Site No. 1 and 4 while at Site No. 2 and 3 the supply pressures were higher than the recommended pressure resulting in higher emitter discharges than expected.

4.7.3 Losses over the length of the drip lateral

The difference in pressure shows the friction and minor losses encountered through laterals, main and sub-main pipes of the zone. For non-pressure compensated driplines, this drop-in pressure will cause a drop in the uniformity. To maximise uniformity the pressure, drop over the drip lateral should be less than 10 m. A reasonable pressure drop is defined as those systems with a smaller drop over their length. Heavy losses have been observed in Zone No.1 of the Site No. 1. While at all other sites the pressure drop through the lateral was reasonable and matching with the emitter results.

4.7.4 Flow rate measurements

The average emitter’s flow rate recorded at Site No. 1 and 4 was approximately 0.63% and 14.3% lower than the manufacturer’s average flow rate. While at Site No. 2 and 3 the average emitters’ flow rates measured was approximately 17% and 40% higher than the manufacturer’s average flow rate. These high flows can be explained by the higher than expected supply pressures at the upstream end of the laterals as discussed above.

4.7.5 The ease / difficulty of conducting the measurements in the field

At the Site No. 5, measurements could not be taken due to unavailability of electricity at first visit and damaged control panel on the second visit. The sub-main and main flow rates could not be measured at all sites as they were buried underground. A maximum of two zones have been selected at each site due to limitations associated with travel and time issues. Pressures at individual emitter could not be measured, at Site No. 2 and 3 as the pressure range was higher than the maximum measuring capacity of portable pressure gauge. The flow rates along the main and submain could not be recorded as they were buried underground at all sites. Measurements could only be taken at the zones operating at the time of testing.

4.8 General observations during the collection of case study data from systems already installed in Punjab Pakistan

The pressure and flow rates were measured were taken using pressure gauges and catch cans and the following observations were made:

- At all sites the main and submain pipes were buried underground.
- The main water supply was from canals and tube well or sometimes in combination.
- Two of the four sites had average emitter flow rate higher than the manufacturer’s flow rate, while at two sites the average flow rate was lower than the manufacturer’s flow rate.
- The soil at most of the sites in the Punjab region was a sandy loam and was medium textured.
- The depth to the water table from the ground surface water varies from site to site.

- At most of the sites the pressure gauges were too sensitive to measure the high pressures in the laterals as they stopped working when the pressure was too high.
- At all sites the availability of electricity supply was the major issue and had been neglected by farmers and system suppliers, (Mongat et al., 2015) have also mentioned this major issue.
- The labourers managing and monitoring the installed systems had no knowledge of the systems and their working and maintenance.
- The system operators were checking pressures only at the end of each lateral to check the working of the system. No pressure and flow have been measured for main submain in the start of lateral and individual emitters.

The observations confirmed the expected negligence and lack of knowledge among farmers and farm operators. No alternative arrangements were made for the outage of electricity and the systems were poorly managed at most of the sites.

4.9 Conclusions

Large numbers of drip irrigation systems have been installed in the past but have now stopped working or have been abandoned. From the analyses and review of the previously installed drip irrigation systems, the failure of drip irrigation systems could be defined as outright crop failure in terms of yield, crop quality or hydraulic failure. Due to economic and technical limitations observed resulted into non-acceptability of these systems by farmers due to high initial cost, high skill requirements, lack of local manufacturing facilities and limitations in sensitive and highly skilled technical areas in terms of hydraulic design, system capacity, installation, maintenance and trouble shooting. Further no performance measurement, field-testing and evaluation of pressurized irrigation systems has been undertaken to check the approved designs pre and post installation. Hence, this project will help the researchers and design companies to improve and study further into the drip irrigation design in broader sense to improve the design adequacy, performance and success rate of drip irrigation systems in Punjab, Pakistan.

It has been analysed that most of the drip irrigation systems were designed and installed without the farmers consent and approval, particularly regarding future crop rotation, land zoning, lateral sizing and alignment. The selection of drip irrigation systems is based on availability rather than detailed system requirements. Intermittent water and power supplies on farm make management of the drip irrigation systems extremely difficult. There are not only problems in the field design but the whole supply system including pre-installation techniques, post installation maintenance and follow up. The results obtained from the field testing of selected case studies predicted the similar issues as acknowledged and observed in the review of already installed drip irrigation systems in Punjab, Pakistan as explained in Sections 4.4 and 4.5 these outcomes are discussed in detail in CHAPTER 6.

After the successful selection and replication of typical Pakistani drip irrigation system at the field test site, the same selected drip irrigation design was replicated into the software packages i.e. Hydrocalc and Eaucadi. These measured field and simulated results have been compared, analysed and discussed in CHAPTER 5.

CHAPTER 5 RESULTS FROM EXPERIMENTATION IN AUSTRALIA

5.1 Introduction

The inadequacy of the current design procedure initiated the need for attaining irrigation performance results from design information and field measurements. To analyse the adequacy of the parameterisation of modern drip irrigation design software packages to achieve the above goal, the measured results are obtained following the laboratory testing of the equipment and handmade equipment and the installation of the selected system at the field test site. The emitter flowrates and pressures were recorded, and similar results were measured using software packages. Simulated and measured results will be projected into the spreadsheets and charts will be generated for emitter flowrates and pressures along with the calculation of performance of the system in terms of emission uniformity and coefficient of variation. The detail of the results and comparison of measured and simulation results is provided in the following sections.

5.2 Laboratory testing results of replicated equipment

Four number of trials were performed in the laboratory in order to test the methodology and to test and finalise the measurement equipment. The dripline specifications and measured results are shown in Table 5.1. Two different driplines were used, and end pressure was maintained at 10 m during each test.

Table 5.1: Comparison of four number of trials performed in the laboratory.

Serial No	Specifications	Units	Trial Number 1	Trial Number 2	Trial Number 3	Trial Number 4
1	Inside diameter of emitter	mm	14.20	14.20	14.20	14.60
2	Outside Diameter of emitter	mm	16.0	16.0	16.0	16.0
3	Exponent *x*		0.46	0.16	0.16	0.16
4	Constant *k*		0.69	2.00	2.00	2.00
5	Emitter Flow rate	L/h	2.00	2.00	2.60	2.60
6	Kd		0.40	0.40	0.40	0.40
7	Dripline end pressure	m	10.00	10.00	10.00	10.00
8	Dripline head pressure	m	10.60	11.20	11.20	10.53
9	Pressure loss in dripline	m	0.60	1.20	1.20	0.53
10	Cum. pressure loss in dripline	m	0.60	1.20	1.20	0.53
11	Velocity	m/s	0.44	0.64	0.64	0.45
12	Time duration	min	7.72	5.30	5.30	7.59
13	Dripline flow rate	L/h	251.60	365.65	365.65	364.66
14	Ave. emitter flow rate	L/h	2.01	2.93	2.93	2.92
15	Flow rate variation	%	2.60	1.79	1.79	0.82
16	Emission uniformity	%	95.51	95.72	95.72	95.98

Pressure gauges catch cans, measuring beakers, handmade fittings with pressure gauges, flowmeters and accessories were tested and identified to be used at field test site using the methodology given in Section 3.4. Using emitter flow rate and emitter pressure, exponent x and constant k was measured using Equation 2.8. Velocity (m/s) of the water in dripline was measured dividing dripline flow rate (m^3/sec) with the area (m^2) of dripline using inside diameter of dripline (mm). Dripline head pressure, end pressure and pressure loss were measured using handmade pressure gauges. These results were analysed to identify the equipment which produce results equivalent to the manufacturer's provided specifications. It was observed that the Trial No. 1 produces the most accurate and similar results to the manufacturer's provided specifications as given in Section 3.3. The measurement equipment used in Trail No. 1 was finalised to be used for field-testing at field test site.

5.3 Measured results from the field testing of the replicated design at agricultural plot area

The results obtained from the field test system installed at the agriculture plot area as introduced in Section 3.6.2 are given in the following sections. Field tests were conducted on the installed drip irrigation system to evaluate the performance of the system and the components using different irrigation performance measures in terms of uniformity. The measured and simulated results have been plotted and analysed.

5.3.1 Introduction to the tests performed

The explanatory table given below shows the detail of tests performed with different nominal supply pressures, Water supply end (general slopes) and dates on which test was performed using the trial system.

Table 5.2: Tests performed at the field test site with different slopes and nominal supply pressure.

Test No	Water supply end	Nominal supply pressure (metres)	Date
1	Highest	3.52	10th Oct, 2014
2	Highest	9.14	9th Oct, 2014
3	Highest	10.62	12th Oct, 2014
4	Highest	10.55	28 Oct, 2014
5	Highest	18.63	28 Oct, 2014
6	Highest	27.07	29 Oct, 2014
7	Lowest	3.52	08 Nov, 2014
8	Lowest	7.73	09 Nov, 2014
9	Lowest	14.91	09 Nov, 2014
10	Lowest	21.45	10 Nov, 2014
11	Lowest	31.99	10 Nov, 2014

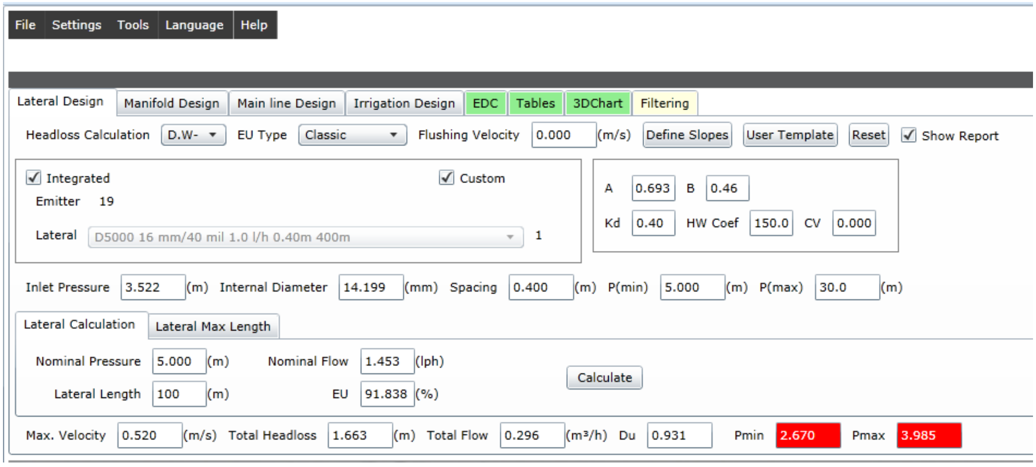
Table 5.2 provides the detail of the 11 of tests performed on the field test site. Test No. 1 to 6 have been performed with the water supply into highest end of dripline while, Test No. 7 to 11 have been performed with water supply placed into the lowest end of the dripline. Water supply into the highest end of dripline means the water is supplied at the highest end with dripline falling in the direction of flow of water, while, water into the lowest end of dripline means water is supplied at the lowest end of the dripline with the dripline rising in the direction of flow of water. Height of pipe is taken from the datum (reference point selected). Nominal supply pressure is the pressure measured at the first emitter from the supply end in metres head of water.

5.4 Simulated results obtained using Eaucadi and Hydrocalc software packages

As the Eaucadi and Hydrocalc were selected for this research project, these software packages were configured using the characteristics of the experimental dripline. To verify the correct parameterisation of these packages, the simulated and field measured results were calculated and compared. The field test site configurations were replicated in these packages and the results were obtained as follows.

5.4.1 Results from the replication of measured field configurations into the Eaucadi with water supply placed into the highest end

Following the methodology provided in Section 3.7.2, the results obtained are shown below in Figure 5.1.



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☑ Show Report

☑ Integrated ☑ Custom

Emitter 19

Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1

A 0.693 B 0.46

Kd 0.40 HW Coef 150.0 CV 0.000

Inlet Pressure 3.522 (m) Internal Diameter 14.199 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.453 (lph)

Lateral Length 100 (m) EU 91.838 (%)

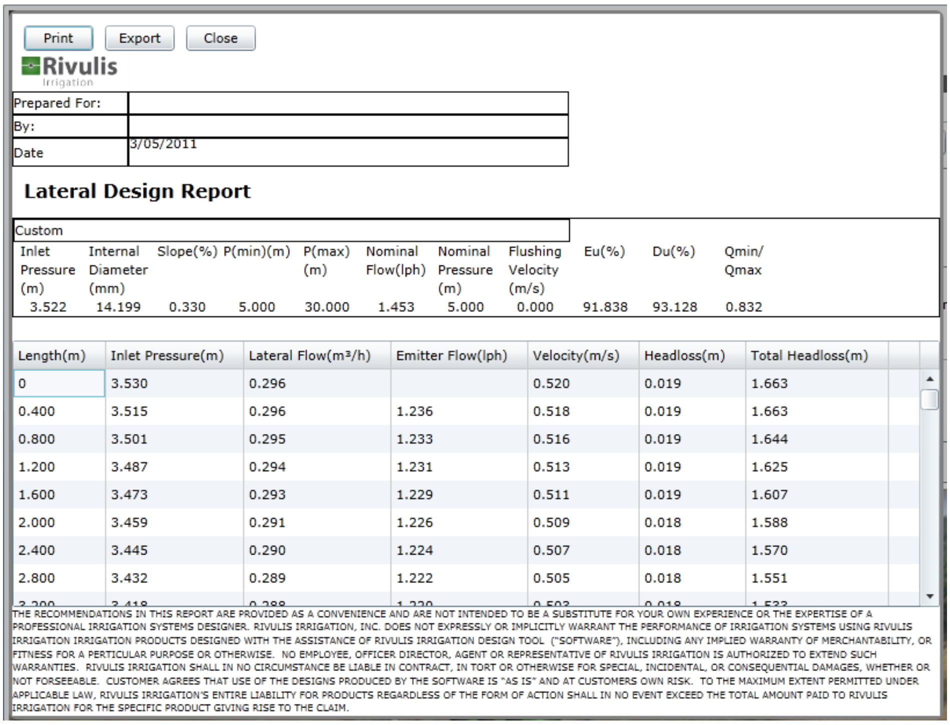
Max. Velocity 0.520 (m/s) Total Headloss 1.663 (m) Total Flow 0.296 (m³/h) Du 0.931 Pmin 2.670 Pmax 3.985

Figure 5.1: Lateral design tab showing all the specifications and design parameters selected to replicate Test No. 1.

- Nominal pressure: 5.00 m
- Nominal flow:1.453 L/h
- *Eu*: 91.838%
- Maximum velocity: 0.520 m/sec
- Total head loss: 1.663 m

- Total flow: 0.296 m^3/hr
- *Du*: 93.1%
- Minimum pressure: 2.670 m
- Maximum pressure: 3.985 m

The lateral design report was exported as a spread sheet to get further results as shown in Figure 5.2. The design report provides the inlet pressure (m), lateral flow (m^3/hr), emitter flow (L/h), velocity (m/sec), head loss (m), and total head loss (m) at each emitter along the length of dripline. A similar procedure has been repeated for Test No. 2, 3, 4, 5, and 6 for different inlet pressures using the water supply into the highest end of dripline. These outcomes have been further compared with the measured and other software results.



Prepared For:	
By:	
Date	3/05/2011

Lateral Design Report

Custom

Inlet Pressure (m)	Internal Diameter (mm)	Slope(%)	P(min)(m)	P(max) (m)	Nominal Flow(lph)	Nominal Pressure (m)	Flushing Velocity (m/s)	Eu(%)	Du(%)	Qmin/ Qmax
3.522	14.199	0.330	5.000	30.000	1.453	5.000	0.000	91.838	93.128	0.832

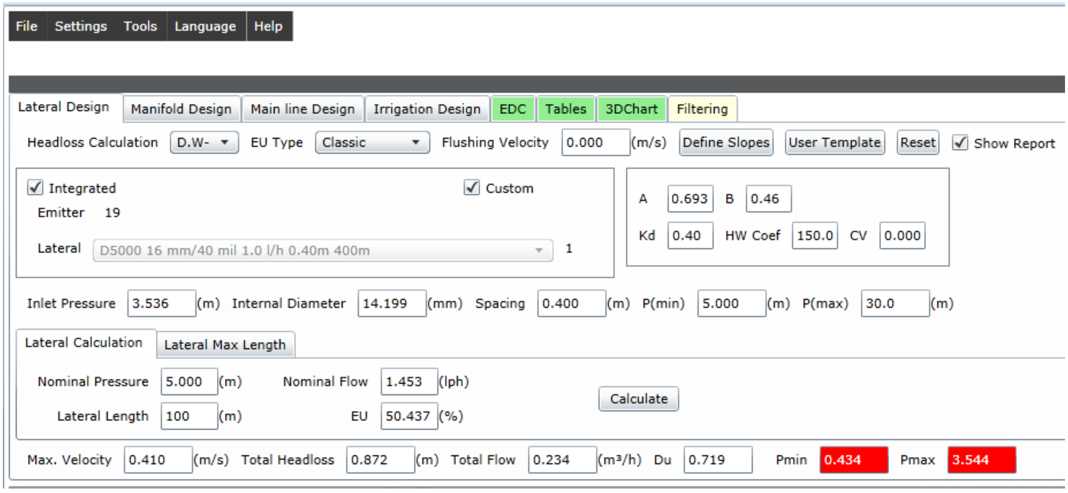
Length(m)	Inlet Pressure(m)	Lateral Flow(m³/h)	Emitter Flow(lph)	Velocity(m/s)	Headloss(m)	Total Headloss(m)
0	3.530	0.296		0.520	0.019	1.663
0.400	3.515	0.296	1.236	0.518	0.019	1.663
0.800	3.501	0.295	1.233	0.516	0.019	1.644
1.200	3.487	0.294	1.231	0.513	0.019	1.625
1.600	3.473	0.293	1.229	0.511	0.019	1.607
2.000	3.459	0.291	1.226	0.509	0.018	1.588
2.400	3.445	0.290	1.224	0.507	0.018	1.570
2.800	3.432	0.289	1.222	0.505	0.018	1.551

Figure 5.2: Lateral design final report, providing individual emitter's distance from the lateral head, inlet pressure, lateral flow rate, emitter flow rate, velocity, head loss and total head loss.

5.4.2 Results from the replication of measured field configurations into the Eaucadi with the water supply placed into the lowest end of the dripline

Following the methodology provided in Section 3.7.3, the results were obtained as shown in Figure 5.3. The results were obtained for later analysis.

- Nominal pressure: 5.00 m
- Nominal flow: 1.453 L/h
- *Eu*: 50.437%
- Maximum velocity: 0.410 m/sec
- Total head loss: 0.872 m
- Total flow: 0.234 m^3/hr
- *Du*: 71.9%
- Minimum pressure: 0.434 m
- Maximum pressure: 3.544 m



Headloss Calculation D.W- EU Type Classic Flushing Velocity 0.000 (m/s) ☑ Show Report

☑ Integrated ☑ Custom
Emitter 19
Lateral D5000 16 mm/40 mil 1.0 l/h 0.40m 400m 1

A 0.693 B 0.46
Kd 0.40 HW Coef 150.0 CV 0.000

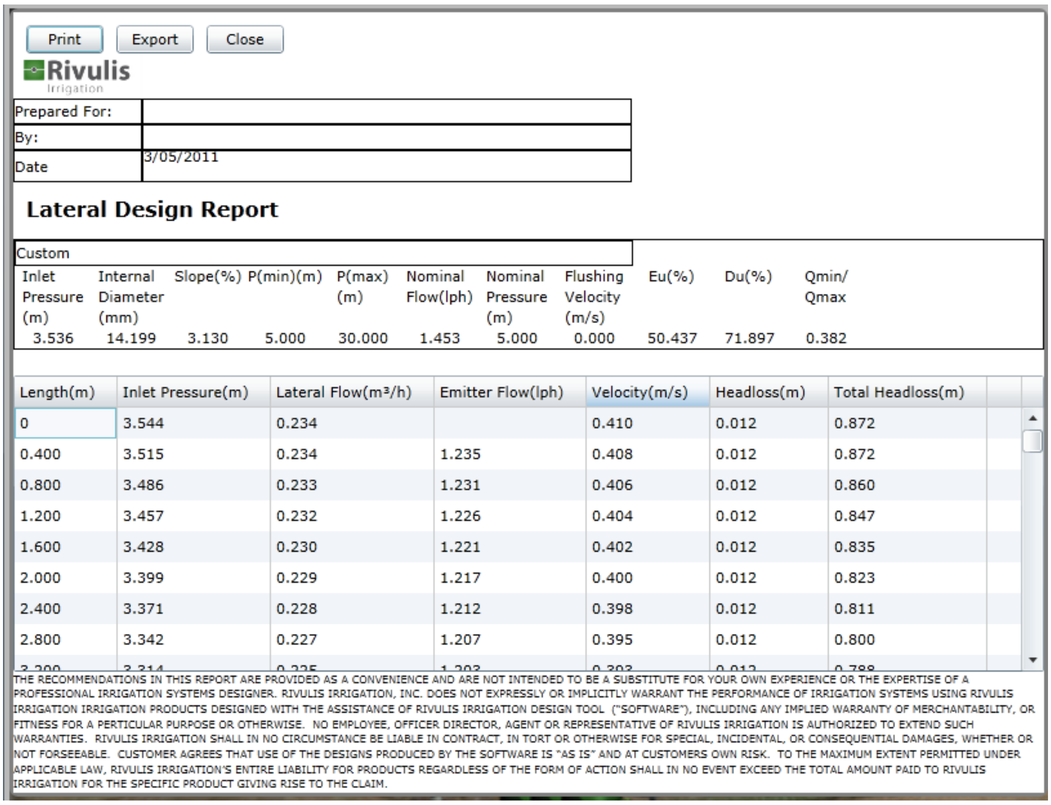
Inlet Pressure 3.536 (m) Internal Diameter 14.199 (mm) Spacing 0.400 (m) P(min) 5.000 (m) P(max) 30.0 (m)

Nominal Pressure 5.000 (m) Nominal Flow 1.453 (lph)
Lateral Length 100 (m) EU 50.437 (%)

Max. Velocity 0.410 (m/s) Total Headloss 0.872 (m) Total Flow 0.234 (m^3/h) Du 0.719 Pmin 0.434 Pmax 3.544

Figure 5.3: Lateral design tab showing all the specifications and design parameters selected to replicate Test No. 7.

The lateral design reports have been exported as a spread sheet to get further results. The design report (Figure 5.4) provides the inlet pressure (m), lateral flow (m^3/hr), emitter flow (L/h), velocity (m/sec), head loss (m), and total head loss (m) at each emitter along the length of dripline. Repeating a similar procedure, results for Test No. 8, 9, 10, and 11 with different inlet pressures using the water supply at the lowest end have been obtained. These outcomes will be compared with the measured, and the results from other software results.



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By:	
Date	3/05/2011

Lateral Design Report

Custom

Inlet Pressure (m)	Internal Diameter (mm)	Slope(%)	P(min)(m)	P(max) (m)	Nominal Flow(lph)	Nominal Pressure (m)	Flushing Velocity (m/s)	Eu(%)	Du(%)	Qmin/ Qmax
3.536	14.199	3.130	5.000	30.000	1.453	5.000	0.000	50.437	71.897	0.382

Length(m)	Inlet Pressure(m)	Lateral Flow(m³/h)	Emitter Flow(lph)	Velocity(m/s)	Headloss(m)	Total Headloss(m)
0	3.544	0.234		0.410	0.012	0.872
0.400	3.515	0.234	1.235	0.408	0.012	0.872
0.800	3.486	0.233	1.231	0.406	0.012	0.860
1.200	3.457	0.232	1.226	0.404	0.012	0.847
1.600	3.428	0.230	1.221	0.402	0.012	0.835
2.000	3.399	0.229	1.217	0.400	0.012	0.823
2.400	3.371	0.228	1.212	0.398	0.012	0.811
2.800	3.342	0.227	1.207	0.395	0.012	0.800

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Figure 5.4: Lateral design final report, providing individual emitter distance from the lateral head, inlet pressure, lateral flow rate, emitter flow rate, velocity, head loss and total head loss.

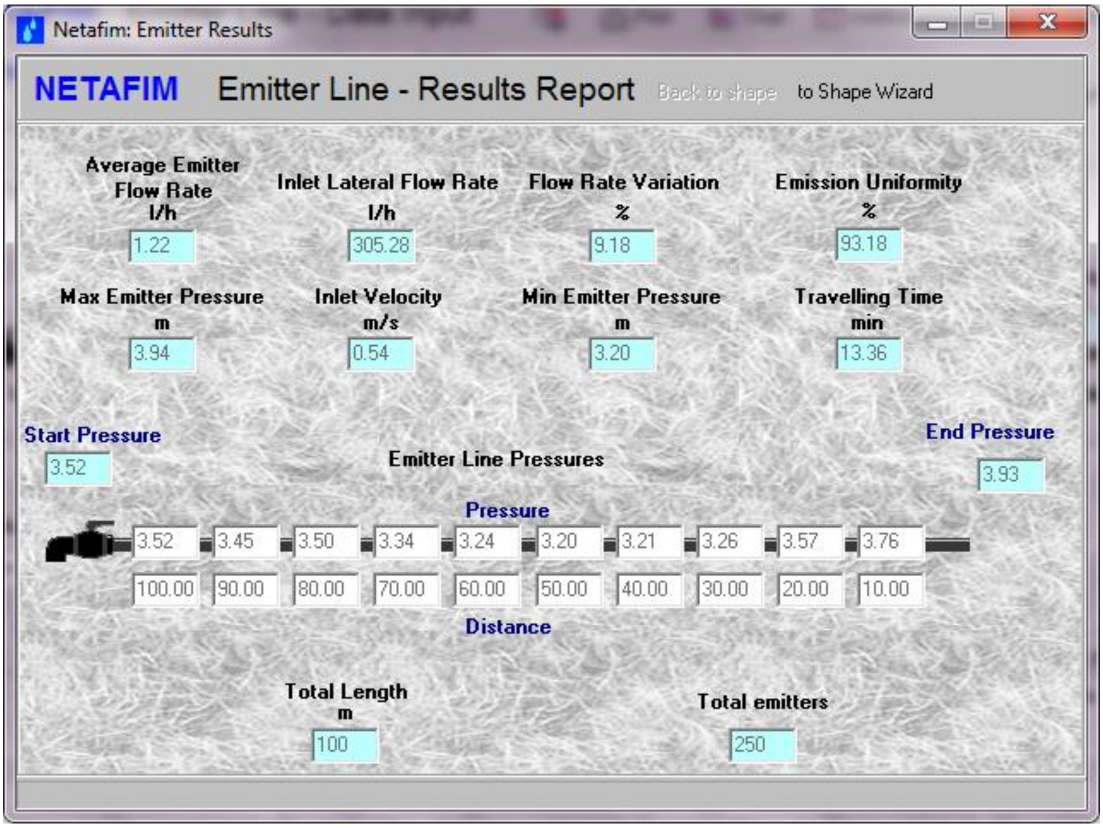
5.4.3 Results from the replication of measured field configurations in the Hydrocalc with water supply placed into the highest end of the dripline

Using a methodology provided in the Section 3.8.2, the results were calculated as shown in Figure 5.5.

1. Average emitter flow rate: 1.22 L/h
2. Inlet lateral flow rate: 305.28 L/h
3. Flow rate variation: 9.18%

4. Emission uniformity: 93.18%
5. Max emitter pressure: 3.94 m
6. Min emitter pressure: 3.20 m
7. Inlet velocity: 0.54 m/s
8. Travelling time: 13.36 min
9. It also gives the start and end pressure i.e. 3.52 m and 3.93 respectively.

The results also provided emitter pressures at ten nominal distances down the dripline as shown in Figure 5.5.



Average Emitter Flow Rate l/h: 1.22

Inlet Lateral Flow Rate l/h: 305.28

Flow Rate Variation %: 9.18

Emission Uniformity %: 93.18

Max Emitter Pressure m: 3.94

Inlet Velocity m/s: 0.54

Min Emitter Pressure m: 3.20

Travelling Time min: 13.36

Start Pressure: 3.52

End Pressure: 3.93

Emitter Line Pressures

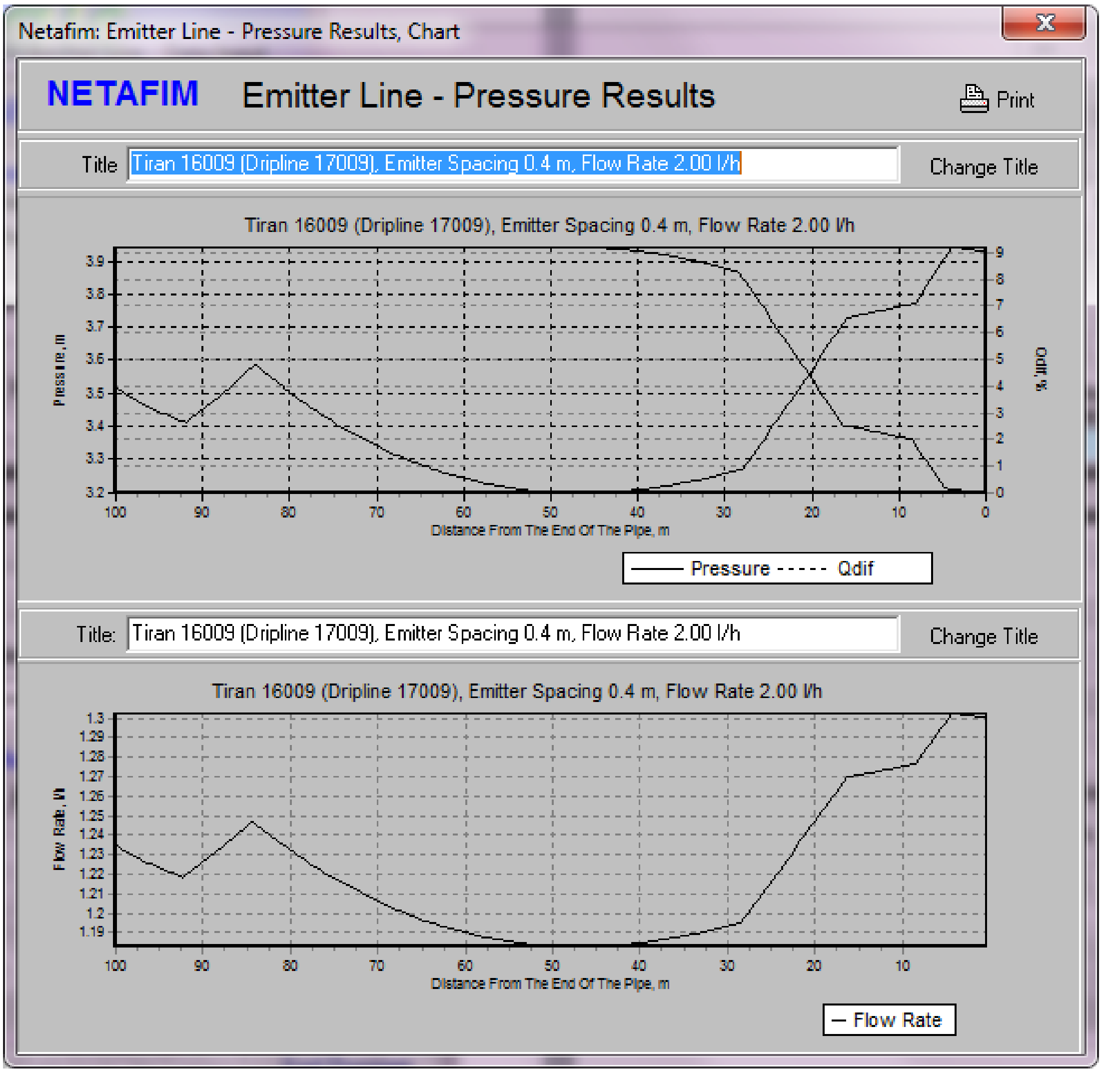
Pressure	3.52	3.45	3.50	3.34	3.24	3.20	3.21	3.26	3.57	3.76
Distance	100.00	90.00	80.00	70.00	60.00	50.00	40.00	30.00	20.00	10.00

Total Length m: 100

Total emitters: 250

Figure 5.5: Emitter line result report showing all the results obtained.

The plots of emitter pressure (m) and emitter flow rate (L/h) against distance from the end of the pipe (m) were obtained for emitter line pressure results as shown in Figure 5.6 for the given data input.



Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Figure 5.6: Graph of emitter line plotting pressure (m) and flow rate (l/h) against the distance from the end of the pipe (m) using water supply into the highest end of the dripline.

The results were saved into the spreadsheets to compare with the measured field results, and similar results were obtained for field Test No. 2, 3, 4, 5, and 6.

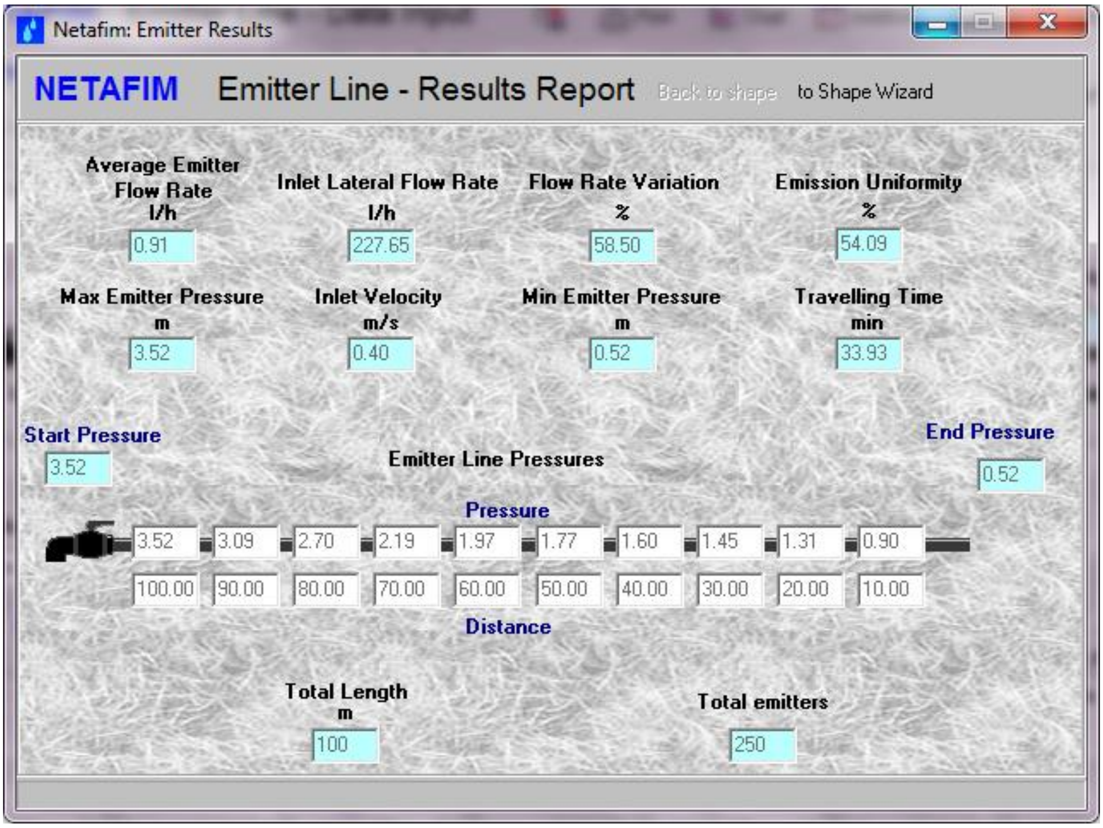
5.4.4 Results from the replication of measured field configurations in the Hydrocalc with water supply placed into the lowest end of the dripline

Using a methodology provided in the Section 3.8.3, following results were measured.

1. Average emitter flow rate: 0.91 L/h
2. Inlet lateral flow rate: 227.65 L/h
3. Flow rate variation: 58.50%

4. Emission uniformity: 54.09%
5. Max emitter pressure: 3.52 m
6. Min emitter pressure: 0.52 m
7. Inlet velocity: 0.40 m/s
8. Travelling time: 33.93 min

The results also provided emitter pressures at ten positions and the corresponding distances from the inlet as shown in Figure 5.7.



Emitter Line - Results Report

Average Emitter Flow Rate l/h: 0.91
Inlet Lateral Flow Rate l/h: 227.65
Flow Rate Variation %: 58.50
Emission Uniformity %: 54.09
Max Emitter Pressure m: 3.52
Inlet Velocity m/s: 0.40
Min Emitter Pressure m: 0.52
Travelling Time min: 33.93
Start Pressure: 3.52
End Pressure: 0.52

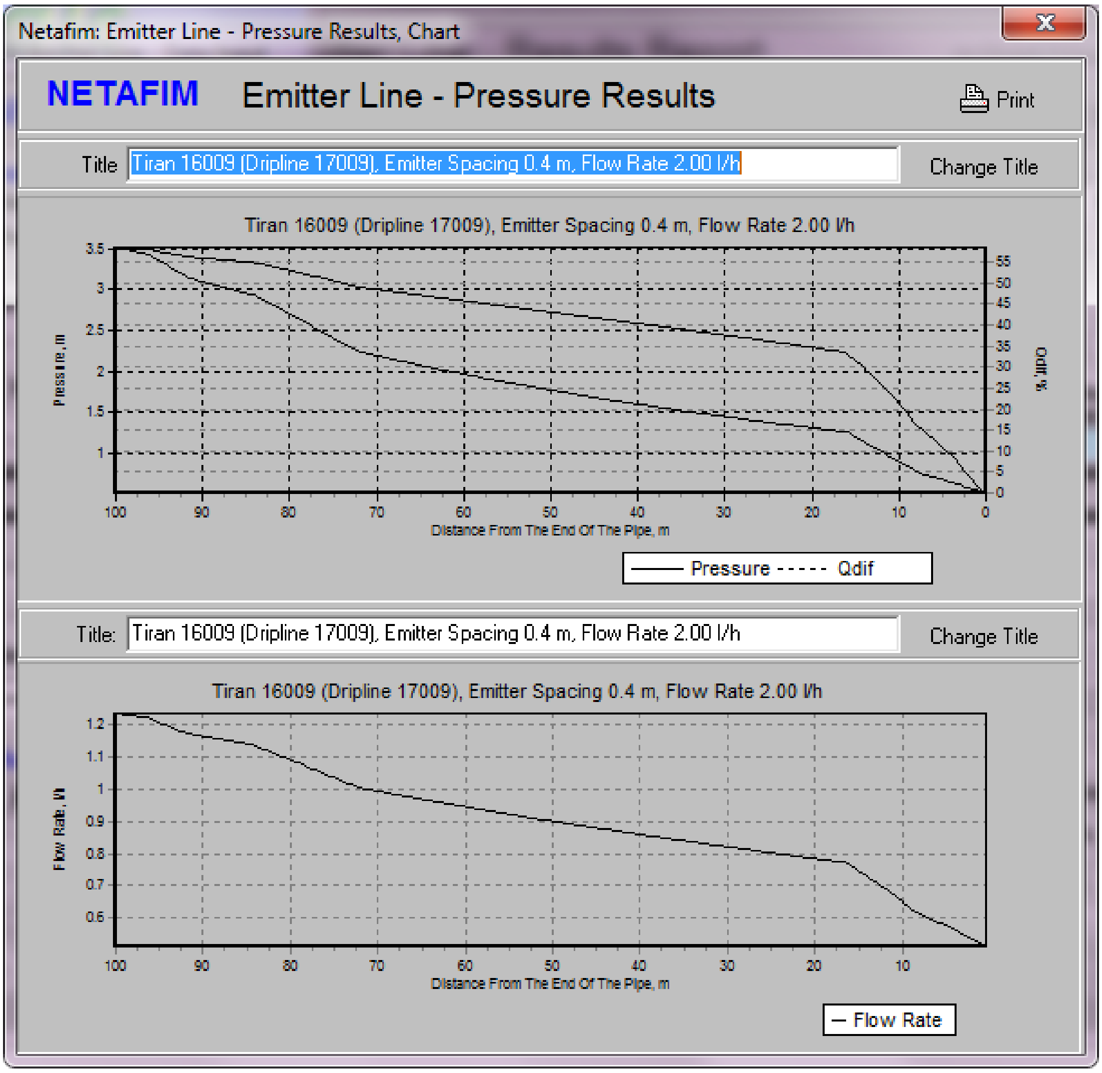
Emitter Line Pressures

Pressure	3.52	3.09	2.70	2.19	1.97	1.77	1.60	1.45	1.31	0.90
Distance	100.00	90.00	80.00	70.00	60.00	50.00	40.00	30.00	20.00	10.00

Total Length m: 100
Total emitters: 250

Figure 5.7: Emitter line result report showing the additional results obtained.

The plots of emitter pressure (m) and emitter flow rate (L/h) against distance from the end of the pipe (m) were obtained in the emitter line pressure results with water supply placed into the lowest end as shown in Figure 5.8. The chart also shows the changes of the pressure and flow rate variation along the line. The chart shows the increase in pressure and flow rate along the length of dripline.



Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Title: Tiran 16009 (Dripline 17009), Emitter Spacing 0.4 m, Flow Rate 2.00 l/h

Figure 5.8: Graphs of emitter line plotting pressure (m) and flow rate (l/h) against the distance from the end of the pipe (m) using water supply into the lowest end of the dripline.

Similar results were also obtained for the conditions tested in field Test No. 8, 9, 10 and 11. The results were saved into the spreadsheets to further compare with the measured field results, and with similar results from the Eaucadi software as follows.

5.5 Results from the comparison of measured and simulated results

To analyse if the modern computer software packages can be parameterised correctly to match the hydraulic performance of drip irrigation systems in the Punjab region of Pakistan, measured and simulated results are compared in terms of emitter discharges, emitter pressures, performance measures, flow rates and derivation of constant k and exponent x for the characterisation and selection of emitter.

5.5.1 Comparison of measured and simulated emitter discharges

From the tests of volume captured for different nominal supply pressures as described in Section 3.6.2.4, plots of emitter discharges over distance from the supply end have been developed. These are presented in the following sub-sections.

Plots between emitter discharge (L/h) and the distance from supply end (m) have been drawn for the 11 number of field tests with different nominal supply pressures for water supply into the highest end and the lowest end of the dripline. Along with the measured field test results, results obtained from the Eaucadi and Hydrocalc software packages have been plotted on the charts to display the results obtained from measured field measured results and the simulated results.

5.5.1.1 Comparison of measured and simulated emitter discharge for the water supply into the highest end

Plots of emitter discharge (L/h) and elevation compare to the distance from supply end (m) have generally configured with different supply pressure at highest and lowest end of the dripline. Figure 5.9 shows a plot of emitter discharge (L/h) and the distance from supply end (m) with the supply pressure of 3.515 m (5.0 psi) and the water supply into the highest end of the dripline for Test No. 1. Emitter discharges have been taken on left vertical axis, elevation on right vertical axis and distance from the supply end on horizontal axis.

5.5.1.1.1 Test No. 1

Figure 5.9 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) for Test No. 1 with a supply pressure of 3.52 metres (5.0 psi) using a water supply into the highest end of the dripline.

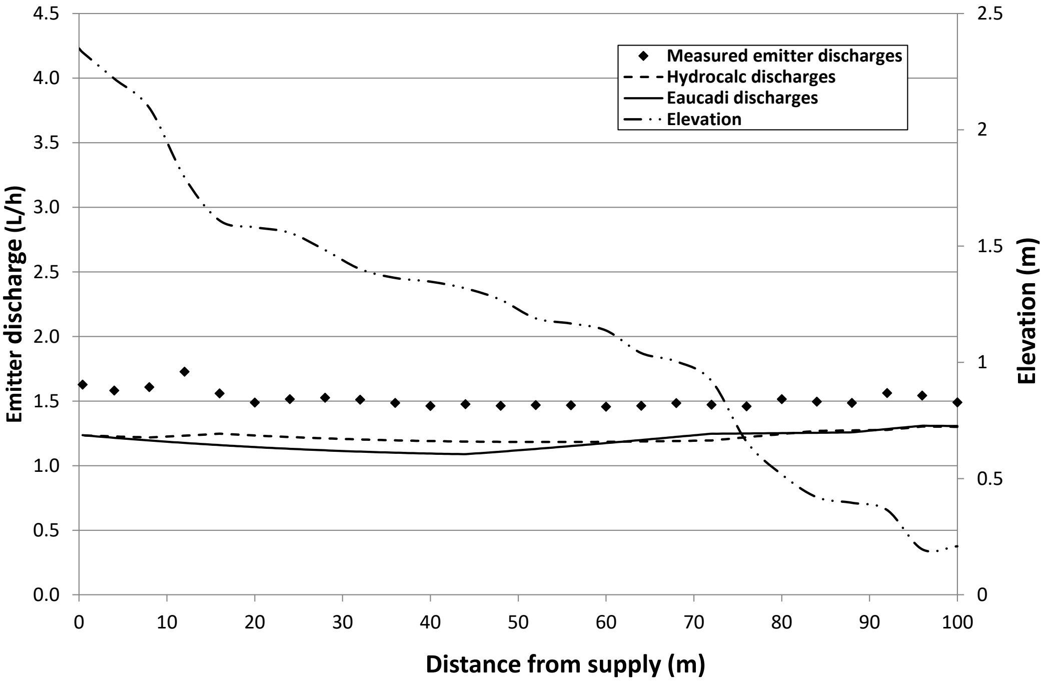


Figure 5.9: A graph between emitter discharge and the distance from the supply for Test No. 1 with water supply placed into the highest end of the dripline, with a nominal supply pressure of 3.52 m pressure head (5.0 psi).

Figure 5.9 indicates that the measured results have emitter discharges much higher than the discharges predicted from simulated results. 60 m length of pipe the average Eaucadi emitter discharges results are roughly 6% lower than the Hydrocalc results but after 60 m length, the two models produced precisely identical results. The results of average measured emitter discharges at trial site are approximately 25% higher than the discharges from simulated results for the same distances from supply. The highest emitter discharge measured is 1.73 L/h at 12 m from the supply end.

5.5.1.1.2 Test No. 2

Figure 5.10 shows a plot of emitter discharge (L/h) compared to the distance from supply end (m) with the supply pressure of 9.14 m (13 psi) using a water supply into the highest end of the dripline for Test No. 2.

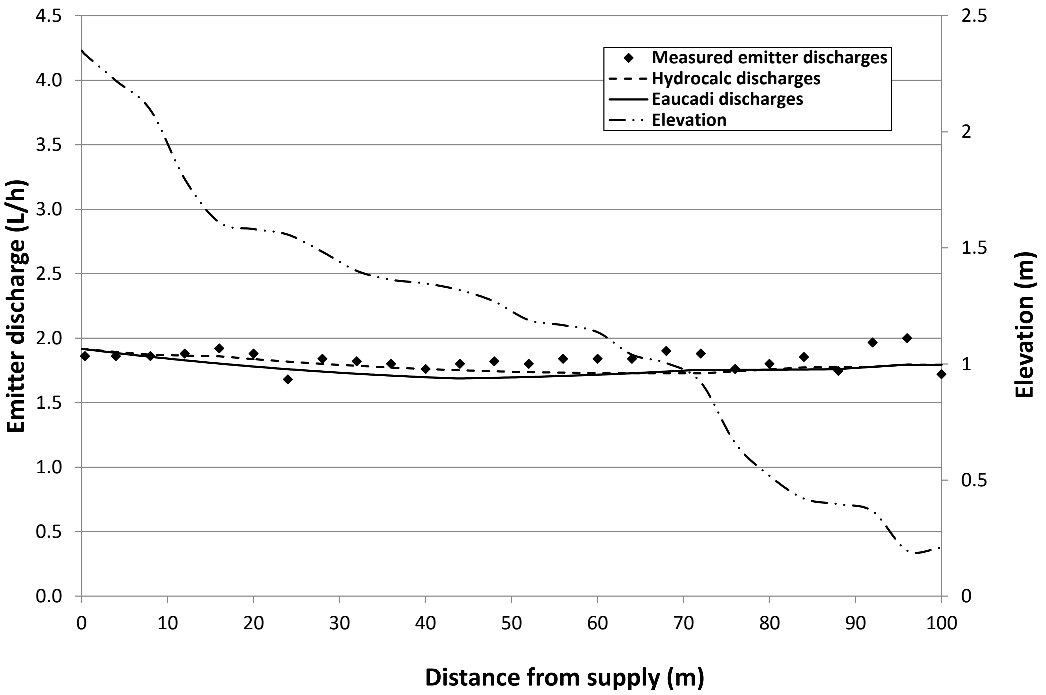


Figure 5.10: A graph between emitter discharge and the distance from the supply for Test No. 2 with water supply placed into the highest end of the dripline, and a nominal supply pressure of 9.14 m pressure head (13 psi).

Figure 5.10 explains that the measured field test results have a general trend to match the results predicted by the Hydrocalc software package and average emitter discharges in field are generally 1% higher than the Hydrocalc results. for the first 60 m length of pipe, the Eaucadi results are roughly 3% lower than the Hydrocalc results and after 60 m length, the results are closer matched between the models. The measured emitter discharges are generally showing increasing trend as the distance increases from the supply end and the maximum discharge recorded as 2 L/h at 96 m from the supply end. The emitter discharges are tending to increase as the elevation decreases along the dripline.

5.5.1.1.3 Test No. 3

Figure 5.11 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) with a supply pressure of 10.62 m (15.1 psi) using a water supply into the highest end of the dripline for Test No. 3.

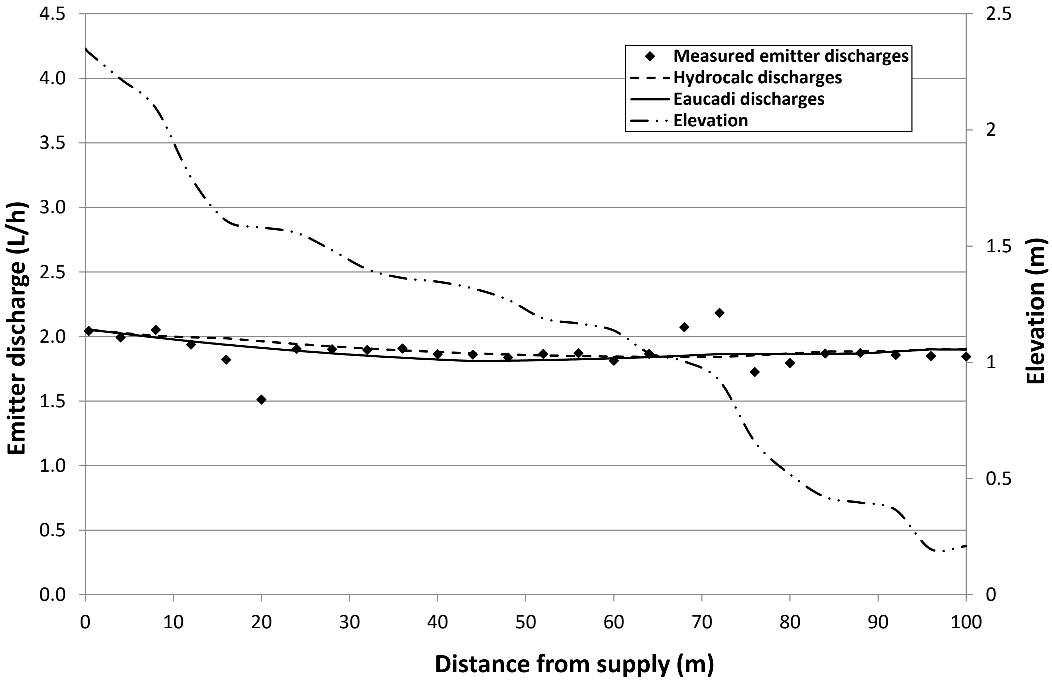


Figure 5.11: A graph between emitter discharge and the distance from the supply for Test No. 3 with water supply placed into the highest end of the dripline, and a nominal supply pressure of 10.62 m pressure head (15.1 psi).

The measured field measured results have a general trend to match the simulated results as shown in Figure 5.11. The results from the Hydrocalc and Eaucadi are following the same trend. Only the discharge of emitters at 16, 20, 76 and 80 m from the supply end are lower than the discharges predicted by the simulated results at the same distance from supply end. Similarly, the measured discharges at 68 and 72 m from the supply end are much higher than the discharges predicted by the simulated results. The highest and lowest measured emitter discharges recorded as 2.46 L/h and 1.88 L/h respectively.

5.5.1.1.4 Test No. 4

Figure 5.12 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) with a supply pressure of 10.55 m (15.0 psi) using the water supply into the highest end of the dripline for Test No. 4.

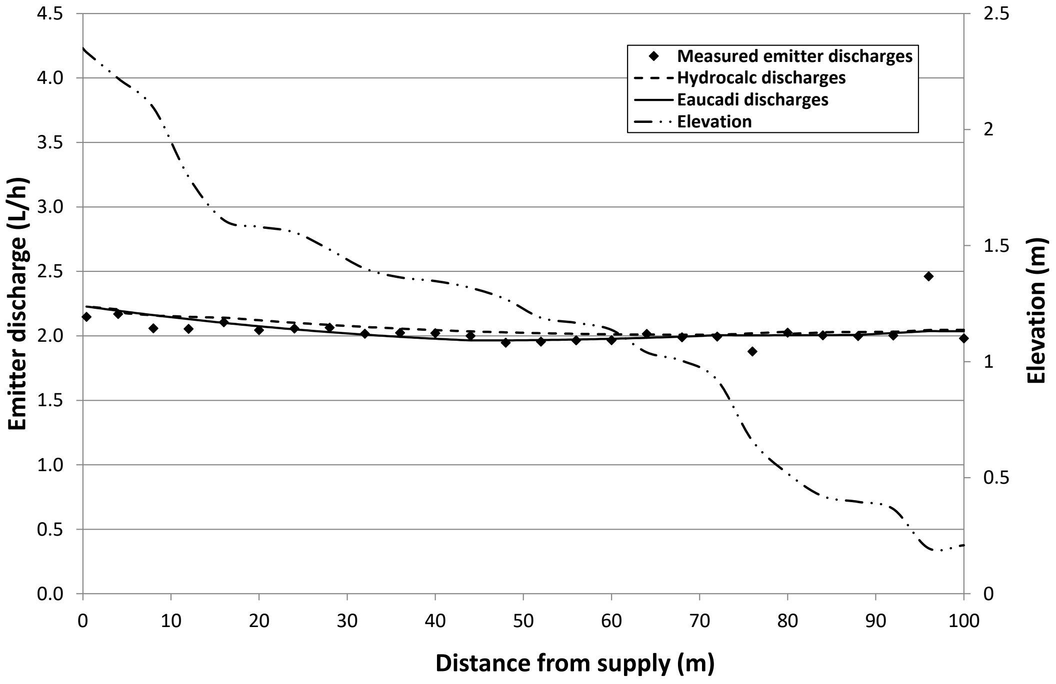


Figure 5.12: A graph between emitter discharge and the distance from the supply for Test No. 4 with water supply placed into the highest end of the dripline, and a nominal supply pressure of 10.55 m pressure head (15.0 psi).

Figure 5.12 shows that the measured field test results have a general trend to match with simulated results. It is observed that the measured emitter discharges at 8, 12 and 76 m are lower than the simulated results while at 96 m is higher than the simulated results. The simulated results from the two models are reasonably identical to each other. The highest and lowest emitter discharges have been recorded at 96 m and 76 m from the supply end i.e. 2.46 L/h and 1.88 L/h respectively. The measured emitter discharges are quite linear along the elevation change from the supply end.

5.5.1.1.5 Test No. 5

Figure 5.13 shows a plot of emitter discharge (L/h) compared to the distance from the end (m) with a supply pressure of 18.63 m (26.5 psi) using the water supply into the highest end of the dripline for Test No. 5.

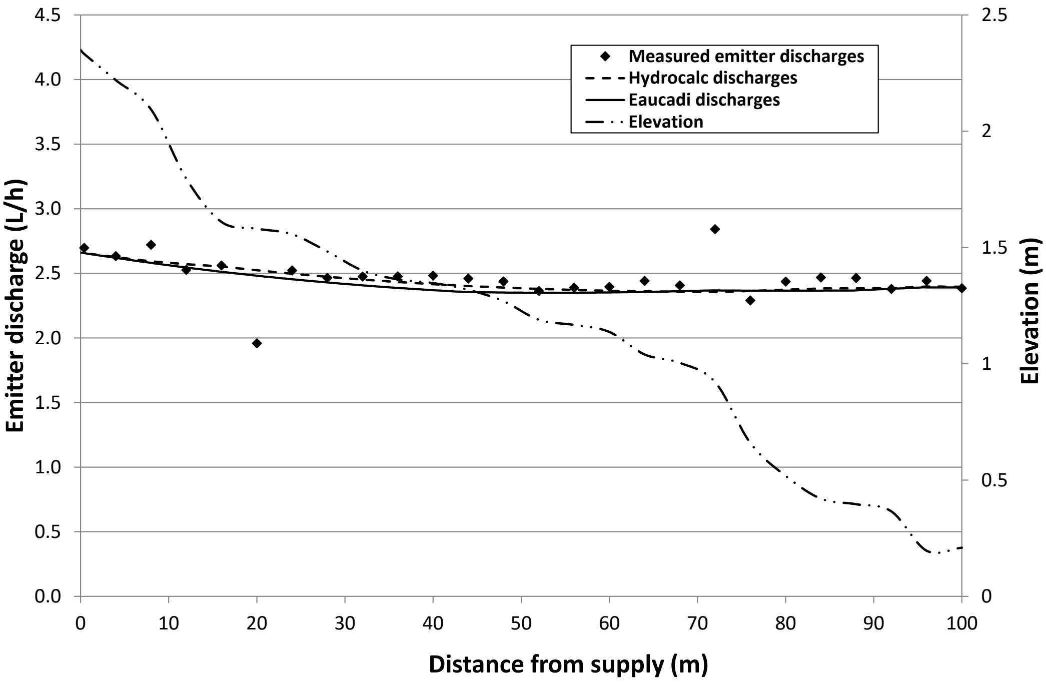


Figure 5.13: A graph between emitter discharge and the distance from the supply for Test No. 5 with water supply placed into the highest end of the dripline, and a nominal supply pressure of 18.63 m pressure head (26.5 psi).

The measured results from the above Figure 5.13 seem to be in a good agreement with the simulated results obtained from the software packages. The unusual emitter discharges are observed at 20 metres and 72 m from the supply end, as the lowest and highest emitter discharge i.e. 1.96 L/h and 2.84 L/h respectively. The average measured results are approximately 1% higher than the Hydrocalc results and approximately 2% higher than the Eaucadi results. The emitter discharges seem to be decreasing along the dripline as the elevation changes.

5.5.1.1.1 Test No. 6

Figure 5.14 shows a plot of emitter discharge (L/h) compared to the distance from supply end (m) with a supply pressure of 27.07 m (38.5 psi) and the water supply into the highest end of the dripline for Test No. 6.

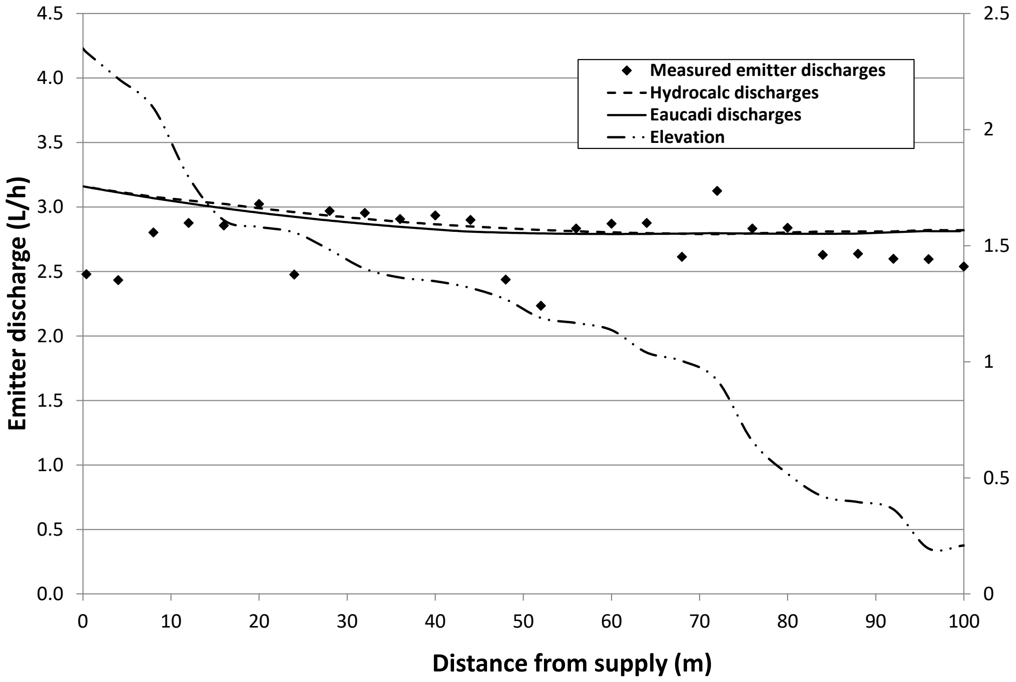


Figure 5.14: A graph between emitter discharge and the distance from the supply for Test No. 6 with water supply placed into the highest end of the dripline, and a nominal supply pressure of 27.07 m pressure head (38.5 psi).

Figure 5.14 shows many variations between measured and simulated results. The plots of measured emitter discharges show extremely scattered results throughout the field. The results of measured emitter discharges are highly scattered and not matching the simulated results due to heavy wind during the test, which means it was difficult to accurately capture the volume from each emitter in the catch cans. The average measured emitter discharges are approximately 5% higher than the average Hydrocalc results, while the Eaucadi results are like the Hydrocalc results i.e. approximately 0.6% lower than the Hydrocalc results. The maximum and minimum emitter discharge has been recorded at 72 m and 52 m i.e., 3.13 L/h and 2.23 L/h respectively.

5.5.1.2 Comparison of measured and simulated emitter discharge for the water supply at the lowest end

5.5.1.2.1 Test No. 7

Figure 5.15 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) with a supply pressure of 3.52 m (5.0 psi) using the water supply at the lowest end of the dripline for Test No. 7.

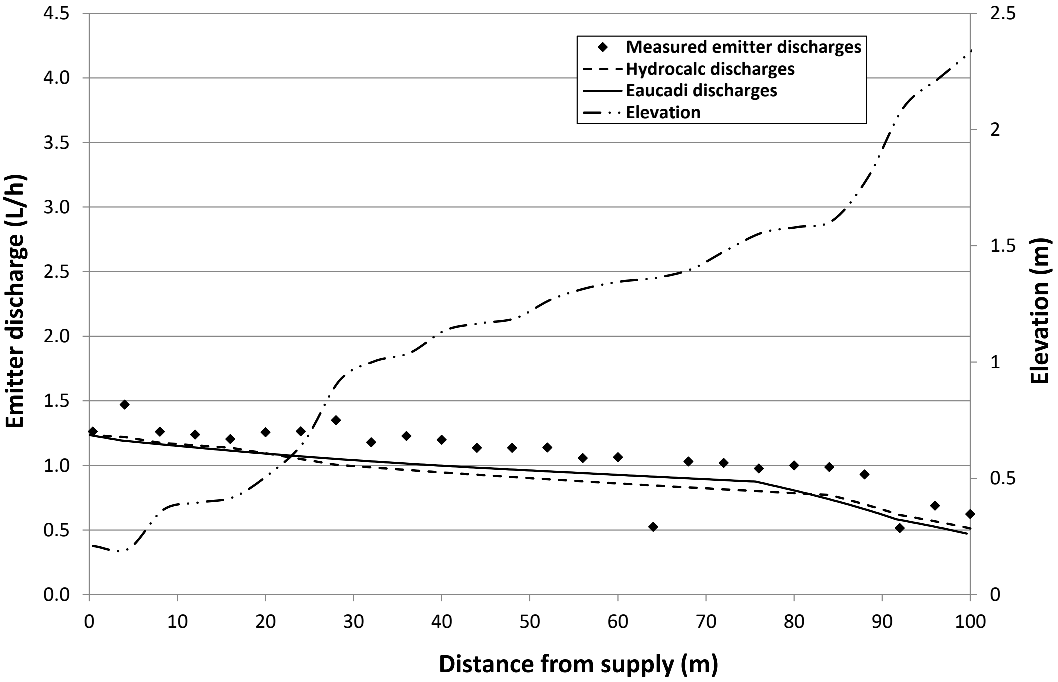


Figure 5.15: A graph between emitter discharge and the distance from the supply for Test No. 7 with water supply placed into the lowest end of the dripline, and a nominal supply pressure of 3.52 m pressure head (5.0 psi).

Figure 5.15 shows that the measured field test results have emitter discharges much higher than the discharges predicted from simulated results. The Hydrocalc and Eaucadi results generally follow the same trend and the average emitter discharge recorded by the Eaucadi is approximately 3% higher than the Hydrocalc results. The measured emitter discharges recorded are roughly 14% and 17% higher than the Eaucadi and Hydrocalc average emitter discharge's respectively. Out of total twenty-six tests stations 24 have a measured emitter discharges higher than predicted, while at two the measured emitter discharge is lower than the simulated results. The emitter discharge is showing a decreasing trend along the dripline as the elevation increases from the supply end. The highest and lowest emitter discharges are recorded at 4 m and 64 m i.e. 1.47 L/h and 0.52 L/h respectively.

5.5.1.2.1 Test No. 8

Figure 5.16 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) with a supply pressure of 7.73 m (11.0 psi) using the water supply at the lowest end of the dripline for Test No. 8.

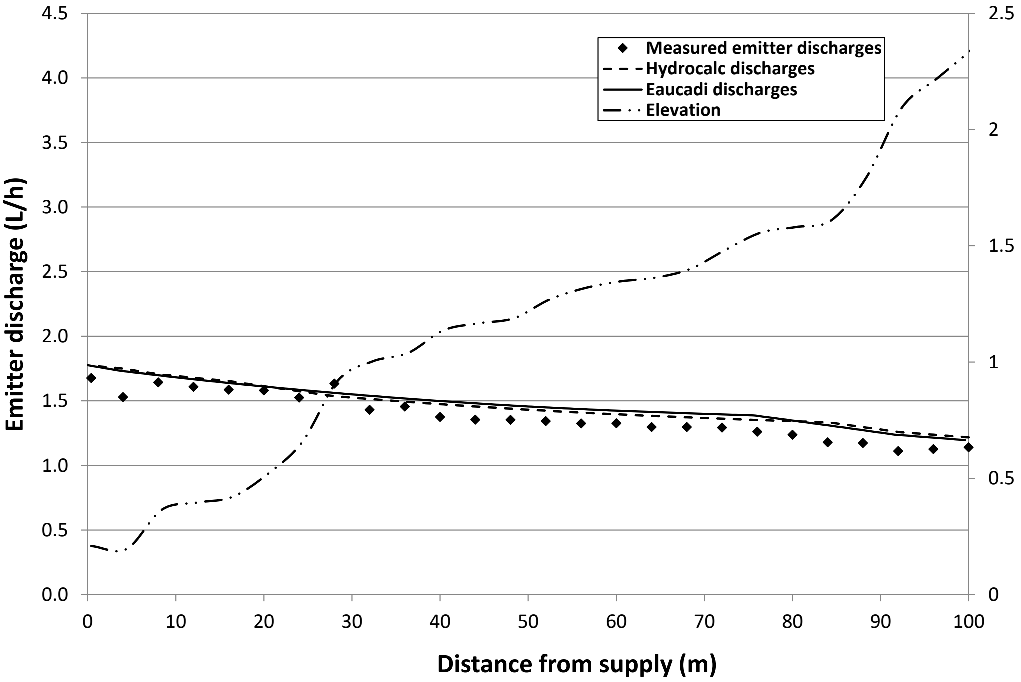


Figure 5.16: A graph between emitter discharge and the distance from the supply for Test No. 8 with water supply placed into the lowest end of the dripline, and a nominal supply pressure of 7.73 m pressure head (11.0 psi).

It is clear from Figure 5.16, that the measured emitter discharges recorded in the field have a general trend to match the simulated results and approximately 7% lower than the Eaucadi results. The average emitter discharges recorded by the Hydrocalc are approximately 0.7%, lower than the Eaucadi Results. The measured emitter discharge is higher than the simulated results, at a single point 28 m from the supply end i.e. 1.63 L/h, while lower than simulated results at the rest of the length of dripline. The maximum and minimum emitter discharges were recorded as 1.68 L/h and 1.11 L/h at a distance 4 m and 92 m from the supply end respectively. The measured and simulated emitter discharges generally show a decreasing trend along the dripline as the elevation increases.

5.5.1.2.1 Test No. 9

Figure 5.17 shows a plot of emitter discharge (L/h) compare to the distance from the supply end (m) with the supply pressure of 14.91 m (21.2 psi) using the water supply into the highest end of the dripline for Test No. 9.

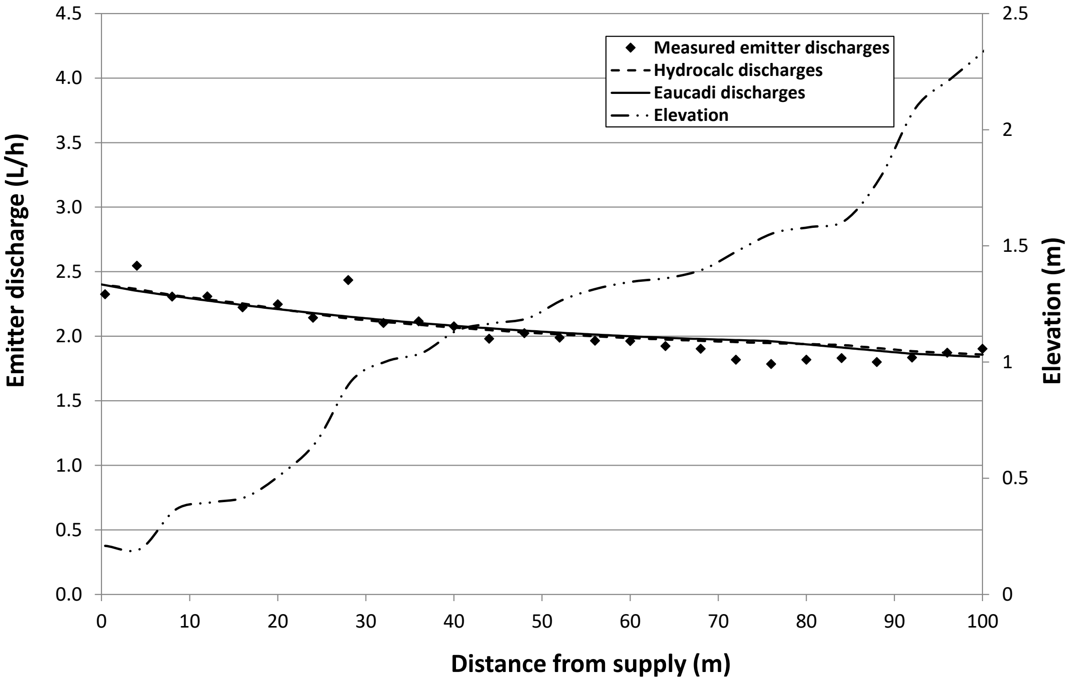


Figure 5.17: A graph between emitter discharge and the distance from the supply for Test No. 9 with water supply placed into the lowest end of the dripline, and a nominal supply pressure of 14.91 m pressure head (21.2 psi).

It is clear from the emitter discharge plots in Figure 5.17, that the measured emitter discharges recorded in the field have a general trend to match the simulated results. The measured emitter discharges are higher than the simulated results at 4 m and 28 m i.e. 2.55 L/h and 2.44 L/h respectively. Conversely, the measured emitter discharges from 68 m to 92 m are lower than the simulated results. Simulating the Eaucadi and Hydrocalc has produced equivalent results provided the approximate difference of 0.2%. Average measured emitter discharges are approximately 0.7% lower than simulated results. The maximum and minimum emitter discharges were recorded as 2.55 L/h and 1.78 L/h at a distance 4 m and 76 m from the supply end respectively. The emitter discharges generally show a decreasing trend along the dripline as the elevation increases.

5.5.1.2.1 Test No. 10

Figure 5.18 shows a plot of emitter discharge (L/h) compare to the distance from the supply end (m) with the supply pressure of 21.45 m (30.5 psi) using the water supply at the lowest end of the dripline for Test No. 10.

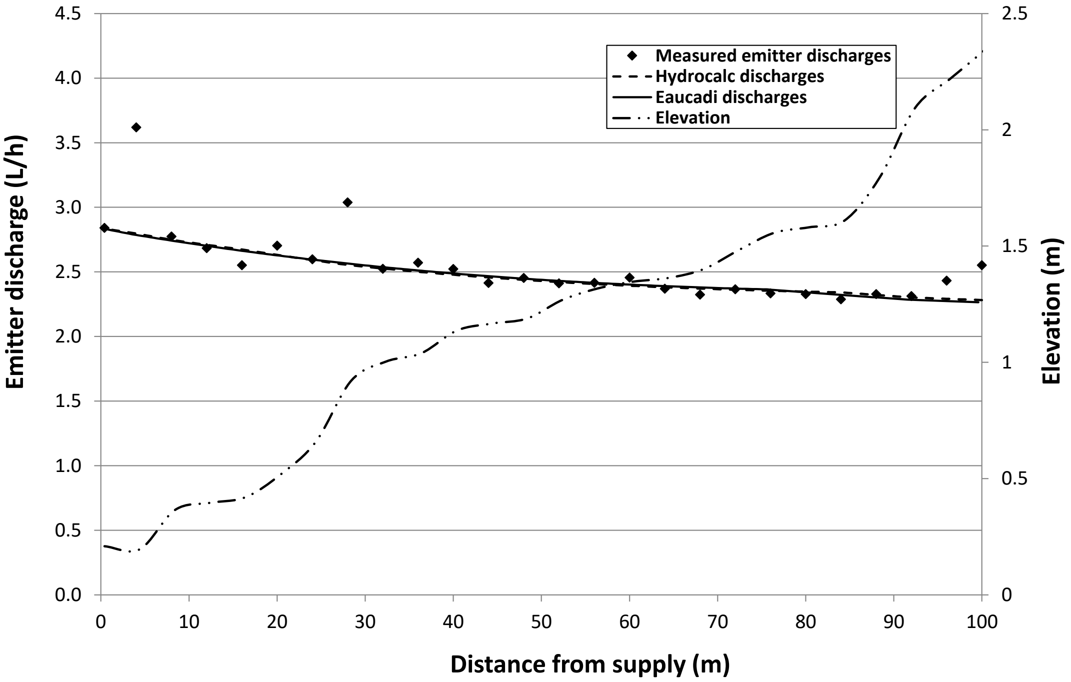


Figure 5.18: A graph between emitter discharge and the distance from the supply for Test No. 10 with water supply placed into lowest end of the dripline, and a nominal supply pressure of 21.45 m pressure head (30.5 psi).

The results evaluated from Figure 5.18, shows that the measured emitter discharges recorded in the field are in a good agreement with the simulated results. The measured emitter discharge at all test positions is the same as the simulated results, while in the 8 m length of dripline in the end of the dripline it shows an unexpected increasing trend. Highly unmatched measured emitter discharges have been recorded as 3.62 L/h and 3.04 L/h, at 4 m and 28 m from the supply end respectively which are likely caused by measurement error. The average measured emitter discharge recorded is roughly 4% higher than the Hydrocalc and Eaucadi results, while the Eaucadi and Hydrocalc and results vary roughly about 0.04%. The maximum and minimum emitter discharge were recorded as 3.62 L/h and 2.29 L/h at a distance 4 m and 84 metres from the supply end respectively. The emitter discharges generally show a decreasing trend along the dripline as the elevation increases except after 92 m the measured results shows increasing trend.

5.5.1.2.1 Test No. 11

Figure 5.19 shows a plot of emitter discharge (L/h) compared to the distance from the supply end (m) with the supply pressure of 31.99 m (45.5 psi) using the water supply at the lowest end of the dripline for Test No. 11.

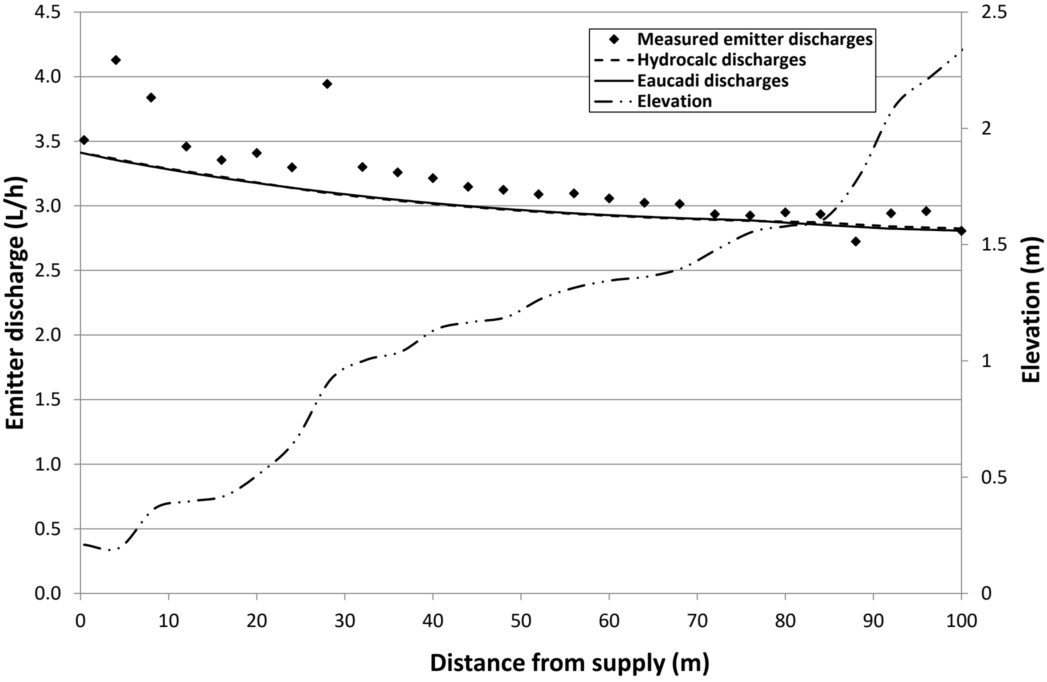


Figure 5.19: A graph between emitter discharge and the distance from the supply for Test No. 11 with water supply placed into the lowest end of the dripline, and a nominal supply pressure of 31.99 m pressure head (45.5 psi).

The plots from the Figure 5.19, shows that the measured emitter discharges are higher than the simulated emitter discharges along the length of dripline except at 88 m from the supply end. The Hydrocalc and Eaucadi results are reasonably similar and the average measured emitter discharge recorded is roughly 6% higher than the simulated results. Highly unmatched and higher measured emitter discharges have been recorded at 4, 8 and 28 m respectively from the supply end. The highest and lowest emitter discharge measured is 4.13 L/h and 2.72 L/h at 4 m and 88 m from the supply end respectively. The emitter discharge is showing a decreasing trend along the dripline as the elevation increases.

5.5.1.3 Results and discussion

A comparison of the measured and simulated emitter discharges provides the following observations.

The lowest and highest supply pressures at the inlet of the dripline, with the water supply at the highest end, were 3.5 m and 27 m, respectively. A pressure of 3.5 m and 32 m were the lowest and highest supply pressures for the tests where, water supply was into the lowest end of the dripline.

The emitter at a distance of 72 m from the supply end produced 17%, 20%, 12%, 29%, 81%, 13% ,18% and 27% higher emitter discharge than the simulated results in Test No. 3, 5, 6, 7, 8, 9, 10 and 11 respectively and the emitter at a distance of 96 m from the supply end also produced 12%, 21%, 24%, 8%, 30% and 32% higher emitter discharge rate than the simulated results in Test No 2, 4, 7, 9, 10 and 11 respectively. It was also noted that the emitter at a distance of 76 m from the supply end have produced 8% and 6% lower emitter discharge than simulated results in Test No. 3, 4, respectively and the emitter at a distance of 20 m from the supply end in Test No. 3 and 5, have also produced 21% and 22% lower emitter discharge than the simulated results. These results highlight the unusual performance of specific emitters, producing fairly high or low discharges, in all the tests.

In Test No. 2, 3, 4, and 5 with water supply placed into the highest end, and Test No. 8, 9 and 10 with water supply placed into the lowest end of the dripline, the measured and simulated emitter discharge results match quite reasonably. The percentage difference was merely 1% to 3% through all emitters in the above-mentioned tests. The difference between the measured and simulated emitter discharges was quite noticeable in Test No. 1, and 6 with water supply placed into the highest end and Test No. 7 and 11 with water supply placed into the lowest end. The failure of the packages to predict the flowrates in tests 1 and 7 indicate that either the models or the emitter characteristics tend to diverge from the correct value at low operating pressures. The scatter observed in tests 6 and 11 at high operating pressures indicate that similar inaccuracies occur at high pressures.

5.5.2 Comparison of measured emitter pressure and simulated results

The explanatory Table 5.2 given in Section 5.3.1, shows the detail of tests performed with different nominal supply pressure, general slope and the dates of the tests performed using the trial system.

From the tests performed in the field at different nominal supply pressures, as described in Section 3.6.2.5, plots of measured emitter pressures and the simulated results over the distance from the supply end have been developed. These results are presented in the following sub-sections.

5.5.2.1 Comparison of measured emitter pressure and simulated pressure results for the water supply into the highest end of the dripline

Plots of measured emitter pressure (m) and elevation compare to the distance from supply end (m) have generally configured with different nominal supply pressure at highest and lowest supply end of the dripline. Figure 5.20 shows a plot of measured emitter pressure (m) compared to the distance from supply end (m). The water supply provided into the highest end of the dripline with the nominal supply pressure of 3.52 m (5.0 psi) and the similar plots have been generated for all 11 tests as given in the subsections below. Measured emitter pressures have been taken on the left vertical axis, elevation on the right vertical axis and distance from the supply end on horizontal axis as shown in Figure 5.20.

5.5.2.1.1 Test No. 1

Figure 5.20 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 3.52 m (5.0 psi) using the water supply into the highest end of the dripline for Test No. 1.

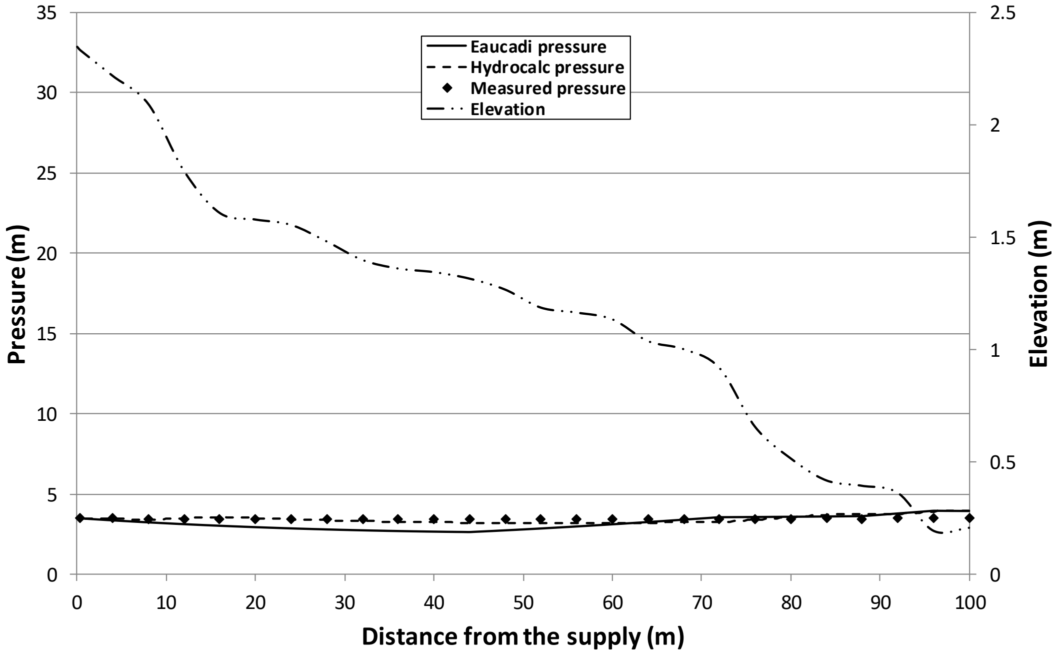


Figure 5.20: A graph between measured emitter pressure and distance from the supply end for Test No. 1 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 3.52 m (5.0 psi).

Figure 5.20 indicates no significant difference between measured pressure results and simulated results. While the Hydrocalc results are roughly, 6% higher than the Eaucadi results and the measured pressure results are roughly 0.34% higher than the Hydrocalc results.

5.5.2.1.1 Test No. 2

Figure 5.21 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 9.14 m (13.0 psi) using the water supply into the highest end of the dripline for Test No. 2.

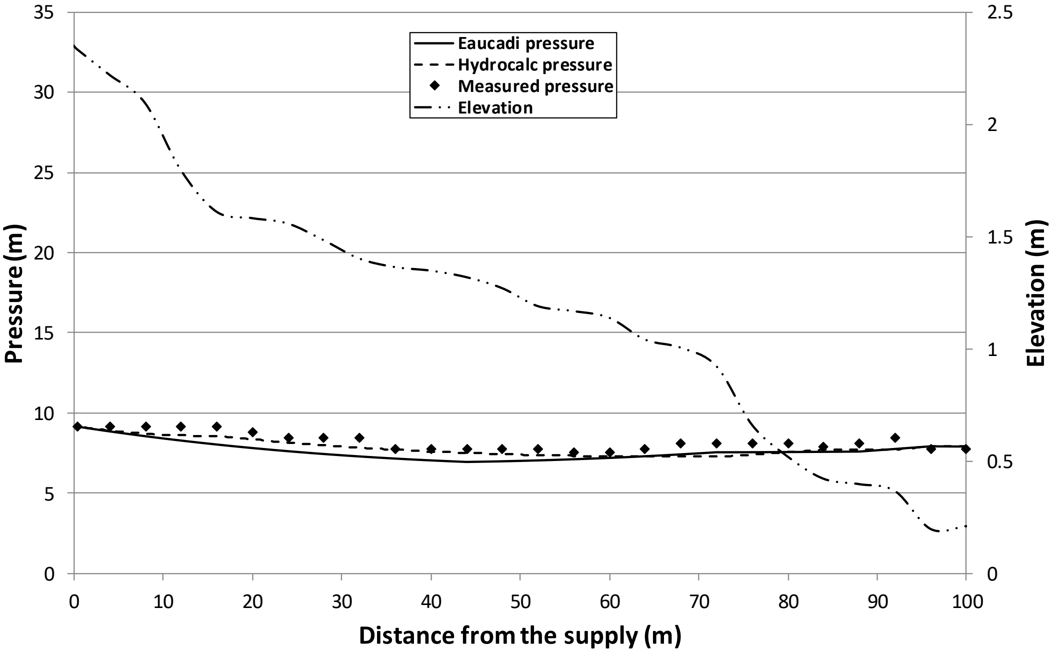


Figure 5.21: A graph between measured emitter pressure and distance from the supply end for Test No. 2 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 9.14 m (13.0 psi).

Figure 5.21 illustrates that the measured pressure results generally follow the same general trend as the predicted results with the measured results being roughly 5% and 8% higher than the Hydrocalc and Eaucadi results respectively. The Hydrocalc results are approximately 3% higher than the Eaucadi results.

5.5.2.1.1 Test No. 3

Figure 5.22 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 10.62 m (15.1 psi) using the water supply into the highest end of the dripline for Test No. 3.

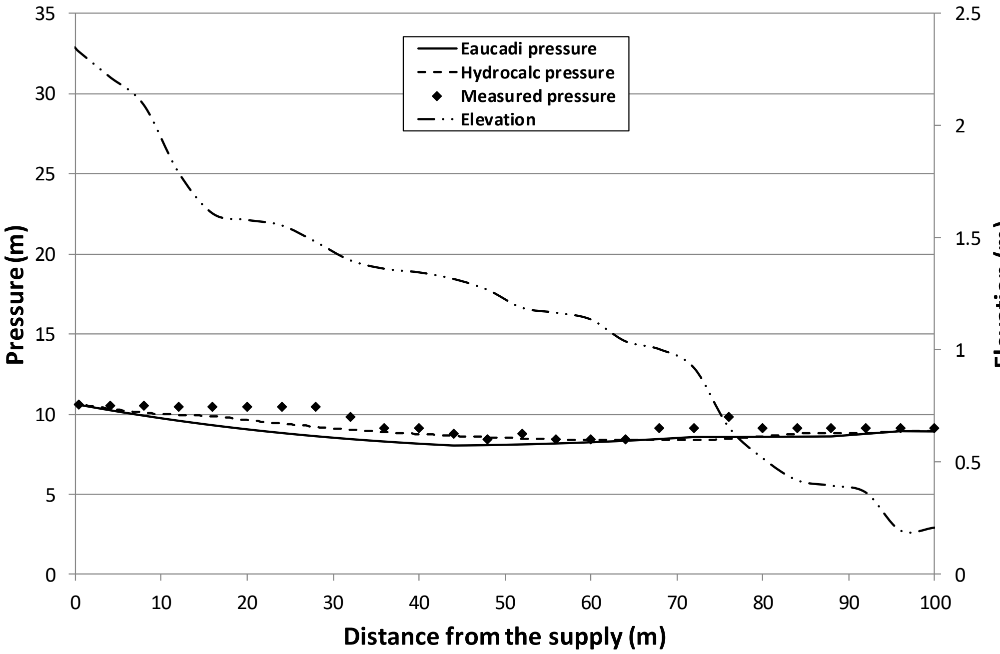


Figure 5.22: A graph between measured emitter pressure and distance from the supply end for Test No. 3 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 10.62 m (15.1 psi).

The measured pressure results are generally higher than the simulated results, and roughly 5% and 8% higher than the Hydrocalc and Eaucadi results respectively as shown in Figure 5.22. The Hydrocalc results are approximately 3% higher than the Eaucadi results.

5.5.2.1.1 Test No. 4

Figure 5.23 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 10.55 m (15.0 psi) using the water supply at the highest end of the dripline for Test No. 4.

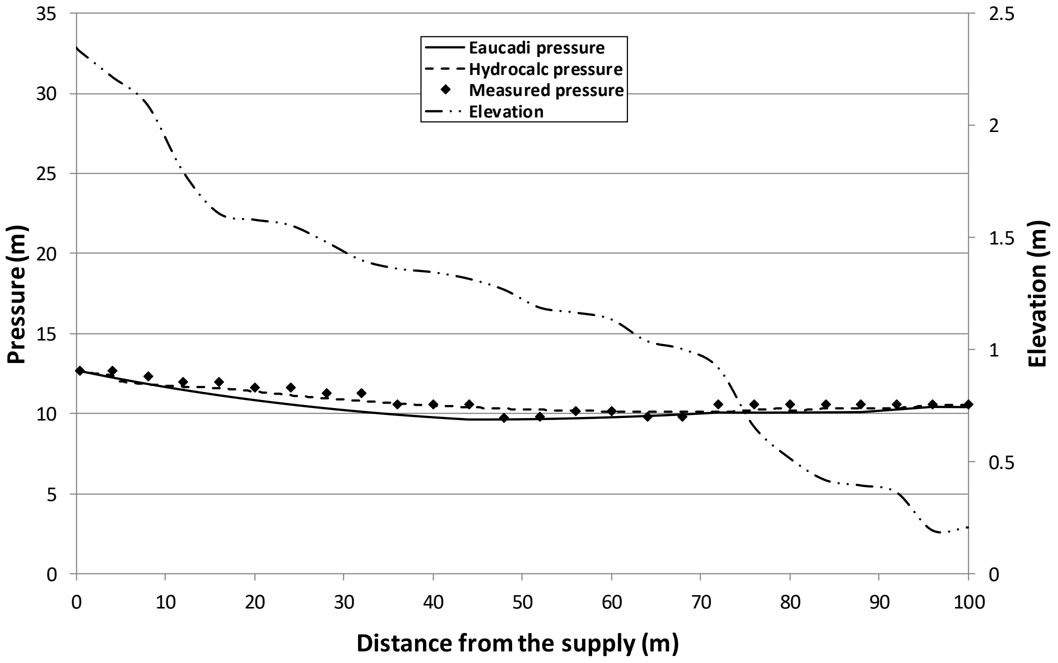


Figure 5.23: A graph between measured emitter pressure and distance from the supply end for Test No. 4 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 10.55 m (15.0 psi).

Figure 5.23 indicates that the measured and simulated results has generally follow the same general trend as the average measured pressure results are roughly 1.5% and 5% higher than the Hydrocalc and Eaucadi results respectively. The Hydrocalc results are approximately 3% higher than the Eaucadi results. Pressure is increasing as the distance increases from the supply end.

5.5.2.1.1 Test No. 5

Figure 5.24 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 18.63 m (26.5 psi) using the water supply at the highest end of the dripline for Test No. 5.

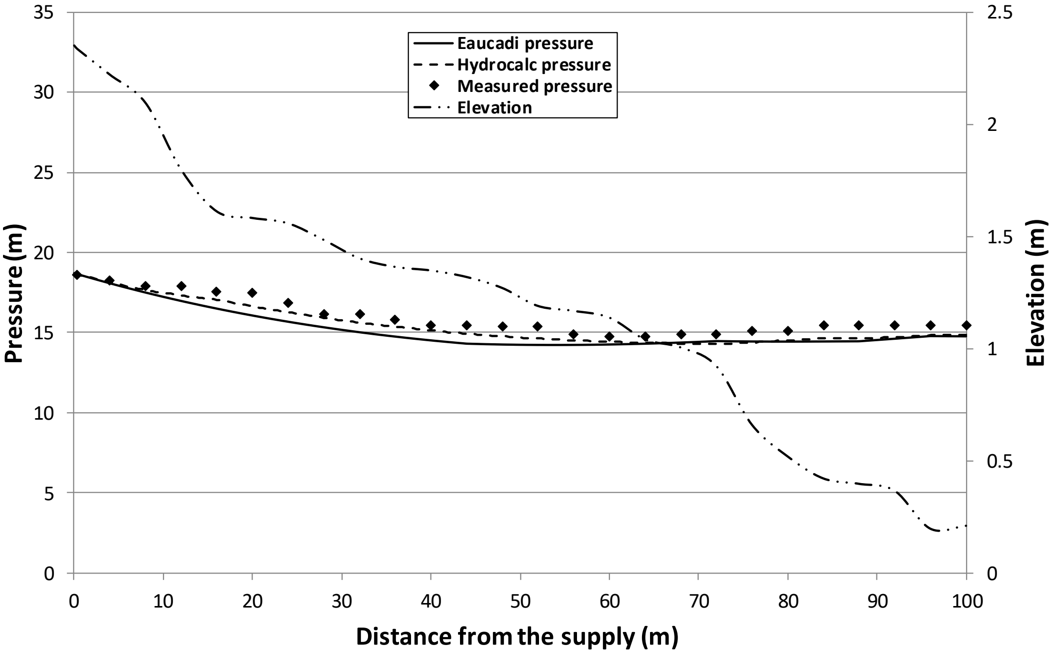


Figure 5.24: A graph between measured emitter pressure and distance from the supply end for Test No. 5 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 18.63 m (26.5 psi).

Figure 5.24 illustrates that the pressure measured in the field in good agreement with the Hydrocalc results. The measured pressure results are roughly 4% and 6% higher than the Hydrocalc and Eaucadi results respectively. The Hydrocalc results are approximately 5% higher than the Eaucadi results.

5.5.2.1.1 Test No. 6

Figure 5.25 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with a supply pressure of 27.07 m (38.5 psi) using a water supply at the highest end of the dripline for this Test No. 6.

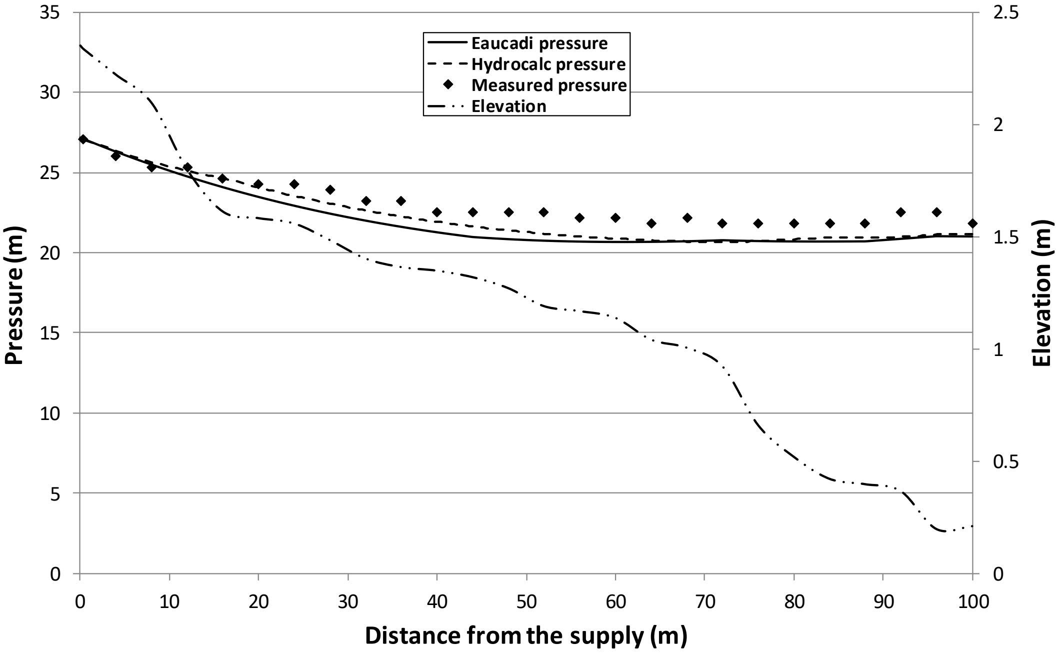


Figure 5.25: A graph between measured emitter pressure and distance from the supply end for Test No. 6 with water supply placed into the highest end of the dripline for predicted and software results for nominal supply pressure of 27.07 m (38.5 psi).

The reader can see in Figure 5.25, that for a length of dripline up to 8 m from the supply end, the measured pressure results match the Eaucadi results. For 20 m of length from the supply end, the measured pressure results match the Hydrocalc results. From 20 to 100 m of dripline length, the measured pressure results are different, and the average is approximately 4% and 5% higher than the Hydrocalc and Eaucadi results respectively. While the Hydrocalc results are roughly 1% higher than the Eaucadi results.

5.5.2.2 Comparison of measured emitter pressure and simulated pressure results for the water supply at the lowest end

5.5.2.2.1 Test No. 7

Figure 5.26 highlights the plot of emitter pressure (m) compared to the distance from the supply end (m) with a supply pressure of 3.52 m (5.0 psi) using a water supply at the lowest end of the dripline for Test No. 7.

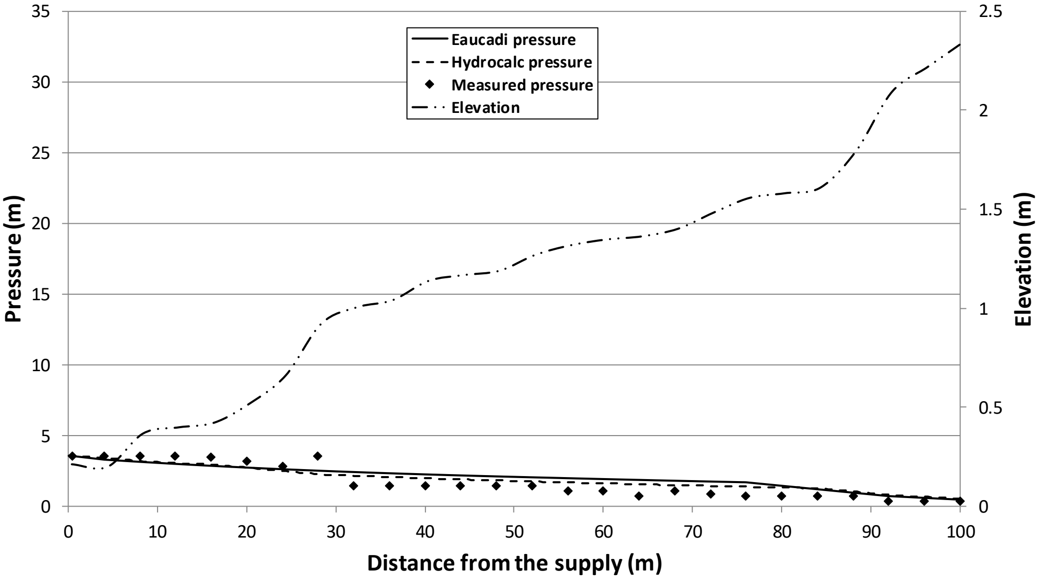


Figure 5.26: A graph between measured emitter pressure and distance from the supply end for Test No. 7 with water supply placed into the lowest end of the dripline for predicted and software results for nominal supply pressure of 3.52 m (5.0 psi).

The measured emitter pressure follows the same trend as the simulated results as presented in Figure 5.26. The average measured emitter pressure up to the distance of 28 metres is roughly 12% and 13% higher than the Hydrocalc and Eaucadi results respectively. While from 28 metres to 100 metres from the supply, end the average measured emitter pressures is roughly 37% and 40% lower than the Hydrocalc and Eaucadi results respectively. The Hydrocalc results are roughly 6% higher than the Eaucadi results.

5.5.2.2.1 Test No. 8

Figure 5.27 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 7.73 m (11.0 psi) using the water supply at the lowest end of the dripline for Test No. 8.

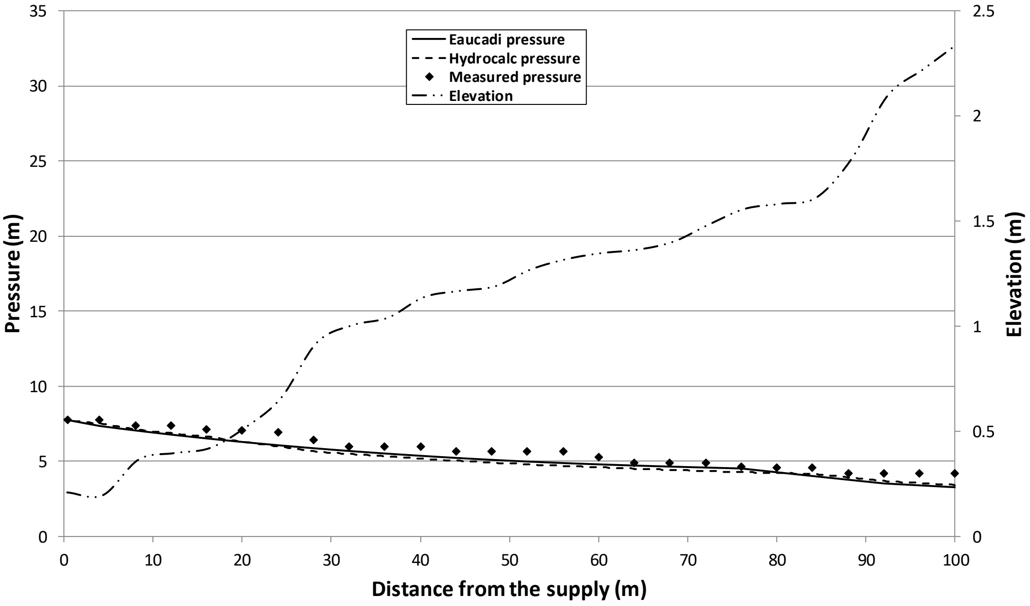


Figure 5.27: A graph between measured emitter pressure and distance from the supply end for Test No. 8 with water supply placed into the lowest end of the dripline for predicted and software results for nominal supply pressure of 7.73 m (11.0 psi).

It can be seen from Figure 5.27 that the measured emitter pressures are generally following the same trend but higher that the simulated results. The average measured emitter pressure is roughly 10% and 11% higher than the Hydrocalc and Eaucadi results respectively. The Hydrocalc results are roughly 1% higher than the Eaucadi results. The pressure seems to be decreasing as the elevation increases along the dripline.

5.5.2.2.1 Test No. 9

Figure 5.28 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 14.91 m (21.2 psi) using the water supply at the lowest end of the dripline for Test No. 9.

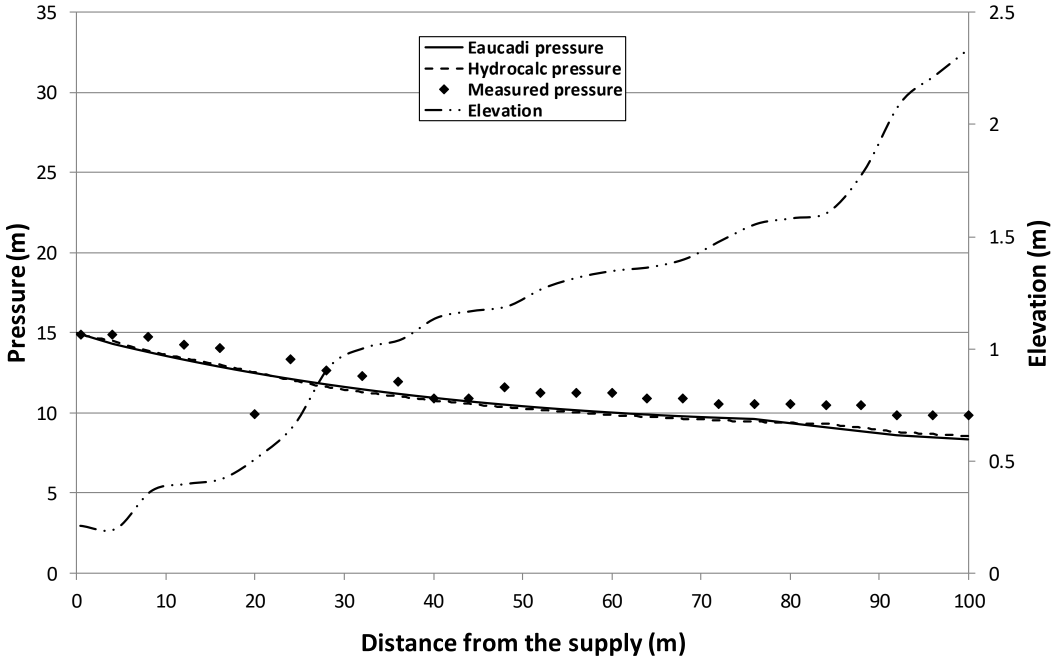


Figure 5.28: A graph between measured emitter pressure and distance from the supply end for Test No. 9 with water supply placed into the lowest end of the dripline for predicted and software results for nominal supply pressure of 14.91 m (21.2 psi).

While, Figure 5.28 clearly depicts that the measured emitter pressure is higher than simulated results at all test positions except at a distance of 20 m from supply end i.e. 9.91 m. The average measured emitter pressure is roughly 7% and 8% higher than the Hydrocalc and Eaucadi results respectively. The Eaucadi results are roughly 0.38% higher than the Hydrocalc results. The pressure seems to be decreasing as the elevation increases along the dripline.

5.5.2.2.1 Test No. 10

Figure 5.29 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) for a supply pressure of 21.45 m (30.5 psi) using the water supply at the lowest end of the dripline for Test No. 10.

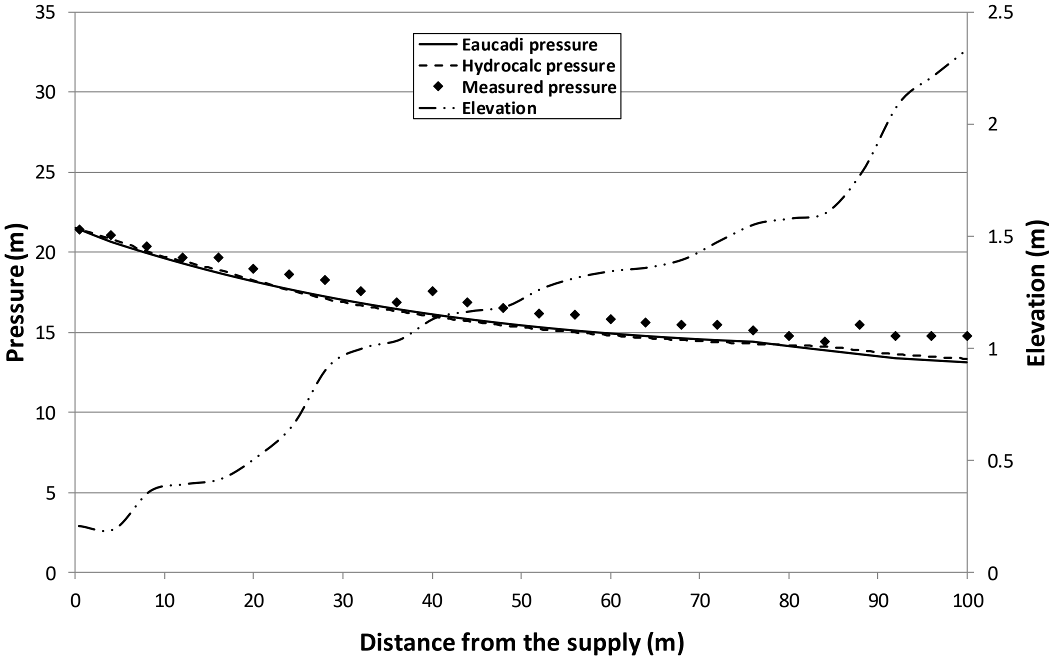


Figure 5.29: A graph between measured emitter pressure and distance from the supply end for Test No. 10 with water supply placed into the lowest end of the dripline for predicted and software results for nominal supply pressure of 21.45 m (30.5 psi).

In Test No. 10 the average measured emitter pressure is roughly 6% higher than both the Hydrocalc and Eaucadi results. The Eaucadi results are roughly 0.11% higher than the Hydrocalc results as shown in Figure 5.29. The pressure seems to be decreasing as the elevation increases along the dripline.

5.5.2.2.1 Test No. 11

Figure 5.30 shows a plot of emitter pressure (m) compared to the distance from the supply end (m) with the supply pressure of 31.99 m (45.5 psi) using the water supply at the lowest end of the dripline for Test No. 11.

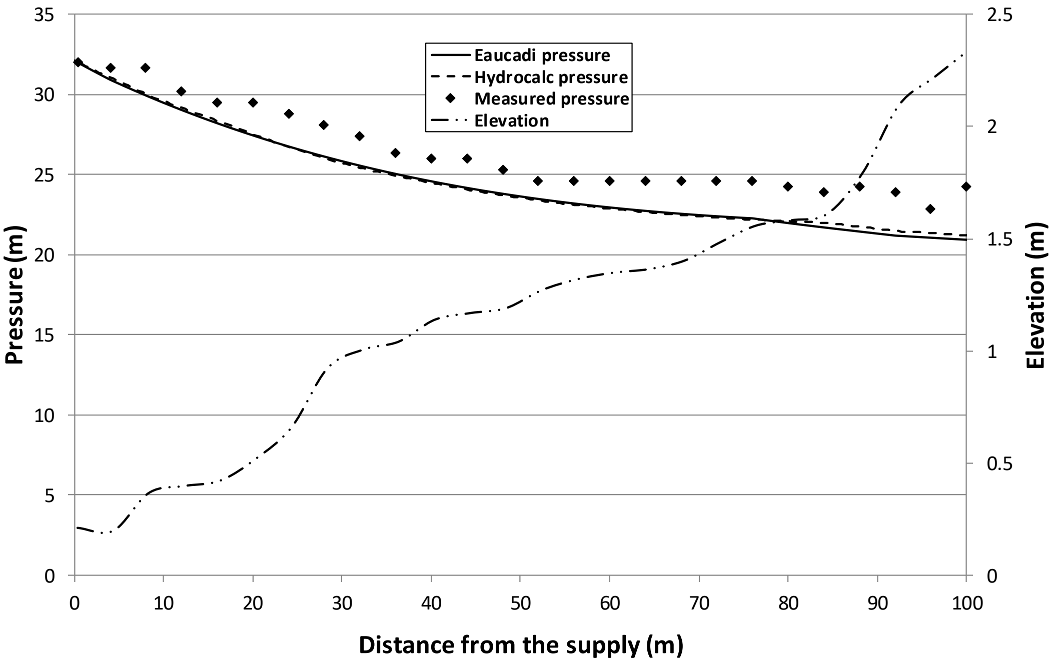


Figure 5.30: A graph between measured emitter pressure and distance from the supply end for Test No. 11 with water supply placed into the lowest end of the dripline for predicted and software results for nominal supply pressure of 31.99 m (45.5 psi).

The emitter pressure plots in Figure 5.30 depict that at all test positions the measured emitter pressure is much higher than the simulated results. The average measured emitter pressure is roughly 7% higher than both the Hydrocalc and Eaucadi results. The Hydrocalc results are roughly 0.02% higher than the Eaucadi results. The pressure seems to be decreasing as the elevation increases along the dripline. The high variation can be observed in measured and simulated results at high supply pressures like 45.5 psi.

Across the results from the eleven tests it appears that the variation between measured and predicted emitter pressures are higher when the inlet pressure is higher. These results have been discussed in detail in Section 6.7.2.

5.5.2.3 Results and discussion

From the comparison of measured individual emitter pressures and simulated results provided in Section 5.5.2, it has been observed that the simulated pressure results using the Eaucadi and Hydrocalc software packages are in good agreement with each other in all the tests performed with water supply placed into the highest of the dripline. Also, the measured pressure results have generally been following the same trend with distance along the dripline as the simulated results recorded using the Hydrocalc and

Eaucadi in Test No. 1, 2, 3, 4 and 5. While, in Test No. 6 the measured pressure results are significantly higher (6%) and the difference of measured pressure results from the simulated results increases with the distance from the supply end using the supply pressure of 32 m. A highly varied flow rates have been observed from the simulated results in Test No. 6 due to the supply pressure being higher than the maximum recommended pressure of 30 m.

A comparison of measured and simulated pressure results where water supply was at the lowest end of the dripline produced measured results for Test No. 8, 9 and 10 that match quite closely to the simulated results, while in Test No. 7 and 11 the measured pressures are much higher than the simulated results. Test No. 7 have been conducted in heavy winds and at a very low supply pressure and resulted in a greater non-uniformity in emitter flow rates collected using the catch cans.

In Test No. 11 the inlet pressure was 32 m, and this is 7% higher than the manufacturer’s recommended maximum working pressure i.e. 30 m. This produced non-uniform and high emitter flow rates in this experimental field setup.

5.5.3 Total flow rate

Table 5.3 shows the total flow rates measured from the system installed at the agricultural plot area and the flow rates measured from the software for all 11 tests performed in the field trial system.

Table 5.3: Flow rate measured at field test site using flowmeter, total estimated flow rate and predicted flow rate by the software packages for 11 numbers of tests conducted.

Test No	Water supply end	Nominal supply pressure (m)	Total estimated flow rate (L/h)	Flow rate from flowmeter (L/h)	Eaucadi Results (L/h)	Hydrocalc Results (L/h)
1	Highest	3.52	394	341	296	305
2	Highest	9.14	477	450	440	446
3	Highest	10.62	490	457	470	476
4	Highest	10.55	529	489	508	511
5	Highest	18.63	641	605	604	609
6	Highest	27.07	713	710	716	721
7	Lowest	3.52	277	210	234	227
8	Lowest	7.73	359	542	368	365
9	Lowest	14.91	532	485	517	516
10	Lowest	21.45	662	922	620	619
11	Lowest	31.99	834	787	754	754

The Table 5.3 shows the number of tests performed, slope and the nominal supply pressure at the inlet. Slope shows the direction of water flow with supply end at highest and lowest end of the dripline. Test No. 1 to 6 were performed with the supply end at the highest end while from Test No. 7 to 11 were performed with the water supply end at the lowest end. As the catch cans were installed at every tenth emitter, the estimated total flow rate for the 100 m of drip tube has been measured by multiplying emitter discharge rate in each can by ten to produce the total estimated flow rate of the system. The flow rates had also been recorded from the flowmeter installed at ag-plot test site for each test. The flow rates simulated by the two software packages, Eaucadi and Hydrocalc were provided to compare the measured and simulated results. It can be seen from Table 5.3 that the flow rates simulated using the Hydrocalc and Eaucadi software packages are fairly similar. The estimated total flow rates from trial site are roughly 24%, 7%, 3.5%, 4%, 5%, 17%, 3%, 6% and 10% higher than the simulated results in Test No. 1, 2, 3, 4, 5, 7, 9, 10 and 11 respectively. While estimated total flow rate are roughly 1% and 2%, lower than simulated results in Test No. 6 and 8 respectively. Furthermore, estimated total flow rates measured are 13%, 6%, 7%, 8%, 6%, 0.4%, 24%, 9%, and 6% higher than the flow rates recorded using flowmeter for Test No. 1, 2, 3, 4, 5, 6, 7, 9 and 11 respectively. The most unrealistic results have been observed with the flow meter in Test No. 8 and 10, provided that the total estimated flow rates are approximately 51% and 39% lower than the flow meter results in Test No. 8 and 9 respectively. These results have been discussed in detail Section 6.7.3.

5.5.4 Irrigation performance results

To evaluate if a mixture of modern computer software design packages and field measurements accurately predict the performance of Punjab drip irrigation systems in terms of uniformity the irrigation performance results for measured and simulated results are compared and discussed below:

Irrigation performance was evaluated using different uniformity measures as mentioned in Section 2.10.2. The performance was evaluated in terms of the emission uniformity (*Eu*) using Equation 2.6 and coefficient of variation (*Cv*) using Equation 2.5 as explained in Section 2.10.2.

Table 5.4: Comparison of performance evaluation results of a drip system operated with different inlet pressures, and placed with downhill or uphill field slope.

Test No	Water supply end	N.S. P	*Eu*					*Cv*		
			%	%	%	%	%			
		Metres	Mea	Eaucadi		Hydrocalc		Mea	Eau	Hyd
			Cal	Cal	Sim	Cal	Sim	Cal	Cal	Cal
1	H	3.515	90.87	85.34	91.84	93.32	93.18	0.042	0.066	0.029
2	H	9.139	87.03	92.20	95.96	93.22	93.11	0.034	0.031	0.029
3	H	10.616	73.50	92.53	96.37	92.99	93.07	0.066	0.031	0.031
4	H	10.546	86.22	92.81	96.35	93.94	93.00	0.052	0.032	0.028
5	H	18.631	72.91	92.95	97.25	92.37	92.98	0.064	0.035	0.035
6	H	27.068	73.18	92.82	97.34	92.22	93.00	0.081	0.036	0.036
7	L	3.515	34.21	37.81	50.44	43.19	54.09	0.229	0.197	0.197
8	L	7.734	67.69	70.92	81.30	72.64	80.13	0.125	0.100	0.101
9	L	14.905	75.61	80.95	89.03	81.92	86.65	0.104	0.071	0.071
10	L	21.444	77.06	84.12	91.34	84.89	88.6	0.112	0.062	0.062
11	L	31.989	73.28	86.57	93.06	87.19	90.04	0.108	0.054	0.055

Note: H: Highest, L: Lowest, N.S.P: Nominal supply pressure at the inlet, Mea: calculated using measured results from field tests, Cal: calculated by spreadsheet using simulated results or field results, Sim: Simulated results directly from software packages, Ea: Eaucadi results, Hyd: Hydrocalc results, *Eu*: Emission uniformity, *Cv*: Coefficient of variance.

The performance results have been calculated using spreadsheets integrating data from the field, and results data obtained from the software packages. Emission uniformity and coefficient of variation has been calculated and simulated for all the eleven tests, which have been previously discussed.

It can be seen from Table 5.4 that emission uniformity calculated using Eaucadi is higher than the Hydrocalc results in all test except Test No. 1 and 7, where it is lower. The emission uniformity computed using both software packages are quite similar, while the measured results shows lower emission uniformity than simulated results in all tests.

The reader can see that measured emission uniformity integrating the emitter discharges and flow rates from the Eaucadi gives different results, while in the Hydrocalc the results are quite similar in Test No. 1, 2, 3, 4, 5, and 6.

Further the Eaucadi and Hydrocalc has produced same coefficient of variation in all tests except in Test No. 1, where Eaucadi has given $Cv = 0.06$. Cv measured using field measured results provides a coefficient of variation ($Cv > 0.05$) greater than simulated results in Test No. 3, 4, 5, 6, 7, 8, 9, 10, and 11. The simulated results also show $Cv > 0.05$ in Test No. 1, 7, 8, 9, 10 and 11.

5.5.5 Results and discussion

Emission uniformity, *Eu* was calculated using field measurements of emitter discharges for each of the tests completed. Measured *Eu* shows a decreasing trend through Test No. 1 to Test No. 6 except Test No. 4 as the nominal supply pressure increases from 3.5 m to 27 m with water supply placed into the highest end. The *Eu* measured as 90.87%, 87.03%, 73.5%, 86.22%, 72.91%, 73.18%, and 34.21% for Test No.1, 2, 3, 4, 5 and 6 respectively. In contrast, emission uniformity results show an increasing trend as the pressure head increases from Test No. 7 to 11 with water supply placed into the lowest end. *Eu* measured as 67.69%, 75.61%, 77.06% and 73.28% for the Test No. 7, 8, 9, 10 and 11 respectively.

On the basis of EU (%), all emitters performed more than 90% in Test No. 1 only and are considered in “excellent class” and according to (Mangrio et al., 2013) it is a good indicator of reduced head losses and saving of energy during system operation.

Emission uniformity results in Eaucadi were not higher than 5% from the Hydrocalc results in all tests except in Test No. 1 and 7; the Eaucadi *Eu* results were 1.5% and 7.2% lower than the Hydrocalc results. The simulated emission uniformity results are greater than 90% in Test No. 1, 2, 3, 4, 5, 6 and 11. Values of 80% to 90% for emission uniformity are achieved in Test No. 8, 9 and 10, while values of roughly 50% to 55%

for emission uniformity were obtained in Test No. 7.

The high variation in individual emitter flow rates and the low emission uniformity was measured from Test No. 7 and 8 as 34.2% and 67.7%, respectively. The minimum emission uniformity recommended for a slope > 2% and line source emitter is 70%. These results can also be attributed to the length of the lateral as 100 m is greater than the recommended maximum lateral lengths of 48 and 60 metres for this amount of uphill and downhill slope.Table 2.3 shows that the ASABE recommended coefficient of variation range for both point source and line source emitter. As the emitters selected for the field test site are line source emitter being integrated in dripline, the *Cv* < 0.10, *Cv*: 0.10 to 0.20 and *Cv* > 0.20 is considered to be good, average and marginal to acceptable respectively. The Eaucadi and Hydrocalc have produced *Cv* results fairly similar and < 0.10 in all tests except in Test No. 7 and 8, *Cv* is between 0.1 to 2. According to ASABE, standards the *Cv* results for all tests except 7 and 8 are considered good and within the permissible limit, while Test No. 7 and 8 *Cv* results are considered average. While measured results of *Cv* < 0.10 (good) for Test No. 1, 2, 3, 4, 5, and 6, while Cv > 0.20 for Test No 7 (acceptable to marginal) and Cv between 0.10 to 2 (average) for Test No. 8, 9, 10 and 11 respectively. The *Cv* from emitter discharges measured in the field was higher than simulated results in all tests performed showing the deviation of emitter discharges in actual field conditions from the ideal simulated results.

The emission uniformities were also measured manually using spreadsheets, computing individual emitter discharges that software packages were using as input to produce results. The measured *Eu* using input of the Eaucadi were less than 5% in Test No 2, 3, 4, 5, and 6. While it is 25% and 13%, lower than the Eaucadi results in Test No. 7 and 8 respectively. The measured *Eu* using the Hydrocalc input data was 20%, 9%, 5%, 4% and 3% lower than the Hydrocalc results for Test No. 7, 8, 9 and 10 respectively. Which also shows that the uniformity has a linear relationship with either pressure head or slope and with the optimisation of lateral length and diameter higher *Eu* can be achieved, but a desirable level of uniformity has to be set to maintain the cost of the system with in a permissible limit.

Therefore, an overall performance of a drip system depends on the choices made between maximising profits and reducing cost and minimising impacts on environment and maximising irrigation efficiency. Hence, these choices have to be made at design stage according to the individual site and famer’s requirements.

5.5.6 Constant k and exponent x calculation from predicted and software results with water supply placed into the highest end for Test No. 1 to 6

The basic component of emitter characteristics is the flow rate (l/h) vs pressure head (m). This relationship specify that discharge increases with the increase of pressure head. Therefore, the development of the flow pressure curve is essential in the selection of emitter type and system design. As given in Section 2.4 the relationship between emitter operating pressure and flow rate is defined as:

$$Q = kH^{x} \tag{2.1}$$

Where Q is the emitter flow rate (L/h), while k is the constant, H is the pressure (m) and x is the emitter exponent.

In this study, the emitter exponent x and emitter constant k were derived using poly nominal regression in Microsoft Excel for the pressure-discharge relationship. As the exponent x describes the flow regime and emitter type, it is also an indirect measure of the sensitivity of flow rate to the change in pressure. The value of x typically ranges between 0-1.0, where a lower value indicates a lower sensitivity and a higher value indicates a higher sensitivity, moreover value of x, near zero, confirms that emitter is a pressure-compensating one (Mangrio et al., 2013).

Thus a scatter chart for water inlet at highest end (downhill) implementing emitter flow rates (L/h) from measured and simulated results against the emitter inlet pressures (m head) has been produced and shown in Figure 5.31. The best fitted curve has been drawn and statistical analysis was used with power function for the investigation of regression correlation (r^2) between pressure and discharge for selected emitters. Based on the regression analysis of flow and pressure data, flow-pressure equations were established for measured and simulated results. So, constant k and exponent x from field and simulated results were derived by fitting power curve to each data set, using polynomial regression analysis in Microsoft Excel. These values were then compared to the results from the manufacturer’s provided values in the catalogue as 0.693, 0.46 and 1 for constant *k*, exponent *x* and r^2 respectively. The constant *k* indicates the magnitude of the flow and is related to the internal size of the emitter.

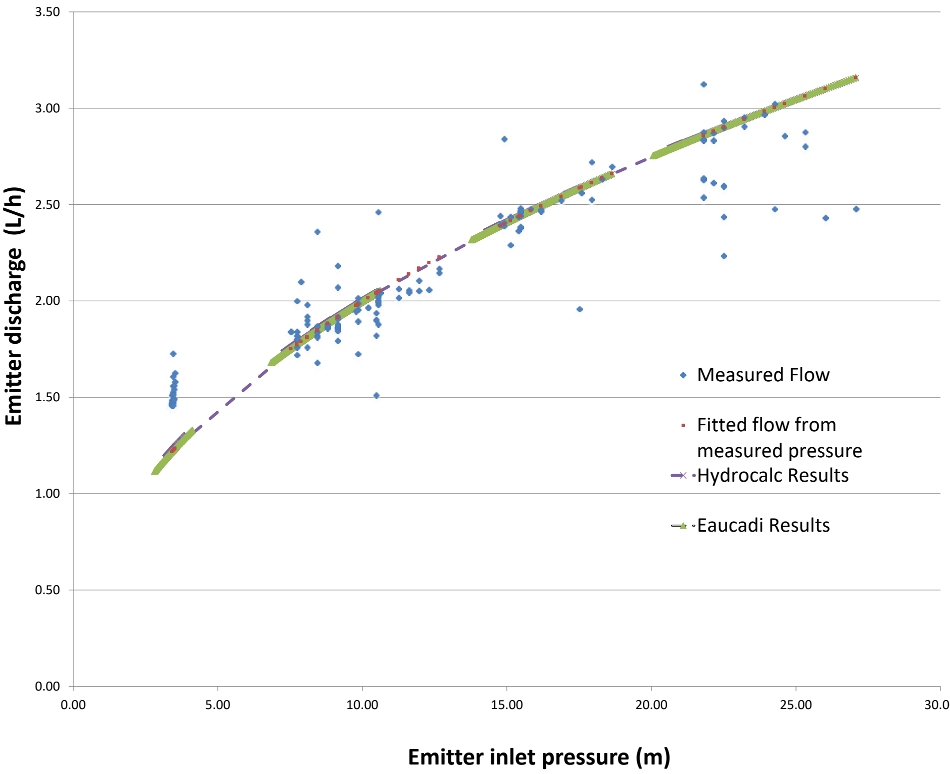


Figure 5.31: Chart between emitter discharge and emitter inlet pressure using the water supply into the highest end of the dripline for Test No. 1 to 6.

The constant *k* and exponent *x* and r^2 measured fitting power curve to the measured and simulated results are then compared with manufacturers predicted results as shown in Table 5.5. The constant *k* and exponent *x* measured from software results and manufacturer’s predicted results are similar, which is expected as the software is using the manufacturer’s values for the coefficients. Also, the Eaucadi and Hydrocalc results obtained are identical. The constant *k*, exponent *x* and r^2 measured, using field measured results produced a constant *k* higher and exponent *x* and r^2 lower than manufacturer’s predicted results.

Table 5.5: Comparison between the constant *k*, exponent *x* and r^2 for Test No. 1 to 6.

Results	Constant *k*	Exponent *x*	r^2
Manufacturer's predicted	0.693	0.46	1.00
Measured Results	0.975	0.318	0.87
Eaucadi Results	0.693	0.46	1.00
Hydrocalc Results	0.693	0.46	1.00

5.5.7 Constant *k* and exponent *x* calculation from predicted and software results with water supply placed into the lowest end of the dripline for the Test No. 7 to 11

A similar scatter chart for water inlet into the lowest end (uphill) implementing emitter flow rates (L/h) from measured and simulated results against the emitter inlet pressures (m head) has been produced and shown in Figure 5.32. Similarly, the best fitted curve has been drawn and statistical analysis was used with power function for the investigation of regression correlation (r^2) between pressure and discharge for selected emitters.

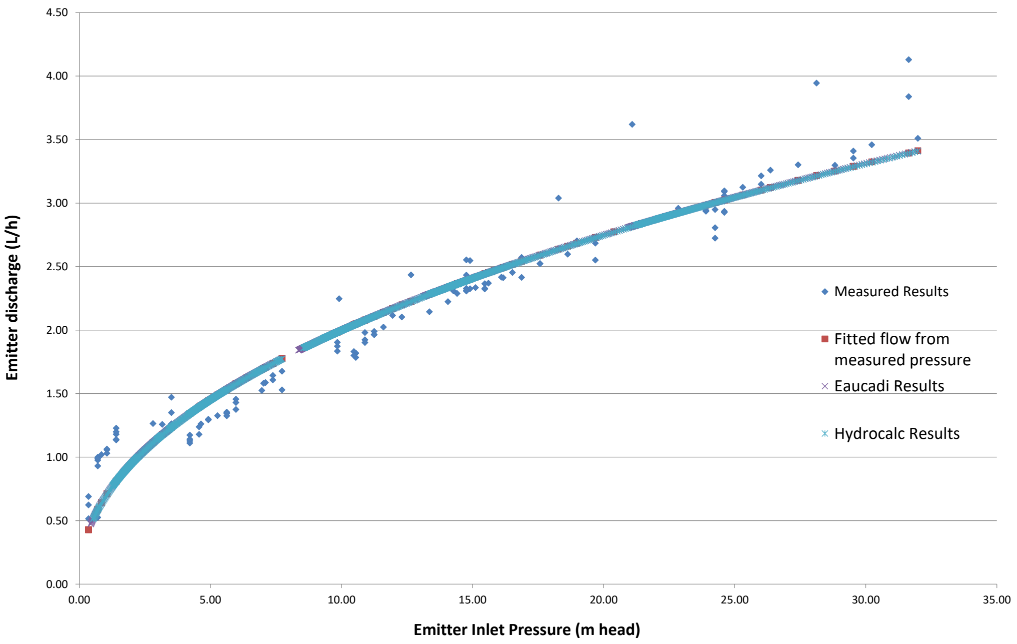


Figure 5.32: Chart between emitter discharge and emitter inlet pressure using the water supply into the lowest end of the dripline for Test No. 7 to 11

Constant *k* and exponent *x* and r^2 from field and simulated results was measured by fitting power curve to each data set to compare the results with the manufacturer who has provided values as 0.693, 0.46 and 1 for constant *k*, exponent *x* and r^2 respectively.

The constant *k* and exponent *x* measured from software results and manufacturer's predicted results are quite similar as shown in Table 5.6. While the constant *k*, exponent *x* and r^2 measured, using field measured results produced constant *k* higher and exponent *x* and r^2 lower than manufacturer's predicted results.

Table 5.6: Comparison between the constant *k*, exponent *x* and r^2 for Test No. 7 to 11.

Results	Constant *k*	Exponent *x*	r^2
Manufacturer's predicted	0.693	0.46	1.00
Measured Results	0.856	0.37	0.90
Eaucadi Results	0.693	0.46	1.00
Hydrocalc Results	0.690	0.46	1.00

5.5.8 Results and discussion

The flow-pressure curve, implementing emitter flow rates (L/h) of measured and simulated results against the emitter pressures (m head) with water supply placed into the highest end produced results as r^2: 0.87 and determination coefficient of pressure-flow model adjusted for measured results was 87%, this also indicates that the flow rate versus pressure relationship did not describe the emitter accurately. We also observed a normal fit for the potential flow-pressure model because of a determination coefficient value of 87%, which does not indicate very strong relationship between pressure and flow rates. The emitter exponent x measured was 0.318 and this indicates that we can classify emitter flow regime as turbulent and confirms that emitter is behaving like a typical non-pressure compensated emitter for all pressure ranges and flow rate is relatively less sensitive to the pressure variation. The constant k determined from measured values was 0.975 while the manufacturer's constant k was 0.693.

The flow-pressure curve, implementing emitter flow rates (L/h) of measured and simulated results against the emitter pressures (m head) with water supply placed into the lowest end produced results as r^2: 0.90 and determination coefficient of pressure-flow model adjusted for measured results was 90%, which shows very strong relationship between pressure and flow rates. This also indicates that the emitter discharge versus pressure relationship describes the emitter head discharge relationship accurately. We also observed a good fit for the potential flow-pressure model because of a high determination coefficient value (90%). The emitter exponent x generated was 0.37, and this shows that the emitter flow regime can be classified as turbulent and emitter is behaving as a non-pressure compensated emitter for all pressure ranges, and as such is relatively sensitive to the pressure variation relative to emitter discharges. The constant k from fitting to the measured results was 0.856, while the constant k that the manufacturer is supplied k was 0.693.

It is difficult to make any conclusions based on the values of the constant k and exponent x individually. Instead it is the head discharge characteristic which is important for drip irrigation performance. Figure 5.33 shows a plot of the manufacturer's emitter characteristic along with the emitter characteristic measured with the flow applied from the highest end of the lateral (Tests 1-6) and lowest end of the lateral (Tests 7-11). Here the two lines from the experimental measurements are similar but they clearly differ from the manufacturers curve. The lower exponent value from the experimental tests means that the characteristic has a flatter slope and is less sensitive to changes in pressure than stated by the manufacturer. The manufacturer’s characteristic under predicts the measured results for pressures less than 10 m but over predicts the flows for pressures greater than 10 m.

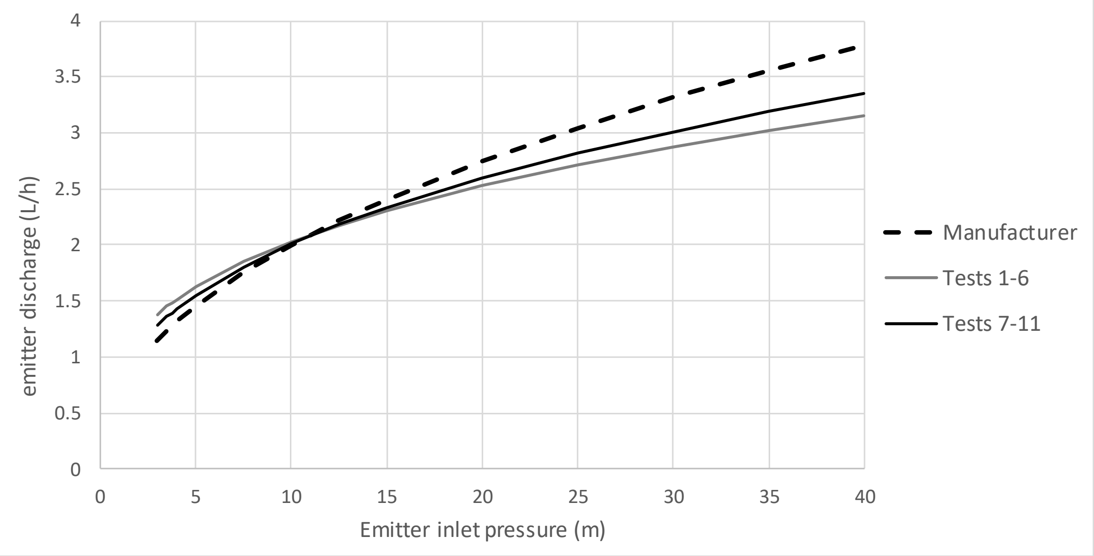


Figure 5.33: Plot of fitted manufacture’s head discharge characteristic with the characteristics fitted from field tests.

5.6 Conclusions

The results obtained comparing the measured and simulated emitter flow rates and emitter pressures along the dripline from the supply end with water supply placed both at the highest and lowest end of the dripline have been analysed in detail. Measured and simulated flow rates and performance measurement results have also been compared. To assess the working of emitters, emitter characteristic as exponent *x* and constant *k* has been measured plotting the results into *the* spreadsheets adding the results from all eleven tests with water supply placed into the highest and lowest end of the dripline respectively. The measured and simulated results were found in a good agreement with each other for emitter flow rates and emitter pressures. Although slight differences have been noticed in terms of performance measures and flow rates calculation for measured and simulated results. The reasons for the variation in simulated and measured results are analysed. The reliability and usefulness of the modern software packages to replicate the standard Punjabi drip irrigation system is validated and the feasibility of the replication of Pakistani drip irrigation systems into the Australian software packages has been proved. These results have been further discussed in detail in CHAPTER 6.

CHAPTER 6 DISCUSSION OF RESULTS

6.1 Introduction

As the population of Pakistan has increased by 25% in the last ten years and is expected to reach 230 million by 2030, it will create alarming food security issues that will require either more water resources or more efficient water use (Iqbal & Iqbal, 2015).

Furthermore, the Indus basin irrigation system is the single largest supply-based system and despite the increase in storage capacity it cannot accommodate future water demands (Bhutta & Smedema, 2007).

Punjab's rice and wheat contribute to the country's major food grain production and these cover about 65% of the area of total rice and wheat cropping systems in Pakistan (Ahmad et al., 2014). Punjab receives 69 million MegaLitres of water although only 32 million MegaLitres reaches the farm gate due to heavy losses in canals and watercourses (Eleazar, 2018). Additionally, only 15 to 17% of the country's budget is used for the maintenance of irrigation infrastructure and drainage, and these insufficient investments for maintenance result in poor drainage. Therefore, issues like water logging and salinity have developed which result in the 40 to 60% production losses.

Due to water logging, decreases in surface water supplies, and inequity in canal water access between head and tail-water users, more than a million tube wells have been installed (Afreen et al., 2013). Although this over-exploitation has disturbed the natural water balance and has dropped the ground water levels at unjustifiable rates. This has also compromised the ground water quality and has escalated pumping costs.

Therefore, it is crucial to use the remaining water assets wisely, producing more crop per drop of water, and increasing crop productivity. Hence, numerous research gaps were noticed and pointed out through this research. Major deficiencies are observed not only in the management and operation of Indus basin irrigation system but also in on on-farm water management. So, it was essential to evaluate the causes for the low performance of Indus basin irrigation systems, and the prevailing conventional irrigation practices used in Punjab, and reviewing the factors affecting performance. This research analysis has provided a deep insight on into the prevailing problems and their impacts, along with their possible practical solutions. The recommendations provided will help to generate a plan to examine and include the major neglected areas in Indus basin management and planning.

6.2 Outcomes and observations made from the review and analyses of Indus Basin irrigation system

The major factors influencing agriculture water management are water infrastructure, socio-economic component, assess to knowledge, land use and cropping pattern, water pricing, water policy and climate and hydrology. To analyse the reasons for low farm productivity, it was necessary to locate and understand problems at the ground level in the Indus basin irrigation system, and in its operation, which were evaluated in terms of efficiency and performance at basin, canal and farm levels. Both technical and operational inefficiencies were observed at the structural and management level of Indus basin irrigation system.

The major issues observed are the lack of connection and linkage between agriculture, irrigation, energy, environment and social divisions, and a shortage of knowledge regarding the nature and extent of interdependencies between these sectors (Rothausen & Conway, 2011). Further, inadequate participation of consumers, water related stakeholders, and relevant departments have resulted into the poor management of the irrigation system (Bakhshal & Masood, 2012).

Similarly, no data and information are available on energy consumption in different sectors (Afreen et al., 2013) and no statistics are available on groundwater resources, its quality, withdrawal and impacts on agriculture, irrigation and energy sources and consumptive crop water requirement (Watto & Mugera, 2015).

Other irregularities are the poor canal maintenance (Ahmad et al., 2007), inefficient water policies, inequitable water distribution (Ahmad et al., 2014) and improper pricing (Bakhshal & Masood, 2012). A lack of strategic system governance, and the absence of a drainage system, along with inadequate financing assigned to the irrigation and drainage system (Bakhshal & Masood, 2012), over-exploitation of groundwater resources, regular canal breaches, increased fuel (diesel) cost, and electricity outages (load -shedding) (Ahmad et al., 2014) have further worsened the situation.

However, it is very important to understand that improved irrigation efficiency does not always translate into “real” water savings, as these can only be accurately measured after evaluating and measuring all of the hydrologic interactions between the farm, watercourses, canals and the river basin. In fact, water savings and the comprehensive impacts of water resource conservation technologies are not well understood and documented beyond the farm level. The real water savings can be much lower than the measured or anticipated results, and in order to effectively evaluate the real water savings, water recycling needs to be assessed and contained within the conjunctive use of surface and groundwater in Punjab (Ahmad et al., 2007).

Efficient management and conservation of existing water resources can be achieved by implementing all of the suggestions provided in Section 4.2. These results also prove and identify the need for the performance evaluation of prevailing irrigation systems on a larger scale. Those outcomes and recommendations will help manage the issues at ground level and improve the efficiency and performance of the Indus basin irrigation system, as well improve on-farm efficiency with precise conjunctive water management.

6.3 Need for improved irrigation performance in Pakistan

Agriculture is the backbone of Pakistan’s economy and contributes to 21.4% of national GDP using 98% of the freshwater resources extracted for agriculture (Iqbal & Iqbal, 2015). Pakistan is the world’s sixth most populous country with 50% of the population already characterised as food insecure, with 28% severely food insecure, and has per capita water availability estimations falling to reach 915 m3/person by 2020 (Ahmad et al., 2014).

Water productivity is also the lowest in the world because of the water wastage and low irrigation efficiency (30%). Water productivity recorded for wheat in Pakistan was about 0.6 kg/m3 as compared to California and India which is 1.0 kg/m3 (Qureshi, 2011). Similarly, maize yields calculated were 0.4 kg/m3 which is nine times lower than Argentina (2.7 kg/m3) (Bastiaanssen, 2000) Out of 69 million MegaLitres of water extracted only 32 million MegaLitres reaches the farm gate due to heavy losses in canals and water courses (Eleazar, 2018). Farmers are not receiving their share of water supplies, so crop water requirements cannot be met in a timely manner.

There will be an estimated shortfall of 20 million MegaLitres of gross water supply for agriculture, due to the declining Indus basin water availability (Hussain et al., 2011) and despite the increase in storage capacity in the Indus Basin Irrigation system, it cannot accommodate the changing water demands (Bhutta & Smedema, 2007).

Small farmers are the majority water users, and the small net water savings may not be re-used on farm. Instead, water savings can only allow large and medium farmers to get more safe and substantial water supply (Ahmad et al., 2007). Further poor irrigation management and inadequate irrigation practices on-farm, result in inefficient water application (Watto & Mugera, 2015).

Therefore, an efficient, economic, and environmentally acceptable integrated approach is needed to arrive at sustainable solutions. It is analysed that the performance of the canal irrigation system, as well as on-farm water productivity and application efficiency has to be improved, using water-saving high-efficiency irrigation systems such as drip irrigation, to fulfil the current and future agriculture needs of the rapidly growing population of Pakistan. Following and implementing the suggestions proposed in Section 2.6 will help improve the canal system maintenance, an operation and drainage system with improved efficiency and performance at a basin, canal as well as on-farm level, under real field conditions. The main objective is to ensure equitable water distribution and improve on-farm productivity and water application efficiency. Implementing these findings will not only be beneficial to the medium and large farmers but the majority of small farmers, who will also be able to achieve higher farm profitability, yield and quality of agricultural products. Moreover, the precise management of groundwater resources will help conserve the remaining water resources and its quality, with effective overall management of total water resources.

6.4 Review and analyses of drip irrigation systems in Pakistan

This project aims to investigate the factors associated with the failure of previously installed drip irrigation systems, to improve the adaptability and broad technological performance of drip irrigation systems in Punjab. Therefore, the potential and need for the adoption of drip irrigation, limitations in its adoption, and the need for performance evaluation of drip irrigation systems will be discussed in further detail.

6.4.1 Potential and need for the promotion and adoption of drip systems in Pakistan

The study showed that the gap between water availability and demand is expanding and without appropriate planning and methodology, escalating water scarcity will restrict the agriculture sector and Pakistan’s economy to fulfil the food and fibre requirements of the country. Hence the selection of best agriculture practices and improving water use efficiency using water conservation practices in rain-fed and irrigated agriculture, is essential to future agricultural sustainability and financial progress.

Due to the current water scenario, current low water productivity, and current low performance of traditional irrigation methods in Pakistan, the researchers and government bodies are highly interested in the promotion and implementation of drip irrigation systems in Pakistan. The major reasons and motivations behind the emergence of this need to promote the adaptability of drip irrigation systems are given in the following sections.

Pakistan has the lowest crop yield per unit of water in the world (Alam et al., 2006). Moreover, conventional irrigation systems have provided efficiency not higher than 50% (Director General Agriculture, 2011). As wheat is generally under irrigated in Punjab province, due to the lack or absence of canal water during winter (Ahmad et al., 2014), a huge amount of water can be saved by using drip irrigation systems to irrigate the wheat crop.

A significant drop has also been observed in rice production due to the water shortages and conventional low efficiency irrigation methods, Punjab and Sindh have a potential to increase exports by up to $4 billion annually, if the water resources are precisely managed (Iqbal & Iqbal, 2015). Drip irrigation not only increases rice production, but also uses 70% less water than traditional paddy rice, with highly reduced methane emissions and arsenic uptake (Netafim Ltd, 2020). It has also been shown that a 57% water saving can be achieved with sugarcane, while a 50% water saving for both citrus and potato crops occur against conventional irrigation methods, and a 34%, 39% and 105% yield increase has been recorded using drip irrigation for potato, sugarcane and citrus, respectively (Ashraff & Yasin, 2012). Also, a 26% increase in yield is recorded for sunflower crops using drip irrigation over furrow irrigation method (Qureshi et al., 2015).

The country's edible oil production is only 24% of the total demand and the remaining 76% is imported. There is a potential to increase the cultivation of sunflower by up to 540,000 ha with production increases up to 1,660,000 tonnes with the implementation of drip irrigation methods (Qureshi et al., 2015). Ahmad et al., (2014) also records that the yield of oil seed crops and area under cultivation can be increased using water saving technologies.

Moreover, improved product quality is observed using drip irrigation with transplant survival rates of 97%, compared to flood irrigation which was 60% (Bank, 2014). In addition, 12 ML of precious ground water and 1365 kWh of energy can be saved for each hectare using drip irrigation system with a potential to achieve efficiency as high as 95%, compared to the traditional flood and furrow irrigation (Reddy & Satyanarayana, 2010). Drip irrigation has also shown an increase in water use efficiency by 50% and yield from 35 to 100%, with reduced mortality rate of the plants. It also gives easy and efficient nutrient distribution with a reduction of labour of about 20% (Bank, 2014).

Ahmad et al., (2014) also mentioned that with the use of water saving technologies, not only can secondary soil salinization be avoided, but the irrigation cost can also be reduced. Beneficial water usage can be increased by reducing irrigation application, reducing evaporation losses, and reducing water losses in seepage and drainage.

Although surface irrigation system efficiency can be improved with improve design and maintenance, the efficiency will not be higher than drip irrigation systems (Masih et al., 2014). Similarly, developments in manufacturing technology have also considerably decreased the initial cost of installation of pressurised irrigation systems (Pakistan Agriculture Research Centre, 2010) that will improve the acceptability of these systems for the majority of small farmers in Pakistan.

Water resources can be managed properly with improved crop water productivity either by increasing the crop yields or by minimising water losses, or managing both (Jehangir et al., 2007). These factors can be well managed using high efficiency drip irrigation technology, as appreciable water savings and high crop yields are observed using this technology (Dagnino & Ward, 2012) because it allows the effective and timely application of water, fertilizer and nutrients as per the plant's requirement at various stages of its growth.

Another major benefit with using drip irrigation system is that saline water can be applied, but it is important to select the correct emitters and filtration practices, and drip tapes need to be regularly flushed, due to reduced evaporation losses. However, drip irrigation systems can only perform better than traditional irrigation methods, if they are well designed and efficiently managed.

Water saving technologies like drip irrigation have been highly recommended by World bank and other researchers (Muhammad et al., 2010). Local government officials and private organisations are also extremely interested in providing services to farmers, and researchers are also very interested in further developing and studying highly efficient irrigation application methods. Other major advantages of the drip irrigation system are discussed in detail in Section 2.2.

Therefore, as the implementation and adoption of drip irrigation has been highly by many other researchers (Kumar & Palanisami, 2010; Mangrio et al., 2013; Ahmad et al., 2014; Qureshi et al., 2015; Arya et al., 2017; Netafim Ltd, 2020) to preserve scarce water resources and promote crop diversification and improve water use efficiency, this technology which will not only enhance crop yield and quality, but will deliver energy savings.

6.4.2 Constraints in adaptability and successful implementation of drip irrigation system in Pakistan

Although the drip irrigation systems have been effectively used all over the world and has shown considerable water savings, most of the drip irrigation systems installed in Pakistan have been abandoned due to low operational and hydraulic performance. Therefore, major constraints in the adoption of pressurised irrigation systems in Pakistan are now evaluated in detail from past research analyses and personal observations, and a list of the main constraints is given below:

- Warabandi (rotational supply-based water delivery system) (Bandaragoda, 1998).
- Imbalance between supply and demand of water supplies, low discharge rates, and unreliability and unpredictability of available water resources (Ahmad et al., 2007).
- Discriminatory and inequitable water distribution.
- Farm location in terms of the distance from the canal or water course head. (Ahmad et al., 2007).
- Poor maintenance, water theft, and conveyance losses in irrigation system. (Ahmad et al., 2007).
- Inadequate current water policies and depletion of ground water due to over exploitation.
- Increased petroleum prices and constant unscheduled electricity outages with irregular supply (Mongat et al., 2015).
- Farming of close growing crops (Bakhsh et al., 2015).
- High initial cost as one of the main hindrances to the adoption of drip irrigation systems in Pakistan (Iqbal & Iqbal, 2015).

- Lack of local manufacturing facilities, and low availability of drip irrigation spare parts and components in Pakistan.
- Lack of awareness regarding the advantages associated with drip irrigation technique (Alam et al., 2006).
- The lack of knowledge and expertise with the drip irrigation technology (Iqbal & Iqbal, 2015).
- Lack of quality check and control in installed systems may have compromised the results in terms of suboptimal materials, poor design and services (Mangrio et al., 2013).
- High-skill requirements and lack of expertise in sensitive technical areas regarding design, installation, maintenance and troubleshooting of drip irrigation systems (Alam et al., 2006)
- Extensive maintenance requirement of system components, like emitters, due to clogging, damage to pipes due to rodents and insects causing leakage (Alam et al., 2006).
- Designers and farmers also need training and awareness regarding proper installation of the systems.
- Farmers also lack technical guidance regarding operation and maintenance of these systems (Mangrio et al., 2013).
- Farmers lack experience and support regarding irrigation and fertigation scheduling using drip irrigation system.
- Farmers also need awareness regarding proper filtration and maintenance to avoid emitter clogging.
- Lack of careful analysis and inclusion of all the relevant and updated factors like land topography, soil, water, crop and agro-climatic conditions.

- Lack of research on the impacts of drip irrigation adoption on water depletion at farm to catchment levels, groundwater recharge, and reduced flows to the users at the downstream end.
- Additional research is required on the evaluation of subsurface drip systems installed for irrigating different crops as farmers cannot visualise the water that is applied.
- Likewise, further investigation is required on drip irrigation systems to be installed in arid and semi-arid regions, where water is of high salinity or alkalinity, which can turn the land barren due to inadequate rainfalls (Iqbal & Iqbal, 2015).
- Massive research is required on the irrigation application time and scheduling in drip irrigation system for different crops (Bakhsh et al., 2015).
- Another potential hazard is the increase in salinity due to reverse pressure gradient in saline areas with the use of drip irrigation systems (Alam et al., 2006).
- As the additional on farm storage is required due to the inequitable and reduced surface water supplies, which will involve additional expenses, (Kahlown et al., 2007)
- The most crucial concern is the lack of updated, efficient and technically suitable design processes available for drip irrigation systems as the current farmer friendly systems are designed by third party sales representatives, even though technical professionals are required to design these systems (Bakhsh et al., 2015).

From the above-mentioned results and observations, the following recommendations are suggested:

Further ground water depletion and application limits need to be implemented to control and preserve the remaining assets, and it is suggested that the additional policies need to be implemented to improve the distribution security and equity of access to water. Farmers also need to be educated and informed regarding the state and quality of current and future groundwater resources and water scarcity that can be managed by achieving high irrigation water efficiency (Watto & Mugera, 2015).

Due to the increase in energy and petroleum prices, and electricity outages, alternative energy sources such as solar, wind, biomass, hydro and geothermal sources needs to be considered for the future sustainability of agriculture (Mongat et al., 2015). However, drip irrigation systems need to be tested with alternative energy sources to evaluate the suitability and affordability for the majority of the farmers in Pakistan.

Drip irrigation design is a complex process and requires the careful study and inclusion of all relevant and updated factors like land topography, soil, water, crop and agro-climatic conditions and suitability of drip irrigation systems and their components for varying farm locations, farm conditions and cropping patterns, as these are vital in design and performance. While drip irrigation systems are considered high efficiency irrigation system, they can also produce low performance and yield along with the water wastage, if not carefully designed and installed. Therefore, additional investment in research and development efforts are required to evaluate installed drip irrigation systems in terms of their performance on different crops and soils.

More awareness needs to be developed regarding the benefits associated with drip irrigation technology for its promotion in Pakistan. Further extensive trainings and promotion campaigns can be arranged for farmers and operators. Designers needs to be broadly skilled in terms of optimal design, and extensive training needs to be arranged for operators and farmers regarding installation, operation and maintenance of drip irrigation systems after installation.

Installed drip irrigation systems need to be evaluated in terms of materials quality and design, and further wide-ranging studies need to be carried out to analyse the impacts of drip irrigation adoption on water depletion at the farm to catchment level, on groundwater recharge, and in reduction of water delivery to downstream users. Subsurface drip irrigation needs careful evaluation and supplementary research for irrigating different crops, as the irrigation water is not visible to the operator.

The study conclusions also prove that besides the right selection of technology and irrigation method, the most critical component to achieve desired water productivity, or water saving, is the management of the system in terms of design, installation, and monitoring. Precise management can only be established by assessing systems in terms of performance and efficiency at regular intervals.

From the above-mentioned observations it is determined that the acceptability of drip irrigation systems can be improved with the introduction and involvement of skilled professionals, experienced designers, and advanced software packages. The above-mentioned recommendations will also help with improved performance, affordability and adaptability of these systems in Punjab. Due to the high initial cost and high-level of skill required, the adoption of drip irrigation systems depends entirely on government involvement and financial and technical support to make these expensive systems affordable and successful in Punjab, Pakistan (Iqbal & Iqbal, 2015).

6.4.3 Need for the evaluation of hydraulic design and improved performance evaluation

In Pakistan, three major gaps are observed which are the “extension gap”, the “research gap” and the “science gap”, with the extension and research gaps ranging from 31% to 75%, and 25% to 57%, respectively (Bhatti et al., 2009).

There is a need to develop and introduce cheap and innovative methods to improve the water productivity and irrigation efficiency, and prevailing drip irrigation methods have not been evaluated in terms of suitability and economic viability, performance and cost benefit analysis (Bakhsh et al., 2015). Further, substantial studies are required on different soils at different locations to see the performance and adoptability of drip irrigation with respect to economic material cost, payoff and constant management (Qureshi et al., 2015).

The drip irrigation design process is a highly intricate process and needs expertise as it is dependent on many factors such as type of crop, soil characteristics, land slope, climatic conditions, water source, and quality. Each factor plays an important role in the design and selection of drip irrigation system components, and traditional standard spreadsheet analysis is too basic and may lead to poor performance (Kahlown & Kemper, 2007). Hydraulic design is the key element of drip irrigation design and needs to be evaluated to determine the performance and efficiency of drip irrigation systems.

Asif et al., (2015) also agrees that the performance of these systems needs to be evaluated, tested and standardized, because drip irrigation systems can only apply irrigation water quite efficiently, if they are well designed.

Also, according to the latest scenario with installed drip irrigation systems in Punjab, system efficiencies have been improved by approximately 25% to 30% in terms of operational performance only, and no evaluation has been made on hydraulic design performance in terms of uniformity and emission measures (Khan, 2019).

Javed et al., (2015) have also stressed the importance of testing and evaluation of drip irrigation systems in order to improve the irrigation efficiency and to reduce the cost of the system. Minimum water losses with improved yield and quality had been noticed using drip irrigation systems. Due to the lack of data available on the evaluation of installed drip irrigation systems in Pakistan, a drip irrigation system installed in Punjab was evaluated and re-designed. The re-design has not only substantially reduced the head losses in lateral, sub-mains and main lines, but also reduced the installation cost from $12,000 AUD to $10,700 AUD for 4.60 hectares. These results also validate the research findings found in the present study.

These results also validate the need to evaluate the performance of drip irrigation systems installed already in Punjab. This can prove that the correct selection of technology and irrigation method can achieve the desired water productivity or water saving through overall management of the system, the design, installation, and monitoring by evaluating the systems is terms of hydraulic performance and efficiency.

Over the years, considerable advancements have taken place because of computer-assisted design tools, with developments in manufacturing technology, better simulation and analysis techniques, that can achieve more reliable and optimal designs (Pakistan Agriculture Research Centre, 2010). The latest innovations and simulation packages need to be introduced in Punjabi Pakistani drip irrigation systems, as recommended in this research project.

Multi-disciplinary analysis, and further research and development efforts are required in order to determine the best adoption process and for the impact of water saving technologies in food production, and to verify real water savings at field, farm and system level. It is also very important to have a clear understanding of the different water balance components, along with a knowledge of how certain interventions (e.g. drip irrigation systems) influence them under given field conditions (Ahmad et al., 2014).

Ahmad et al., (2007) also corresponds that the water saving impacts of water resource conservation technologies need to be well understood and documented beyond the field level as the real water savings can be much lower because of water recycling and the conjunctive use of surface and groundwater in many areas.

The performance evaluation of drip irrigation systems already installed in Punjab, Pakistan has not been completed by the irrigation industry, and an inadequacy has been observed in the current design procedure. It was necessary to propose a research project to analyse and improve the design procedure for drip irrigation systems in Punjab, Pakistan. An understanding of the operational problems, low irrigation performance and the complete failure of Pakistani drip irrigation systems has been developed and recorded here through case studies and the performance measurement of the replicated design here in Australia. This research project was formulated to check the feasibility of improving the standard Pakistani design procedure using commercially available software packages in the desktop design stage, and for design validations, post installation. The measured and simulated results produced by the existing design spreadsheets were compared and analysed. The function and accuracy of the software Hydrocalc and Eaucadi offer the feasibility of improving Pakistani drip irrigation system design procedures. A recommendation for the most feasible and reliable design procedure and software package suitable for the improvement of the hydraulic design of Pakistani drip irrigation systems will be discussed in detail in later sections.

6.5 Experimentation in Pakistan

Drip irrigation systems already installed in Punjab, Pakistan were comprehensively examined and discussed in detail in terms of design, installation, monitoring and maintenance after installation.

To achieve the afore mentioned aims and goals, this project has evaluated the causes of the low performance of existing standard designed drip irrigation systems in Punjab, by developing an understanding of operational problems, grower skill set, design practice and drip irrigation performance of the existing “standard designs” from Punjab.

The observations were made from previous personal experiences in a design office in Pakistan, and from the anecdotal evidence provided by colleagues, farmer interviews and the field-testing performed at five selected drip irrigation sites in Punjab, Pakistan. The results obtained validate the accuracy of personal observations made and anecdotal evidence collected, as similar observations were made in experimentation in Punjab at the case study sites, as reported in Section 2.7, Section 4.7 and Section 4.8. A huge number of issues are faced by farmers and operators after installation, under real field conditions. The outcomes obtained show a lack of knowledge and expertise in pre-installation data collection, as well as in design practice, implementation, installation, and management of drip irrigation systems after installation. Each component from data collection to the post-installation monitoring is critical to ensure the efficient operation and performance of drip irrigation systems. Another major limitation observed is the scarcity of data regarding crop, soil and climate for different locations in Punjab, Pakistan. This data is critical for the selection and design of each component of the drip irrigation system, to efficiently fulfil the crop water needs for each individual site. A summary of suggestions were made to improve the performance of drip irrigation systems in Punjab from the evaluation and analysis of the observations provided in Sections 2.7, 4.7 and 4.8. Detail of these suggestions and proposals are provided in the following sections.

6.5.1 Pre-Installation suggestions

According to (Salma et al., 2012) average temperature tends to increase from the north to the south in the Punjab, and in these areas more water is required to compensate for the higher evaporation losses (Qureshi & Akhtar, 2003). They also mentioned that the rainfall varies from northern to southern cities in Punjab and cropping patterns in different locations depends on rainfall distribution, the availability and quality of surface water and groundwater resources.

Therefore, cropping patterns (Qureshi et al., 2010) at each site need to be studied individually in terms of soil type, topography, crops to be grown, water quality and its water source (Bakhsh et al., 2015). Therefore, a network of weather stations along with updated soil and water laboratories should be considered and investigated to update the soil, water, and climatic conditions datasets.

Updated data regarding crop, soil, rainfall and weather will improve the drip irrigation design by optimising the emitter and lateral design to fulfil the crop water needs for varying sites. Daily, peak, and seasonal crop water requirements, accounting for the water losses and soil wetting patterns for individual crops, should be considered at the design stage to ensure optimum productivity throughout the year.

Farmers’ commitment to the improvement of crop water productivity and irrigation efficiency is another important factor to be considered, so as to efficiently select irrigation techniques for their individual needs (Bakhsh et al., 2015). Hence, all drip irrigation systems need to be designed and implemented with the mutual consent of the farmer and the operator considering all of their individual needs, and their yearly plans in terms of different crops grown in different seasons throughout the year. The farmer’s involvement in the design, and their acceptance and inclusion of personal preferences, are very important in terms of zoning, lateral sizing, and the layout required to satisfy their individual needs.

Both the drip irrigation industry, and the larger investment projects require experienced and skilled manpower (Reddy & Satyanarayana, 2010), and there is a lack of capacity building for manufacturers, sellers, installers, and local specialists (Bakhsh et al., 2015). Thus, training will raise the awareness of farmers and operators regarding the operation and maintenance of drip irrigation systems.

Successful operation of these systems demands skills and expertise. It was observed that the proper training of farmers and operators is the key to success and sustainability with the installed systems.

Further adoption of fertigation needs to be promoted to achieve real benefits from drip irrigation. Imported parts and equipment also need standardization (Reddy & Satyanarayana, 2010).

6.5.2 Design suggestions

As illustrated by Cote et al., (2003) the accurate design and management of drip irrigation system depends on the precise selection of emitter, dripline spacing, discharge, irrigation duration and the time interval between irrigations. According to Ghumman et al., (2018) precise selection of emitter discharges and spacing depends upon the soil hydraulic conductivity and soil texture. Thus, additional studies are required to evaluate these characteristics for varying soil and climatic conditions in different regions.

Another major limitation is the lack of modernized, efficient and technically suitable design for drip irrigation systems in Pakistan as the existing drip irrigation systems are designed by third party sales representatives, even though the drip irrigation system design process is a complex procedure and requires highly trained professionals (Bakhsh et al., 2015) with the standard spread sheets are used for designing each drip system.

Instead of using a “standard design” on individual farms, an adaptable and upgraded design should be generated to meet the crop requirements of an individual farm, integrating the updated crop, soil and land characteristics in the recommended software packages. Most of the installed drip irrigation systems in Punjab were found to be inadequate in fulfilling the crop water requirements and should now be evaluated in terms of performance to improve the system adequacy and productivity. Modern software packages should be efficiently used to develop cost-effective drip irrigation system designs without compromising on the quality of components. This can only be achieved with optimised design practices for emitter and lateral selection and sizing. The latest product developments from new manufacturing technology should be introduced to drastically reduce the capital cost of installed pressurised irrigation systems, to make them more adaptable and affordable for every farmer.

Moreover, drip irrigation designers and operators should now be trained with new skills in the design, installation, monitoring and maintenance of drip irrigation systems, utilising the observations and outcomes made through this project and by using modern software packages.

6.5.3 Post installation suggestions

Reddy and Satyanarayana, (2010) have observed that that the participation of the third-party agencies in the monitoring and evaluation of micro irrigation systems installed has encouraged the adoption of micro irrigation systems.

Farmers and operators require follow-up and back-up support and assistance to maintain the system and its components (Bakhsh et al., 2015). Therefore, follow-up assistance and a technical support program regarding installation, operation, and maintenance should be provided to each farmer and operator to maintain the system efficiency and performance after installation.

Farmers and operators should also be provided with the technical support and awareness regarding water and fertigation scheduling and environmentally friendly chemicals and fertilizers (Bakhsh et al., 2015).

Farmers and operators also need training and guidance in operation and maintenance of the drip irrigation systems before installation (Bakhsh et al., 2015). Farmers also lack technical assistance with small seed crop establishment methods using drip, fertilizer requirements, plant protection techniques and other agronomic practices and high value crops growing techniques using drip irrigation systems.

It is suggested to provide training and follow-up assistance to farmers and operators in all of the above-mentioned areas in light of the observations made through this research, to improve the overall performance and adaptability of drip irrigations systems. The analyses have also highlighted that the transfer of traditional surface irrigation management to pressurised irrigation management methods is not a simple solution for the improvement of performance and efficiency of existing irrigation practices and productivity.

6.5.4 Operational problems

To reduce the water and energy consumption (Afreen et al., 2013) suggested that governments need to consider the changes in canal water deliveries and provide support to farmers in on-farm water management and advanced irrigation technologies like drip irrigation.

Introduction and adoption of automation in micro irrigation as well as the processing and promotion of high value fruits and vegetables with the application of drip irrigation, particularly in canal commands areas, is necessary due to the shortage of water supplies (Reddy & Satyanarayana, 2010).

Uncertain electricity supply and irregular water supplies are two of the major obstacles to the success of existing installed drip irrigations systems in Pakistan. Electricity supplies are uncertain in two ways, firstly, that there are frequent blackouts and secondly that electricity supply varies over time. Drip irrigation systems are normally designed to be operated for long hours and often on a daily basis. Electricity outages will ultimately cause failures in meeting the crop requirements unless this has been factored into the managed system capacity. One simple way to accommodate short term power outages is to install a system with larger emitter flowrates so that the correct depth is applied in a shorter time period. Electricity supply fluctuations will result in supply pressure and flow rate changes that can be evaluated using software packages to analyse the impact on application rates and uniformity.

Poor quality components, and a lack of availability of drip irrigation components to replace damaged components are another cause of failures of systems installed in Punjab. This project focused on the hydraulic performance of drip systems rather than the quality of the components, or level of technical support, and therefore these aspects are not discussed any further.

Based on the measurements collected at five sites in Punjab, Pakistan, only Site No. 1, 2, 3 and 4 were in a working condition, while Site No. 5 was closed due to lack of electricity. The results also show that out of the five sites only two sites, Site No. 1 and 4, were performing relatively well, with reasonable pressure drops from pump through to disc filter. When recommended nominal supply pressures were applied, average emitter discharges produced were less than the recommended emitter discharges, as explained in Section 4.7. Although Site No. 2 and 3 have shown significant pressure drops from pump to disc filter, they produced average emitter discharges that were higher than the recommended emitter discharges, due to supply pressures being higher than recommended. These measurements and results show that most of the systems are not performing according to the design recommendations and have never been evaluated in terms of performance. The lack of electricity is also a major issue to run these systems effectively.

These results show that uncertain and irregular electricity and water supplies are the main obstacles for the adoption of drip irrigation systems, while poor design and management were the main reasons for the failure or low performance of drip irrigations systems already installed in Pakistan. The observations made by analysis of these systems also show that the transfer of traditional irrigation management to advanced irrigation methods is not the solution for the low performance and productivity of existing irrigation systems. The success and high performance of any type of irrigation system depends solely on the accurate design and management of the system.

6.6 Review of different components used in Pakistani drip irrigation systems

From the observations and outcomes made from the analysis of the drip irrigation components used in drip irrigation systems in Punjab, Pakistan mentioned in Section 3.2, it has been identified that all of the drip irrigation components used in Pakistan are from ISO certified, or equivalent, manufacturers.

High initial cost is one of the factors preventing the adoption of drip irrigation technology. Because of high equipment costs, the government is implementing World Bank funding for pressurized irrigation projects to install drip irrigation systems at subsidised rates to promote the technology, and to make it affordable for most farmers in the Punjab Province of Pakistan. No local manufacturing facilities are available to produce spare parts for imported drip irrigation systems components when damage occurs to pipes by insects or rodents.

Another major factor in the failure of previously installed drip systems was a lack of performance evaluation of installed systems and components, to mitigate against inadequacy of design practice in Punjab. Hence, locally manufactured system components should be tested for performance and analysis to improve the overall performance of thee drip irrigation systems.

Although this project only focuses on the hydraulic design of drip irrigation systems in Punjab, developments in manufacturing technology have considerably decreased the initial cost of installation of pressurized irrigation systems. These latest developments should be investigated and the latest and cheapest components of drip irrigation systems should be tested for their performance, and introduced into future designs to reduce the initial cost of drip irrigation systems in Pakistan, and solve one of the major deterrent in the adoption these technologies in Pakistan.

6.7 Field testing of the replicated design in Agricultural Plot

This field testing was performed to assess the drip irrigation performance of the existing “standard designs” from Punjab, Pakistan using a replicated system at USQ’s Agricultural Plot. The elements of the standard design were purchased and installed to reproduce the key elements of the Punjabi hydraulic design, to allow the ease of measurement, analysis during operation, performance evaluation and characterisation, under controlled conditions. The results from this replicated Pakistani design will be discussed in the following sections.

6.7.1 Comparison of measured and simulated emitter discharges

Drip irrigation systems are designed to apply water uniformly throughout the field by applying the same emitter water discharge through individual emitters. Proper management is compulsory for both the quantity and timing of water applied and has a great effect on the crop production (Raine et al., 2001). Although the results will be different in actual field conditions, there are lots of factors that influence the emitter flow rates in the field, as explained in Section 2.4, and these factors are discussed in detail below:

The dripline used in the field test had a filtration area of 70 mm^2 on each emitter, and has a labyrinth with a water passage of 0.76 mm × 1.08 mm × 75 mm. For the selected emitter the manufacturer has provided emitter hydraulic characteristics with the constant k and exponent x of Equation 2.1 as 0.693 and 0.46, respectively.

It was noted that specific emitters at certain distances from the supply point were producing exceptionally high or low flow rates, in all the tests performed. The emitter at a distance of 72 m from the supply end produced 17%, 20%, 12%, 29%, 81%, 13%, 18% and 27% higher emitter discharges than the simulated results in Test No. 3, 5, 6, 7, 8, 9, 10 and 11 respectively and the emitter at a distance of 96 m from the supply end also produced 12%, 21%, 24%, 8%, 30% and 32% higher emitter discharge rates than the simulated results in Test No 2, 4, 7, 9, 10 and 11 respectively. It was also noted that the emitter at a distance of 76 m from the supply end has produced 8% and 6% lower emitter discharge than simulated results in Test No. 3, 4, respectively and the emitter at a distance of 20 m from the supply end in Test No. 3 and 5, also produced 21% and 22% lower emitter discharges than the simulated results. These results highlight the unusual performance of specific emitters, producing fairly high or low discharges, in of all the tests.

That implies that despite the manufacturer's given claim for each individual emitter to be exactly the same in terms of filtration area, water passage dimensions, and geometry, it is not true. Despite best efforts, there will always be some level of manufacturing variability between emitters which will cause the flows to vary around the nominal flow rate, and these emitters which are consistently different from the nominal flowrate are a clear example of this manufacturing variability.

As this dripline is new and direct from the factory, it has had very little water passed through it, and yet there are several emitters not performing to the nominal flowrates. This show that the emitters do not produce the same flow rate throughout the field under real field conditions. It is evident that these specific emitters have varying filtration area, water passage dimensions, geometry, flow regime, its constituent material, shape and surface finish, manufacturing process and connection to the line, with varying *Cv*, exponent *x* and constant *k*.-The variation in given characteristics does occur in small magnitudes but these represent relatively large percentages of variation.

An issue with conducting these experiments outdoors was the impact of wind on the collection of small emitted droplets, and this impact has been taken into consideration for the measured results in this project. High winds occurred on the day Test No. 6 and 7 were performed using the nominal supply pressures of 27.1 m and 3.51 m respectively. High winds caused the flow of emitted water from an emitter to move along the suspended dripline from the corresponding catch can, to the catch can for the next emitter down slope. This has produced extremely variable emitter discharges for the Test No. 6 and Test No. 7 only. These extremely variable results were obtained at the highest end of the dripline, which was more influenced by the effect of the high wind. This effect did not occur along the whole length of the dripline. It was only recorded in the first 150 emitters at selected test positions in Test No. 6 and 7, where excessive differences in discharge were observed.

High emitter flow rates imply a larger water passage and temperature, while low emitter flow rate can be attributed to clogging in some emitters along with varied emitter characteristics under actual field conditions. All of the 11 tests were performed in the spring months of October and November in 2014 within 30 days, without any extreme variation in air temperatures during field testing. Furthermore, the water was sourced from a buried municipal supply so, there would be minimal change in the water temperature between tests. Therefore, it can be concluded that the variation in temperature had inconsequential impact on the emitter flow rate variation in the experimental setup at field test site. Nevertheless, temperature variation is one significant factor that may affect the emitter flow rates in the field through the year.

The observations gathered through this testing show that even after accurate design procedures are followed, and a drip system is installed correctly, the individual emitter flow rates could be affected by a wide range of factors, as mentioned above.

It is evident that the software packages produce ideal results with all the emitters producing equal amounts of flow rate while, under actual field conditions there are many important factors such as differences in pipeline pressures, variation in field slope, temperature and variation between actual emitter characteristics which may produce different results and need to be considered in designing a drip irrigation system to achieve the desired rate of emitter discharge uniformity. As the designing of typical drip irrigation systems in Punjab Pakistan lacks the use of updated climatic and field parameters, the above-mentioned factors are suggested to be implemented in the future designs to produce desirable results.

6.7.2 Applying very high and low pressures

As described in Section 2.11, Australian designers will typically choose a range of operating pressures for a typical tape, and design the system for its minimum and maximum capacity to perform within a given pressure range. The design will be limited in terms of lateral size selection to operate within that pressure range, ensuring and achieving a desired uniformity and performance using the latest software packages.

Therefore, a wide range of supply pressures were selected for both types of experimental tests on a steep “field” slope, where the water supply was applied into the highest and lowest end of the test dripline. The selected pressures ranged between the minimum recommended working pressure, up to a pressure equal to or more than the maximum recommended working pressure for the selected emitter. The objective of selecting this extreme pressure range was to evaluate the performance of the emitter and dripline over the entire potential operating range, and to test the software packages for the ability to produce realistic and accurate results for inadequate designs, with incorrect lateral sizing, under a wide range of supply pressures and slopes.

The lowest and highest supply pressures selected at the inlet of the dripline, with the water supply at the highest end, were 3.5 m and 27 m, respectively. Pressures of 3.5 m and 32 m were selected as the lowest and highest supply pressures for the tests with water supply placed into the lowest end of the dripline. A high variation was witnessed between the measured and simulated results of the tests performed using the supply pressure of 3.5 m, and for the pressures well above 30 m for the selected emitter with a nominal flow of 2 L/h, an exponent x =0.693 and constant k =0.46, in this length of dripline. This suggests that the emitter characteristic only provides satisfactory results when the pipe pressure is within the typical operating range, and caution must be exercised with any model predictions when pressures fall outside of this range.

It can be seen from the manufacturer’s tabulated recommendations in Table 3.1, that the maximum recommended lateral length for the selected dripline with inlet pressure of 15 m and 2% downhill and -2% uphill slope for a maximum of 10% flow rate variation, is 48 and 60 m, respectively. A length of 100 metres is selected for this study to test the emitter and dripline performance for a length greater than the recommended length for the given slope.

The actual length and supply pressure range is different from the length and pressure range recommended by the manufacturer for the selected emitter and dripline, and the measured discharge results obtained are highly variable and uneven. Based on these observations, low performing and under-irrigated farms with existing drip irrigation systems in Punjab, Pakistan should be evaluated in terms of size and supply pressures for the installed driplines and emitters, to analyse the errors in the design procedure that have resulted in the low productivity and performance. Additionally, after assessment of their design, alterations should be suggested to improve their performance. Similarly, future installations of drip irrigation systems in Punjab should be carefully designed in terms of lateral sizing, and then managed to obtain a preferred level of uniformity.

It is observed that the selection of operating pressure plays a vital role in the uniformity of emitter discharges along the dripline. Selected supply pressures higher than the manufacturer recommended maximum pressure of 30 m and less than the minimum of 10 m for nominal flow, has produced measured results highly variable to simulated results, which will eventually reduce the emission uniformity and performance of the system installed. To avoid over or under irrigation of the crop, the operating pressure ranges needs to be within the manufacturer's recommended supply pressure limits. The results also show that the software packages only produce ideal results in the optimum supply pressure range and shows sensitivity of the software packages to the pressure range. At supply pressures higher or lower than the recommended pressure ranges the software packages either will not produce results or will produce results that will be different from actual field results. Thus, these factors are significantly important when designing drip irrigation for actual field conditions using modern software packages.

These extreme supply pressures were selected to test the accuracy of the software packages and understand the variation of measured results from the simulated results in actual extreme field conditions. The pressures selected outside the recommended working pressures from the manufacturer will cover the extreme conditions possible in actual fields in Punjab, Pakistan. As high variations of voltage in the electricity network has been observed in Punjab, this can result in fluctuations in field supply pressure. These software packages can be used to execute the extreme conditions possible in Punjab to produce the most feasible and safe design within the recommended pressure ranges. It has been found here that the selected software packages are sensitive to the nominal supply pressure outside the recommended operating range and excess lengths, for given slopes and supply pressure ranges.

All the outcomes derived from these observations are recommended use in evaluations of existing drip irrigation systems in Punjab. These key factors can also be considered for design of future drip irrigation systems.

6.7.3 Total flow rate

The system flow rates were measured using a flow meter installed at the supply end, and the total flow rate of the system was separately estimated using the individual emitter flow rate captured for every tenth emitter during evaluations of the performance of drip irrigation systems. Simulated results for total flow rates were compared with the measured results obtained with the flow meter.

A variation in measured and simulated flow results is observed due to a number of factors. Flow results were quite comparable with measured results in all the tests performed, except Test No. 8 and 10, which clearly showed the measurement error that occurred in taking readings from the flow meter for these tests. The only difference observed was due to the limitation of the measured results taken using catch cans at every tenth emitter. More realistic results could have been taken by increasing the test sample size, using emitter flow rates from each individual emitter considering their individual emitter characteristics, but this was not possible to achieve in this project due to time and resource constraints. Different flowmeters have different levels of measurement accuracy, sensitivity, range, and response time. Therefore, selection and testing of flow meters is very important in designing drip irrigation systems.

It is not generally recommended to install flow meters close to valve elbows or tee sections, so as to avoid any turbulence that causes variation in the results. At the field test site the flow meter was installed next to the electromagnetic flow meter that had stopped working during the experimentation, and that flow meter has been attached inappropriately to the pipe with two elbows, as shown in Figure 3.8. Turbulence in this pipe section, or faults in the flow meter will result in variation of results from actual flow rates at the site. Thus, selection and installation of flow meters also plays a vital role in measuring accurate flow rates in the field. The observations show that the catch can methodology is an effective approach to measure individual emitter flow rates and can be used successfully to estimate emitter characteristics under actual field conditions. The performance and uniformity of drip irrigation systems can be measured and improved using these techniques. Furthermore, measurement and instrumental error should be considered in existing drip irrigation systems, as detailed in Section 3.9. All these observations and calculations can be used in the assessment of existing and future drip irrigation systems to be designed and installed in Punjab.

6.7.4 Constant *k* and exponent *x* calculation from measured and simulated results

As given in Section 2.4 the major factors influencing drip irrigation performance are emitter flow-pressure relation, head loss along the main line, sub-main line and lateral driplines, as these parameters constitute the hydraulic characteristics that influence irrigation performance (Thebaldi et al., 2016).

A well-designed system will not only be economically feasible but will also apply nearly same amount of water to each plant to meet crop water requirement. Under real field conditions the emitter flow rate varies due to emitter clogging, emitter type, manufacturing variations (its constituent material, variation in water passage dimensions, emitter manufacturing process, design and connection to the line), pressure changes, aging, frictional head losses, and irrigation water temperature variations (Arya et al., 2017).

According to (Kirnak et al., 2004) the variation in the supply pressure, heat during the emitter manufacturing, and the use of a heterogeneous mixture of building materials used for the production also results in alterations in the emitter geometry. Ideal drip irrigation systems will deliver the same amount of water to each plant.

Although these variations occur at the small scale of emitter passage size, shape, and surface finish, they represent a relatively large percent flow variation. This difference in the flow rates of emitters represents varying characteristics and inner workings of specific emitters.

Moreover, the variation in supply pressure and heat variability during emitter manufacturing can also change the emitter geometry and affects the emitter flow rate. (Mangrio et al., 2013)

As the flow rate versus pressure head relationship is the basic component of the emitter characteristic, the development of the flow pressure curve is essential for the emitter selection, system design, and management (Cuenca, 1989). Therefore, it plays a substantial role in drip irrigation performance. A scatter chart of the emitter flow rates

(L/h) from measured and simulated results against the pressure head (m) with water supply placed into highest end (downhill) and lowest end (uphill) of the dripline was produced. The constant k and exponent x from Equation 2.1 were derived from measured and simulated results by fitting a power curve to each data set. These were compared with manufacturer's provided values of $k= 0.693$, $x= 0.46$ and $r^2=1$.

The exponent x indicates the flow regime and emitter type and measures the flatness of the discharge-pressure curve, while the magnitude of x is the measure of sensitivity of the emitter discharge rate with respect to pressure variation on the flow rate (Mangrio et al., 2013). The value of x provided by the manufacturer for the selected emitter should be 0.46, and results obtained from two sets of experimental result calculations highlighted that x is 0.318 and 0.37 for water supply into the highest end, and lowest end, respectively. The results show that emitter is behaving as a non-pressure compensated emitter with a turbulent flow, and is relatively less sensitive to the pressure variations from water supplied at the highest end, as compared to the x measured with water supply placed into the lowest end. From these observations it can be said that the non-pressure compensated emitter is relatively more sensitive to the pressure variation for the uphill slope due to high friction losses. Emitters with x values such as 0.318 and 0.37, can be considered as medium pressure compensating types that are expected to give reasonably constant discharge over a range of operating pressures as given by (Cuenca, 1989).

The constant k indicates the magnitude of flow and contains variables such as the coefficient of discharge and emitter geometry (internal size of the emitter). The k is a constant and depends on the flow-path size and the magnitude of the flow. It was provided by the manufacturer as 0.693, whereas the measured value of k in two data sets with water supply placed into the highest and lowest end of the dripline was 0.975 and 0.856, respectively. This error in k is quite significant and higher than the manufacturer provided k of 0.693. This portrays a higher magnitude of emitter flow than expected, and an abnormal behaviour of some emitter due to variation in characteristics.

The emitter characteristics shown in Figure 5.33 indicate that the measured emitters are less sensitive to changes in pressure than indicated by the manufacturer. Furthermore, the measured dripline has higher flows at pressures less than 10m, and lower flows at pressures greater than 10m, compared to statements by the manufacturer. The reason for this behaviour is that the manufacturer’s characteristic under-predicts the measured results for pressures less than 10 m, but over predicts the flows for pressures greater than 10 m. The conclusion drawn here is that these analyses are essential for improving drip irrigation performance under real field conditions, through the evaluation of emitter flow and pressure relationships.

Drip irrigation is generally adaptable to any farmable slope. Normally the crop is planted along contour lines and water supply pipes (laterals) would be laid along the contour also. This is done to minimize changes in emitter discharge as a result of land elevation changes. There also appears to be a slight difference in the characteristic depending on whether the dripline is rising or falling with distance, due to the impact of the direction of the slope and the changing elevation along the dripline.

The simulated results obtained by fitting a power curve to each data set from the software packages show exactly the same results as provided by the manufacturer, which indicates that they are correctly utilising the manufacturers’ values. As mentioned above a slight difference in emitter geometry can cause a high variation in flow rates in actual field conditions. The variation in material quality standards, emitter’s hydraulics or low emission uniformity is unavoidable in drip irrigation systems so, these changes in emitter pressure and discharge are expected under real field conditions. These are the likely primary causes for the difference between measured and simulated results. The software packages can accurately apply the given emitter characteristics producing ideal results, assuming that there is no manufacturing variability between emitters. This shows one of the limitations of the software packages is that they cannot consider the possibility of varying emitter flows due to the factors mentioned above. Therefore, these analyses will help locate faulty emitters and abnormal flows so as to rectify issues with these measurements at regular intervals in real field settings.

A similar methodology is suggested for use on existing drip irrigation systems in Punjab, to evaluate the head and pressure relationship, and assess the true operation of working emitters under actual field conditions. These results will also help to identify further reasons for the failure of these drip irrigations systems. Any such investigation will also improve the characterisation and selection of emitters according to the crop requirements, but must include consideration of field slope to achieve the desired level of uniformity in future drip irrigation system designs in Punjab, Pakistan.

6.7.5 Irrigation performance

As the most important drip irrigation feature is uniform water distribution, it must play a most significant role in the design, management and adoption of the drip irrigation systems.

A study conducted by (Kahlown & Kemper, 2007) showed that approximately 71% of the drip irrigation systems installed in Baluchistan, Pakistan have been abandoned. The main reasons were ground water depletion, poor design and management, along with the lack of farmer training in operation and maintenance of these systems. Limitations in the design, poor handling, and non-availability of the system components also led to failure of these systems.

The average operational efficiency of the recently installed drip irrigation systems in Punjab is between 50% to 65% (Khan, 2019). There is also a lack of research and studies on the hydraulic performance evaluation of drip irrigation systems installed in different regions of Pakistan, although it is critical to test and evaluate these systems after installation. Regrettably, this is generally neglected, partly due to a lack of awareness and knowledge. Therefore, this study has been planned to analyse the performance of drip irrigation systems in Punjab, Pakistan. Many of the components are like elsewhere in the world, but the design practices are not up to date with global practices.

The failure of existing drip irrigation systems in Punjab occurs due to either complete crop failure in terms of yield and crop quality, or hydraulic failure in terms of insufficient system capacities to meet crop needs. To evaluate the system capacities of the Punjabi drip irrigation systems, irrigation performance results are measured and analysed in terms of uniformity.

Uniformity is critical in selection, design and management of irrigation systems, as ideal uniformity is not always achievable with the under and over-irrigation resulting in uneven water distribution during irrigation (Mangrio et al., 2013).

Therefore performance measures explain how well crop needs are met in terms of an irrigation water balance (Burt et al., 1997). Hence, it is necessary to evaluate the performance at regular intervals under actual field conditions, so that the shortcomings and inadequacies can be detected on time, and suitable improvements can be made.

According to Table 2.4 the recommended design emission uniformity for the selected emitter type and spacing according to the ASABE standards should be 80 to 90% and 70 to 85% for < 2% and > 2% slope respectively. According to these recommendations, the emission uniformities calculated from measured field results are only just acceptable in Test No. 1, 2, 3, 4, 5 and 6. In all other tests, the calculated *Eu* is less than 80%, which is unacceptable according the ASABE (2008) standard.

Emission uniformity depends on the minimum and average emitter discharges in the field, and it is hard to predict these before the system is installed (Mahrous et al., 2008). Mangrio et al., (2013) stated that the *Eu* is a comparative index of the variability between emitters, and measures the consistency of water application in the field during irrigation, and can be used to evaluate the quality of the emitters.

The emission uniformities were calculated using spreadsheets using the individual emitter discharge results. The *Eu* from the Eaucadi and Hydrocalc software packages were different from the measured results.

Emitter flow and flow regime is critical in drip irrigation design and this is acquired through the manufacturing variation coefficient and the emitter characteristic equation (Thebaldi et al., 2016). These emitter characteristics have not been evaluated in Pakistan

Variation in manufacturing of individual emitters results in the non-uniformity of emitter flow rates and is measured by a coefficient of variation (*Cv*) that specifies the quality of the material used in emitter manufacturing. A *Cv* greater than 0 shows the incapability of emitters to deliver the same amount of water at the same pressure (Mangrio et al., 2013). The low *Cv* indicates a good performance of the system during the cropping season.

The measured field results show that the *Cv* from emitter discharges measured in the field was higher than simulated results in all tests performed, showing the deviation of emitter discharges under actual field conditions does differs from the ideal simulated results. It is also observed that the Eaucadi and Hydrocalc software produced fairly similar results for *Cv*, in all of the tests performed. The *Cv* results are unacceptable as they rank from "average to marginal" in tests where water was supplied into the highest end of the dripline with lower supply pressure ranges than recommended by the manufacturer.

When different supply pressures and drip-line slope configurations were investigated at the ag-plot to replicate field results in Eaucadi and Hydrocalc software, the emission uniformity results were quite similar. The simulated results are in good agreement and show ideal uniformities for the trial system, as they are based on a perfect head discharge characteristic for the emitters. Under real field conditions, the emission uniformity is lower and *Cv* results are higher than the simulated results due to the variability in emitter characteristics, sampling resolution, and other minor factors such as temperature.

Sampling of every tenth emitter in the field possibly reduces the accuracy of the estimated uniformity. In the measured results taken, the sampling of flow rates and pressures were performed on every tenth emitter along the dripline. It was observed that some specific emitters were producing different output across most tests. With a small sample size there is a greater chance that outliers will skew the results. This is something that should be considered whenever testing of emitters is conducted in the field, as there will probably be the desire to test as few emitters as possible.

Moreover, the effect of temperature on emitter flow has not been evaluated in this research, and a slight difference in the water temperature may cause a variation in emitter flow rates. Temperature also indirectly affect the hydraulics of the system as friction is a function of the fluid viscosity. Furthermore, higher temperatures will cause the drip pipeline to expand, reducing friction losses and therefore potentially increasing the uniformity of flowrates. One prospective area for further investigation is the evaluation of water, pipeline and emitter temperature on the performance of the drip system.

Emission uniformities generated by software packages, and from measurements in the field are lower when using water supplied into the lowest end, compared to those results where water is supplied into the highest end of the dripline, due to a difference in the direction of flow of water. The reason for the low performance in tests with water supplied into the lowest end is the pressure loss that occurred due to the pipe friction in addition to the head loss due to additional elevation. In tests where water supply was placed into the highest end, pressure loss only occurred due to pipe friction and elevation added head to obtain higher performance. The maximum permissible length to achieve the same level of uniformity will also change according to slope, so the performance will be even lower, if the same length is always selected. The performance variation between downhill and uphill slope varies from one test to the other, depending on the supply pressure, slope variation, slope direction, and emitter discharge variation in each test. These make it hard to quantify results based on the direction of slope.

Furthermore, the measured uniformity is lower than predicted by the software packages when the supply pressure is either higher or lower than the manufacturer recommended nominal pressure range. This raises some important points that must be considered in the management of these systems and the use of the software packages. Firstly, drip systems should be supplied with the correct pressure across the entire length of the drip lateral, so that pressures are within the nominal ranges stated by manufacturers. Secondly, software design packages cannot be expected to predict the behaviour of the drip system in the field if the pressures are outside this range. For the farmers in Punjab that were asked to increase system pressures, care must be taken to ensure that these new system pressures are still within the nominal operating range.

It can be concluded that the software packages tested can be parameterised to successfully replicate the typical Pakistani drip irrigation design and can be used to assist in the sizing and selection of emitters, driplines and other important components of the system. These software packages can be used for the performance evaluation of existing drip irrigation systems installed in Punjab, providing that they are parameterised with good field measurements.

6.8 Analysis of the working principles of software packages

A well-designed system will use water efficiently and will leave no water for runoff, evaporation and deep percolation. Therefore, the hydraulic design of drip irrigation systems is the most important component in design that ensures good irrigation performance in any situation. As reported by (Bhutto & Bazmi, 2007) 81% of farms owned by farmers in Pakistan are less than 5 ha, and only 6.8% of farms are more than 10 ha in size.

Therefore, the software packages selected for this study, i.e. Eaucadi and Hydrocalc, are ideal for the design of smaller systems (less than 10 ha).

Bhutto & Bazmi, (2007) also report that small farmers are more interested in using labour intensive and less risky farming systems, while farmers holding big farms choose advanced farming systems due to their affordability and a risk-taking attitude to get higher profits. Therefore, using the recommended software packages will make these systems affordable to the majority of small farmers in Pakistan.

The present research project will also help with the development of efficient drip irrigation systems and has developed a means for analysing and redesigning the already installed drip irrigation systems successfully. It will not only improve the performance and efficiency of the systems but will also reduce the initial cost of the system.

The primary objective was to parameterize and configure both commercially available software packages for typical drip irrigation systems from Punjab, Pakistan, and then analyse the capability of these packages to replicate field measurements. The results obtained have identified the capability of these software packages to successfully and accurately predict the performance of Punjab drip irrigation systems in terms of uniformity.

6.8.1 Review of Eaucadi

Eaucadi was built for and contains a database of John Deere Water products, but it was observed that this software can easily be configured and parameterised for drip irrigation products other than the John Deere Water products. This online software stores the design files on a web server and can be accessed by authenticated users only. Eaucadi allows an unlimited number of slope entries in terms of length (m) as a distance from inlet, slope (%), and direction of slope (uphill/downhill). This package also helps with water, power and fertigation scheduling, so it is a more complete design tool. Eaucadi also gives flexibility to find the desired emitter flow rate, modifying the emitter characteristics such as exponent *x*, constant *k*, and *Kd.* In the lateral configuration, the software allows the user to enter the maximum lateral length for given supply pressure, and the emitter flow rate to achieve the desired uniformity in terms of emission uniformity and distribution uniformity.

To determine how well the Eaucadi software performed in replicating hydraulic designs features of the selected design, the measured and simulated results are compared for all 11 combinations of slope and supply pressure as shown in Section 3.7.2 and Section 3.7.3.

The matching results from three sources demonstrated that Eaucadi can competently replicate field results from Punjab, Pakistan and measure ideal performance results in terms of uniformity as claimed by the manufacturer. Although, the Eaucadi does not provide any chart results for the emitter pressures and flow rates against the distance along the dripline, detail emitter flow rates and pressure results can be exported to the spreadsheets to create charts.

Defining the average peak consumptive use, maximum irrigation time available per day, the number of laterals per row, and the water source flow rate, provides information to calculate the average irrigation rate, time of irrigation per operation, average discharge per operation, water source usage, maximum total irrigation time per cycle, and number of operations per cycle as given in Section 3.7.1.11. These outputs will improve issues regarding irrigation scheduling, explained earlier in Section 4.5.3.

6.8.2 Review of Hydrocalc

Unlike Eaucadi, Hydrocalc is accessible to all growers, designers and students. Similar to Eaucadi, Hydrocalc provides flexibility in designing a drip system, by fixing each emitter line length, pressure range, and flow rate variation and emission uniformity. It also helps with the generation of maximum dripline length for a desired emission uniformity. For cases of variable field slope, the slope can only be entered for a maximum of ten positions along the length of the pipeline.

Furthermore, Hydrocalc does not give the flexibility of modifying the emitter characteristics such as exponent *x*, constant *k*, and *Kd* to achieve the desired emitter flow rate, as this software package is restricted to available Netafim products in the online database. The resultant report generated contains tables showing pressures at ten different emitters, equally spaced along the dripline with the distance from the inlet

(m) at each respective emitter, although detailed results for individual emitters flow rates and emitter pressures along the dripline can be downloaded in the form of spreadsheets for detailed analysis.

The match of measured and simulated results using Hydrocalc highlighted that this software package can also competently replicate field results, and produces ideal uniformity performance results, as claimed by the manufacturer. Similarly, more realistic performance can be measured by testing and verifying the emitter characteristics in the field, capturing pressure fluctuations, and lateral sizes according to supply pressure ranges and slopes. The package also provides charts plotting emitter pressure (m) and emitter flow rate (L/h) against distance from the end of the pipe (m). This package assists with scheduling water application but does not provide any tool for power requirements and fertigation scheduling. The limit of ten slopes inputs, only make it suitable for small farms with less fluctuating slope along the length of the drip lateral. As most farms in Punjab are laser levelled this software package will be suitable to most areas in Punjab, as explained in Section 2.12.

6.8.3 Validation of the accuracy of software packages to replicate the selected hydraulic design

To evaluate the performance of Punjabi drip irrigation systems and to analyse the adequacy of the parameterisation of modern drip irrigation design software, the measured field results were replicated in Eaucadi and Hydrocalc software. It was one of the key objectives of this project to confirm the ability of the software packages to successfully replicate the chosen design from Punjabi drip irrigation systems already installed and to produce accurate and comparable results.

To validate the competency and usefulness of both the software packages to correctly replicate the measured results, the measured and simulated results were compared in terms of individual emitter discharges, emitter pressures along the dripline, total system flow rates, performance measures in terms of *Eu* and *Cv* and derivation of exponent *x* and constant *k*.

Although, the working of both the software packages is different in terms of elevation replication and product customisation they were able to be successfully parameterised to match field conditions and to produce accurate simulated results. Emitter and dripline characteristics were successfully replicated and customised in each software package including emitter exponent *x*, constant *k*, *Kd* and friction coefficients. Similarly, dripline length and changing elevations along the dripline was also successfully entered into both packages.

The software models have produced matching results, following the same general trend as the measured results in most of the tests performed using supply pressures within the manufacturer’s recommended pressure range for the given slope and dripline length. However, tests performed using supply pressures higher or lower than the recommended pressure range, have produced quite varying but comparable simulated results. The degree of the variation between measured and simulated results depends on the variation from the manufacturers’ recommended pressure ranges, for the given length and slope of dripline. That is the major reason for the difference between measured and simulated results.

6.9 Modern computer software design packages and field measurements to predict the performance of Punjab drip irrigation systems in terms of uniformity

As explained by Raine et al., (2001), a high irrigation performance can only be achieved by drip irrigation systems if they are well designed, well installed, and well maintained. The design procedure for any drip irrigation system mainly focuses on uniform application of water through emitters to achieve the desired level of uniformity.

This project investigated the feasibility of improving the design of drip irrigation using different existing design procedures and computer simulation models. Hence, this research was formulated to find out if the mixture of modern computer software design packages and field measurements can accurately predict the performance of Punjab drip irrigation systems in terms of uniformity. Following the methodology used in this project, individual, or a mixture of both, software packages can be used to calculate individual emitter flow rates and pressures along the dripline due to head losses, and ideal uniformity that can be achieved for the given slope and length of dripline in drip systems in Punjab.

The drip irrigation systems can be designed to achieve the maximum emission uniformity and a low coefficient of variation *Cv*, optimising through the selection and sizing of emitter and lateral according to the supply pressure range at the design stage. Hence, the actual field performance of Punjabi drip irrigation systems will not be the same as the performance evaluated using the software packages, as they produce ideal uniformities, considering every emitter has an identical head discharge characteristic, while individual emitter characteristics will vary in actual field conditions. The methodology used at the test field site here in Australia can be used to get measured results for existing drip irrigation systems in Punjab.

Optimising the lateral size and supply pressure range for the given slope and considering the emitter flow rate variation and climatic conditions in actual field conditions, a realistic performance can be evaluated and achieved for Punjab, Pakistan using these software packages. An individual software package, or a mixture of both software packages, along with accurate field measurements, can not only be used to accurately predict the performance of existing drip irrigation systems, but to correctly validate future designs before installation.

As the working of both the software packages is different in terms of replicating elevation, product customisation is necessary to find the most feasible and applicable software package to be used in Punjab.

6.10 Most feasible and applicable commercially available computer simulation model to assist in drip irrigation system design

The reliability and capability of both the Eaucadi and Hydrocalc software packages to replicate and predict the accurate performance of drip systems in Punjab has been evaluated in Section 6.8.3 and Section 6.9. The final task is to find the best software in terms of features and convenience of use for Pakistani drip irrigation systems.

In terms of accessibility, both the software packages are user friendly and available online. However, Hydrocalc is freely accessible to the general public while Eaucadi is available only to authorised users given access by John Deere Water Company. Drip irrigation designers in Pakistan should be able to obtain access after contacting the provider.

It was found that Eaucadi can be parameterised to customise specifications of any hydraulic design component to get the desired results; e.g. emitter specifications can be customised to get the desired flow rate, while Hydrocalc can only be used for the products available in the Netafim database and these databases can be updated but are available only for Netafim products.

Both the proposed software packages are equally able to replicate the slopes for levelled or less undulating farms, while for highly undulating and varying slopes Eaucadi has been found as the most suitable choice.

This study has also concluded that both the selected software packages can be parameterised correctly to match the hydraulic performance of drip irrigation systems in the Punjab region of Pakistan. Varying emitter characteristics and climatic conditions cannot be evaluated using these software packages but can be measured using the methodology proposed in this research project to determine the actual performance of the drip irrigation systems.

Both the packages also assist with the selection and design of other components of drip irrigation systems such as the filters, pumps, venturi assemblies, and water storage tanks. Both the software packages provide a facility to evaluate the ideal performance of the entire system, as well as the performance of individual laterals.

The comparison shows that both the packages are equally applicable in designing and evaluating drip systems in Punjab, but Hydrocalc, is restricted for use on farms with less variations in slope and is applicable to Netafim products only. Thus, Eaucadi will be the most feasible and applicable software package to be used in Punjab to handle unlimited slope entries for farms with varying topography, can be customised for products other than John Deere products, and can provide water, power and fertigation scheduling.

6.11 Improvement of drip irrigation system design procedure in the Punjab region of Pakistan

After investigating the capability of selected software design packages to accurately replicate the hydraulic design, the possibility of improving drip irrigation design procedures, and performance in Punjab is evaluated, comparing measured and simulated results.

6.11.1 Feasibility of improvement of design

No reliable information and data are available on the performance and evaluation of drip irrigation already installed in Punjab, Pakistan. One of the main limitations in the improvement of irrigation system performance is the corruption of data by those involved in funded projects for personal financial benefit. Most of the projects have not been evaluated correctly, and have been reported as satisfactory, contrary to fact.

The observations from Pakistan presented in earlier chapters highlights discrepancies not only in the design process, but also in data collection, installation, evaluation, maintenance and troubleshooting of drip irrigation systems. The suggestions provided in each section can be practically implemented with the drip irrigation systems in Punjab to ensure system adequacy to fulfil crop needs efficiently in terms of productivity and quality.

Data collection can be improved using updated soil, crop and climatic data, improving and enhancing the meteorological and soil water laboratories network for all cities in Punjab. The selected software packages can assist with accurate irrigation and fertigation scheduling, only if the above-mentioned parameters are accurately determined. Another essential component is the provision of training and awareness-raising for design engineers, farmers and operators regarding improved installation techniques, and performance evaluation after installation, along with trouble shooting and maintenance to maintain and improve the performance of these systems after installation. Performance of drip irrigation systems can be evaluated at regular intervals after installation to maintain the uniformity and adequacy of the system throughout the seasons, using the methodology designed in this research. Also, the provision of training to farmers and operators regarding high value crop growing techniques, along with water and fertigation scheduling, can be arranged and will improve the broad technological capability in Punjab, Pakistan.

To make these systems successful in Pakistan, it is the responsibility of companies and organisations providing drip irrigation designs to better understand the farmer requirements, and to make these systems more adaptable, affordable and user friendly. It is also recommended that these companies provide follow-up assistance after installation for the proper functioning of the system.

Clogged emitters, and emitters producing high or low flow rates can be identified using the methodology and difference with the manufacturer’s coefficient of variation, as used at the field test site in Australia.

The testing of Eaucadi and Hydrocalc for a wide range of supply pressures, slope and flow direction, make it feasible to design for different types of farms with varying topography, size, and slope, and supply pressure variations due to the fluctuating electricity supply in Pakistan. These software packages, combined with adequate emitter characteristics and climatic conditions, can be used for future designs to ensure the adequacy of the system to fulfil crop needs.

In Punjab, Pakistan, systems are usually designed manually, and only a few private companies are using modern tools in the design process. However, no data is available on the performance and design capability of these tools in terms of efficiency of drip irrigation systems. Government, private organisations, and the designers will be able to evaluate the performance of their existing hydraulic designs using the procedure outlined in this research. Organisations as well as the designers, farmers and operators will expand their awareness and improve their capability and management for operational performance, maintenance and monitoring of drip irrigation systems after installation.

There is a great opportunity for the improvement of Pakistani drip irrigation systems which includes the performance evaluation of existing systems using software packages and field measurements to improve the design practice, data collection, installation and maintenance, post-installation for systems yet to be installed.

6.11.2 Existing design procedure improvement using computer software packages

Software packages such as Eaucadi and Hydrocalc can be successfully used for the calculation, selection and design of emitter and lateral sizing for the given slope and pressure range. These software packages also predict performance in terms of uniformity measures along with individual emitter discharges, emitter pressures and head losses along the dripline. The simulated performance results can be compared with actual field measurements to determine the factors which may be leading to low performance as shown in this project.

These factors can further be analysed and considered in future designs to improve the efficiency and uniformity of future installations. This assessment and improvement cycle need to be continued to enhance existing and future designs. Asif et al., (2015) suggested that in spite of the increased popularity and acceptability of drip irrigation systems among the farmer community, the performance of these systems needs to be evaluated, tested and standardized.

The manual calculation methods used in Pakistan are inadequate for the evaluation of design adequacy, and the performance of drip irrigation systems. These software packages can be parameterised for varying field conditions for environmental, crop, and soil characteristics to reduce the limitations present in Pakistani design. Peak daily consumptive use (mm/hr) and water peak demand (mm/day) can be calculated in the Eaucadi and Hydrocalc according to the updated crop, soil and environment characteristics to calculate the daily irrigation time (mm/day), average irrigation rate (mm/day), time of irrigation per operation (hrs) etc. Eaucadi also helps with the fertigation scheduling, currently not utilised in Pakistan except for manual calculations. The individual emitters, individual laterals and the pump unit can be parameterised and designed together, in one piece of software. This software is convenient and time saving as compared to the manual calculation methods currently used in Pakistan. The manual spreadsheets are not updated according to the different field sites for different crops, environment and soil factors.

After testing the function and accuracy of these software packages to optimise the lateral design for desired performance in terms of uniformity, both the Eaucadi and

Hydrocalc offer the feasibility of improving drip system design procedures and performance. Pakistan’s current design procedure is significantly inadequate to fulfil crop needs. Selected advanced modern software packages and improved design procedures will assist in improving the adequacy and performance of drip systems in Punjab, Pakistan.

6.12 Improvement in the broad technological performance of drip irrigation systems in Punjab

The abandonment and failure of most of the previously installed drip systems has demotivated and demoralized the famer community. They are not willing to get any more drip irrigation systems installed in their fields. The government sector is also facing rejection of their proposed irrigation improvement programs due to the loss of a large amount of money already spent on these projects. The purpose of this research was to evaluate the reasons for low performance of the systems installed and to propose a methodology using advance software packages and field measurement to improve the overall performance and adequacy of the drip systems in Pakistan. The results of this analysis show that the reason for the poor performance involves faults in all major and minor sections of designing, management and installation. The project has focussed on the issues with the hydraulic design showing an inadequacy to produce a design to be able to achieve desired efficiency and uniformity under actual field conditions.

The improved design process using software packages and interventions suggested in data collection, installation, maintenance and evaluation of these drip systems as mentioned in sections above will improve the design practice as well as the broad technological performance of the drip systems in Punjab, Pakistan. The methodology used in this dissertation to calculate the field and simulated results can be replicated for existing drip systems and to calculate important irrigation performance measures. These performance measures will help in evaluating the inadequacy of the current designs and will assist in ensuring that the installed drip irrigation systems are fit for purpose and are at less risk of being abandoned. Furthermore, the data collection and use of these models will educate the industry professionals and give confidence that they are able to design each individual system rather than reverting back to standard field designs.

Thus, the outcomes and results obtained from this research will not only help in evaluating drip irrigation systems, but conventional irrigation methods can also be evaluated in terms of performance and economic viability, and their comparison will assist with the selection of the best technology for each site and crop.

6.13 Conclusion

The research gaps identified, and the conclusions drawn in this research project are given below:

The population of Pakistan has increased by over 25% in the last ten years and is expected to reach more than 230 million by 2030, making it the world's sixth most populous country. As 50% of the population is already characterised as food insecure, and 28% as severely food insecure, this will generate alarming food security issues (Masih et al., 2014). This population increase is putting enormous pressure on depleting water resources, which must be used efficiently to produce more crop per drop of water, to secure the future in Pakistan.

The single largest Indus basin irrigation system have been assessed and studied in detail to evaluate the inefficiencies and inconsistencies in the entire irrigation system, and surface and ground water resource availability at basin, canal and farm level. The observations and recommendations provided will help generate a strategic system to not only control and monitor water wastage and canal breaches but will also improve the interaction and relation between irrigation, agriculture, energy and social sectors.

Almost 19 million hectares of irrigation in Pakistan is completed with traditional surface irrigation, with overall irrigation efficiency up to 30% (Kahlown & Majeed, 2003; Ahmad et al., 2014).

Due to the low efficiency of conventional irrigation systems, improved water use efficiency and new technology that promotes crop diversification are critical for the future. Therefore researchers, government and private organisations are highly interested in drip irrigation because it will not only improve the overall irrigation efficiency by monitoring and minimising the losses but will also reduce the water consumption that will eventually increase the area under cultivation. Drip irrigation has been recommended by (Muhammad et al., 2010; Bakhshal & Masood, 2012; Afreen et al., 2013; Iqbal & Iqbal, 2015; Qureshi et al., 2015).

Drip irrigation can be promoted and successfully adopted in the areas where farmers are shifting from annual crops towards high value crops due to the shortage of water and labour. As compared to conventional irrigation practices, higher cropping intensity with substantial water conservation along with the higher yields can be achieved using drip irrigation in Pakistan and (Qureshi et al., 2015) have confirmed these results. Widespread benefits associated with drip irrigation as discussed in detail in Section 2.2 will further help the farmer community with better crop and water management.

As these systems have shown appreciable water savings with high yield all around the world, drip irrigation systems have been installed extensively in Punjab. However, due to the lack of knowledge and expertise and lack of performance evaluation, most of the systems installed have failed to perform well in terms of system design adequacy, cost effectiveness and crop yield.

There is a general scarcity of literature on the performance evaluation and current facts and figures regarding the performance of recently installed drip irrigation systems in terms of efficiency, adequacy and uniformity. This has restricted the comparison of the results from this study with other contexts, perspectives and research studies. However, the available literature validates our findings. For instance, the anecdotal evidence provided by Khan, (2019) suggests that average operational performance has only been improved from 25% to 30%, and no evaluation have been made in terms of hydraulic performance.

An updated, efficient and technically suitable design is required for drip irrigation systems in Pakistan, as the rigid “standard predesign” cannot be suitable and efficient for varying crops and land conditions. Therefore, land size, soil and water conditions, crop status and requirements need to be considered for individual site and (Pakistan Agriculture Research Centre, 2010; Bakhsh et al., 2015). This supports our findings and agrees with the need to evaluate these systems in terms of design procedure and adequacy.

In this regard agronomists, engineers and researchers need to work together to attain the optimal design and management of drip irrigation systems, considering the individual field and climatic conditions, and the farmers' financial situation, as similar observations have been provided previously (Iqbal & Iqbal, 2015; Javed et al., 2015).

Major problems of high initial cost can be reduced with precise design and lateral sizing using the selected software packages, and due to the new developments in technology, modern drip irrigation components can be introduced to further reduce the initial cost of the system (Bakhsh et al., 2015). Crop yield and quality can be improved using accurate, updated climatic, soil and water data to precisely measure the consumptive crop water requirement for varying crops and field conditions.

Therefore, the results of this study are important given the outdated and time-consuming manual drip irrigation design process in Pakistan (Kahlown & Kemper, 2007; Kahlown et al., 2007), and a lack of information on the performance evaluation of drip irrigation systems already installed under different government projects. These suggestions can be implemented to not only increase the broad technological performance and operational efficiency but also to validate the system adequacy to fulfil the crop water demand of different crops in Punjab as well as other regions of Pakistan.

A solid understanding is developed of the operational problems, reliability, grower skill set (lack of) and drip irrigation performance of existing "standard designs" installed in Punjab. The detailed findings and suggestions provided here in Section 4.5.1, 4.5.2, 4.5.3, 4.5.4 are insightful and educational for designers, farmers and operators in many contexts.

However, additional research is required to measure the consumptive crop water requirement of different crops in Pakistan, (Watto & Mugera, 2015), which is contributing to the inadequacy of the design to fulfil crop water demand.

These systems can also be made cost effective if managed correctly, and it is essential to determine the effectiveness and acceptance of these systems in terms of cost, benefits and management in different regions of Pakistan with varying soil and climatic conditions.

However, the impact of drip irrigation adoption on the Indus basin, suggests water balance components need careful evaluation at farm and higher spatial scales for varying climatic and land conditions, as they may increase the threat of soil salinization, before recommending them to farmers for large scale adoption. Qureshi et al., (2010) also emphasized this, so that the ground and surface water resources can be used efficiently without disrupting the natural balance and quality of water.

In the light of this research finding, adequate technical expertise should be developed for designing, monitoring and evaluation of drip irrigation systems in Punjab. The discrepancies and complications observed pre-installation, and from post installation assessment techniques, maintenance and follow-up, can be eliminated and controlled in future systems following and implementation of these suggestions.

It is observed that the irrigation performance of drip irrigation under actual field conditions can be lower than the simulated and manufacturer's claimed performance due to natural land conditions including slope variation over the field and varying emitter characteristics, which have been discussed in detail (Kirnak et al., 2004; Mangrio et al., 2013; Thebaldi et al., 2016; Arya et al., 2017)

Analyses of field measurements have proven that emitter flow rates can deviate from the expected flow rate under actual field conditions, due to the variation of emitter flow rates from the manufacturer's predicted flow rates, due to variation in filtration area, water passage dimensions, geometry, flow regime, constituent material, shape and surface finish, manufacturing process, and connection to the line. This variation can be considered as a change in the exponent x and constant k from the manufacturer's values and can be measured and evaluated to understand the emitter characteristics in real field conditions.

Nominal supply pressure range also plays an important role in the performance of drip irrigation systems and needs to be critically checked in the design procedure, as the emitter flows can be highly uneven with low performance at pressures lower and higher than the recommended pressure range. Depending on the selection of the emitter, the minimum and maximum operating pressures and lateral size needs to be restricted within the permissible range for the given slope, to achieve the desired uniform application across the field.

The emitter flow rate versus pressure head relationship can be applied to both existing designs, and future drip irrigation systems, to analyse the working of the emitter and its precise selection according to crop and land requirements, so as to ensure systems efficiently fulfil crop demands.

Other critical aspects to be monitored in any experimental drip setup include the slope, ability to capture flows in catch cans, water temperature, along with the possibilities of human and instrumental errors.

Accuracy of measuring equipment and standard methodology are crucial to accurately perform field measurements. Therefore, measurement equipment as well as the imported and local drip irrigation parts need standardization before implementation.

Use of either of the software packages allow the lateral design to be correctly parameterised to achieve the desired emission uniformity along the dripline depending on the slope of the farm and the drip irrigation products selected for an individual design.

However, the study has also indicated the limitation of the selected software packages to produce realistic matching results to actual field results, at supply pressures higher and lower than the recommended pressure range. Therefore, the recommended pressure range along with the maximum lateral length are key factors to achieve desirable uniformity.

The difference in the results for emission uniformity in measured and simulated results shows the deviation of emitter discharges under actual field conditions from ideal simulated results, neglecting the possibility of the variation of individual emitter characteristics, which play a major role in achieving the desirable emission uniformity under actual field conditions. The methodology used in this research will help identify abnormal emitter discharges, and the emitters can be analysed in terms of varying characteristics and replaced where needed to improve the uniformity.

The uniformity was found to be higher in tests where the water supply enters the highest end of the dripline, as compared to the tests where the water supply was placed into the lowest end. The reason for the low performance in tests with water supplied into the lowest end, is the pressure loss occurring due to pipe friction, in addition to the pressure loss due to elevation gain, while tests with the water supply placed in the highest end, only had pressure loss due to pipe friction. The maximum permissible length to achieve the same level of uniformity will also change according to the slope. The observations made validate the importance of precise design with correct inputs for the slope, dripline sizing, and emitter characteristics to ensure the correct parameterisation of the software packages.

It proves that the drip irrigation performance can be affected by hydraulics, filtration, elevation, performance of components, and hydraulic losses (Joseph et al., 2007).

Incorrect flowrates were recorded due to one of the faulty flowmeters at the experimental site. Hence, the performance of each component of the system needs to be checked thoroughly before and after installation, and also at regular intervals to maintain the performance and adequacy of the system throughout the crop season.

The evaluation of the software packages proved that both packages can be successfully and accurately parameterised according to the hydraulic design of the existing drip irrigation systems in Pakistan. However, Eaucadi is considered to be the most feasible and suitable software package, as Hydrocalc is restricted in terms of the number of slope changes and will only be suitable for farms with less variation in slope. It is also limited to simulation of the emitter characteristics for Netafim products only.

These software packages can not only improve the hydraulic design, but significant improvements can be made in the selection of pumps (calculation of pump power requirements according to the pump efficiency).

Farmers need support in irrigation and fertigation, and these software packages will also assist with the water and fertigation scheduling. Further, electrical power requirements can be calculated, monitored and alternative arrangements can be made for effective constant operation of drip irrigation systems in Punjab.

With the use of these modern software packages, individual emitter flow rates, individual emitter pressures and head losses at each emitter give more precise and controlled management of the system design. Also, these software packages will only produce more realistic and achievable results within the recommended pressure range and recommended lateral length for given slope and the future design procedure will be improved.

Design and performance evaluation procedures developed in this study will not only improve the performance of the systems but can also reduce the cost of existing as well as the future drip irrigation systems to be installed in Punjab. Similar results have been achieved in a study conducted by Javed et al., (2015), for the re-design of an existing drip irrigation system. This will also enhance the adoption and feasibility of these systems and can promote water conservation and increase crop yields in Pakistan.

Additionally, previously abandoned systems can also be evaluated and placed back into working order at suitable sites and crops.

Hence, using the procedure outlined in this study and the selected software packages will not only improve the operational performance up to the anticipated level, but the hydraulic performance can also be further improved in future designs. However, the slope and direction of slope can highly impact performance.

It is concluded that no system can perform well until it is efficiently managed no matter how well the system is designed. So, along with the correct hydraulic design, Pakistani drip irrigation systems must be well operated and well-maintained under actual field conditions, following those instructions, and the observations outlined in this study.

This study will also encourage drip installation companies and researchers to complete further studies on design improvement, installation and evaluation of drip systems, specifically for high value crops. These software packages also provide a quicker and easier way to design drip irrigation systems that will reduce the cost and time of design.

In order to precisely manage surface and ground water resources, it is important to make knowledgeable decisions following a profound understanding of the farmer’s needs, using spatial sampling and surveys to gather and link water data from canal commands, and district aquifer levels.

The outcome of the study can greatly aid in design automation, and the evaluation strategy established will improve the system management and assist with quality control in the adoption of drip irrigation systems in Pakistan. It can also boost the efficient use, equitable distribution of the resources, public as well as administration sector’s participation in decisions, planning and management to achieve sustainable system operation over time, and effective water management using drip irrigation to improve water productivity.

The research findings will not only improve the performance and adaptability of drip irrigation systems in Punjab, but will also help to efficiently manage and maintain the balance between surface and ground water resources and improve crop productivity ensuring the food security, economic returns and agricultural sustainability in future.

CHAPTER 7 CONCLUSIONS AND FUTURE DIRECTION

7.1 Summary

In this project the single largest Indus basin irrigation system type in Pakistan has been studied in detail, and recommendations and suggestions have been provided to improve the overall performance and water use efficiency of this irrigation system. The potential of drip irrigation technology and constraints in their adaptability and feasibility in Pakistan have been assessed in detail. Factors for the failure of previously installed drip irrigation systems have been evaluated to improve the hydraulic and broad technological performance of drip irrigation systems in Punjab. Design of drip irrigation systems is the most important component for the assurance of desired performance and efficiency of the drip irrigation systems to be installed. The importance and need of performance evaluation of the existing designs along with the factors affecting performance have been recognised and analysed in detail. Pakistani drip irrigation systems have been analysed in terms of components, design, installation, and maintenance. A research project has been formulated to improve the hydraulic and operational performance of drip irrigation systems installed in Punjab, Pakistan, focussing on the hydraulic design using the latest simulation models and design software available.

After the selection of typical Pakistani drip irrigation systems, a prototype system was replicated, purchased and installed in the agricultural plot area at USQ. Prior to this these components were tested and verified in terms of performance in the laboratory. The emitter flow rate and pressure were recorded using handmade fittings. The same selected drip irrigation design has successfully been replicated in the software packages Hydrocalc and Eaucadi.

The measured and simulated results were analysed in spread sheets creating charts and tables for the elevation and performance calculations. Emitter flow rates and emitter pressures have been compared with the simulated results. Total flow rates, emission uniformity and coefficient of variation calculated using field and simulation results have also been compared and analysed. The constant *k* and exponent *x* were generated using results from field test site and model simulations. The measured and simulated results have good agreement for emitter flow rates and emitter pressures in most of the tests performed using supply pressures within the manufacturer's recommended pressure range, for the given slope and dripline length. However, highly variable results are obtained using supply pressures higher or lower than the recommended pressure range. Moreover, the degree of variation between measured and simulated results depends on the degree of the variation in supply pressure away from the manufacturers' recommended pressure ranges. As well, these software packages have been tested for dripline lengths longer than recommended lengths, which has also increased the variation between results. It is difficult to quantify the difference in terms of statistical parameters between measured and simulated results, as they can be highly variable for each test. However, average emitter discharges (%) and average emitter pressures (%) are compared for the field measured and software simulated results in Section 5.5.1 and 5.5.2.

The results obtained from the field testing of selected case studies reproduced similar issues and substantiates the observations recorded in the previously installed drip irrigation systems in Pakistan. Particular emitters have been found to produce very high or very low emitter flow rates across a number of tests pointing, towards the difference of the emitter head discharge relationship from the manufacturer's stated characteristics, and indicating that all emitters manufactured are not the same in terms of the size of the opening passage, and other characteristics. Other important factors to be considered in the design of the field trials were the slope, wind capacity and direction of wind flow, along with measurement and instrumental errors.

The actual field performance results can be lower than the predicted manufacturer's performance due to the diverging natural land and environmental factors, slope variation throughout the field, lateral sizing, individual emitter characteristics and nominal supply pressure range.

Two design packages, Hydrocalc and Eaucadi, were tested and evaluated for their use with Pakistani drip irrigation systems. In both these software packages the lateral design can be parameterised to match real drip systems and then the design can be optimised to achieve the desired emission uniformity along the dripline. It was found that performance tends to be higher with the water supply placed into the highest end. The software packages can be used to assist in the correct sizing of the laterals and the orientation of the system, considering the slope and direction of the slope. The main focus of this project was to develop an efficient design practice and devise a process to evaluate the hydraulic performance of the drip systems in Punjab. The cropping zones, cropping patterns, climatic conditions, water source etc are critical in the initial selection of drip system components such as pump size, filtration equipment, emitter selection corresponding to crop water requirements, rainfall data according to agro-ecological zones, and climatic and geographical factors. Pipe sizing, head losses and hydraulic performance are determined using software packages considering the slope. All these environmental, geographical and climatic factors which affects the design process and hydraulic performance have been discussed in CHAPTER 6 in Section 6.5. The software packages have been found to be sensitive to the supply pressure range, and to lateral lengths, greater than the manufacturer’s recommended length for a given slope, as explained in Section 6.7.2.

The evaluation of the both software packages suggests that both software packages can be used for the improvement of the design procedure of drip irrigation systems in Pakistan, with Eaucadi most highly recommended software because of limitations in product selection and permissible slope entries in Hydrocalc.

7.2 Main contributions

The key findings of this project can be summarised in the following dot points:

- This study has provided new information regarding the Pakistani drip irrigation design methodology, and the maintenance and monitoring of systems installed in Punjab, Pakistan.
- The selected software packages were validated for their accuracy, features and ease of use.
- Factors affecting the performance and efficiency of the most dominant irrigation system type in the Indus basin have been analysed, and suitable

suggestions have been provided which will not only improve the efficiency of this Indus basin irrigation system, but will also help in the control and regulation of water usage and conjunctive water management and system maintenance.

- This project has also assisted with the investigation of the current design procedure, and the components of these systems used in Pakistan. After the evaluation of performance and shortcomings in existing design practice in Pakistan, and a comparison of the design practices in Australia and Pakistan, a new and improved design procedure have been developed for drip irrigation systems which are best suited to Pakistani conditions.
- The research has evaluated several drip layouts in Pakistan, and the findings and observations can be used to improve future installations of drip irrigation systems in Pakistan.
- Recommendations are for modelling to be used through the design procedure. Testing, evaluation and application of different commercially available software packages, and field measurements and simulation models performed in Australia, has helped in developing an updated and efficient design procedure suitable for Pakistani conditions.
- Use of the simulation models has highlighted the importance of having correct parameters for any simulation model to be accurate, and has assisted in a fuller understanding of design parameters or design variables and their significance in achieving desired irrigation performance, and the role of different irrigation component characteristics in the final design performance.
- A better understanding of different irrigation performance measures, their role and validity in the improvement and assessment of the overall efficiency of the

irrigation system, has been achieved.

- After assessing the drip irrigation systems, through calibration and testing of these systems using software and irrigation performance measures, the role of design methods, simulation techniques, and the different components used to improve performance in this system, has been evaluated.

7.3 Future work and direction

This study was limited to one specific design, chosen from already designed systems from Punjab, Pakistan and covers only the hydraulic performance of the drip irrigation system. Further work can be completed on aspects other than hydraulic design of the drip irrigation systems.

To improve the current work, more advanced software like IRRICAD or WACADI can be used for the modelling and design procedure of the drip irrigation systems installed in Pakistan. The process to use these software packages will be similar to the methodology presented in this project.

This work can also be extended for the detailed study of emitter characteristics and the impact of clogging and flow variation for the products from different manufacturing companies. The results can also be produced using laterals from different companies using the same software packages to evaluate different products using a range of high and low supplied pressures.

As the subsurface irrigation has become a common irrigation system in agriculture and delivers water and nutrient to the plant without wetting the soil surface. This result into the low evaporation and higher transpiration, permitting efficient water use. Other major benefits are the lower weed growth and plant diseases. Thus, there is a great potential for automation and reduced health risks in case of wastewater irrigation. One problem observed is the change in emitter hydraulic characteristics due to backpressure. Therefore, precise knowledge and further experience is required to design and properly manage the subsurface drip irrigation systems (Thebaldi et al., 2016). Similar research analysis and experimentation can be conducted on subsurface drip irrigation systems to improve the performance and compliance of subsurface drip irrigation systems in Pakistan and can be successfully adopted in the areas with low water quality to increase the area under cultivation and improve productivity.

As mentioned in Section 2.4 soil wetting patterns can be further studied to improve the drip irrigation design procedure by selecting the emitter and emitter spacing in accordance with the depth and width of wetted soil under drip irrigation in different crops and soils in Pakistan.

The precise selection of emitter discharge and spacing depends upon the soil hydraulic conductivity and soil texture. These characteristics can be further studied for varying soil and climatic conditions in different regions of Pakistan.

Similarly, additional studies can be performed on irrigation application timming and consumptive crop water requirements of different crops in Pakistan using drip irrigation technology.

Drip tapes are retrieved by most of the vegetable farmers in the world after each crop, for reuse in the next season. The cost of retrieval, storage and reuse of drip tapes and drip tape life are very important in the selection of drip tapes and emitters and need to be considered in the selection of drip tapes and emitter for different prevalent cropping seasons and cropping patterns in Pakistan.

This project has focussed on the drip lateral, but similar measurements and analysis can be completed for the submain and main line selected from Pakistani designs. The other components used in the drip irrigation systems installed in Pakistan can be evaluated in detail in terms of performance and compared with the products used here in Australia to improve the overall design procedure and performance.

Similar research can be conducted on systems already installed in Australia and can be compared with Pakistani drip irrigation designs to improve the minute details of the overall performance of the drip irrigation systems in Pakistan. A similar methodology can be used on Australian farms with installed drip irrigation products like Pakistan and can be validated with software results to better design the system and further compare the system performance. Test results from the simulation of a replicated drip irrigation design for the Punjab region of Pakistan, and two or three installed drip irrigation systems in Queensland, Australia, will help in the assessment and comparison of the system performance, and the design methods in both countries.

Along with the performance calculations and improvements in the design procedure for different crop growing techniques, the selection of perfect, cost effective systems can be made by comparing them with Australian techniques for growing different crops.

The software performance and accuracy validation, highlights that this can be used for the design of systems for high value crops, including the system selection along with components and management techniques.

Research can be conducted on other components of drip irrigation systems comparing Australian designs with drip irrigation systems of Pakistan in terms of the selection of different drip irrigation components and products along with irrigation, filtration and fertigation scheduling and techniques for different crops.

The research project outcomes and findings need to be shared with the concerned stake holders, departments and organisations to implement and improve the drip design procedure, and the broad technological performance of drip irrigation systems in real field conditions in Pakistan.

Further extensive training can be formulated and organised to educate and create awareness for farmers and operators regarding the latest advancements in drip irrigation, cost reduction, installation, management, and performance evaluation of installed drip irrigation systems, and for troubleshooting after installation. Similar teachings can be planned for designers and stake holders about the use and parametrisation of selected calibrated software packages to precisely design drip irrigation systems in Pakistan. Current water supply policies can be reviewed and altered to better suit the requirements of drip irrigation systems efficient in Punjab, Pakistan. There is a great deal of effort in attempting to improve the performance of irrigation systems by conversion to drip irrigation. Measurements should be completed to evaluate the efficiency, uniformity and adequacy of existing furrow, border and flood irrigation so that the farmers and investors will have a better understanding of the potential advantages and economics involved in conversion from traditional irrigation methods to drip irrigation in Pakistan.

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Appendix A. Detail list of the components used in drip irrigation systems in Pakistan

Appendix B. Design spread sheets of typical drip irrigation system of Punjab, Pakistan