Portable Hybrid High Efficiency Irrigation System

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This Thesis work has been done at School of Mechanical and Manufacturing Engineering (SMME) at NUST, Islamabad under the project *"**Portable Hybrid High Efficiency Irrigation System**"* and is submitted in partial fulfillment of the requirements for the degree of Master of Science program in Design and Manufacturing (DME) at SMME, NUST University.

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DEDICATION

To my Beloved Parents,
Without whom none of my success
would have been possible

&

To my Respected Teachers,
Who acted like compass
that activated the magnets of
curiosity, knowledge and wisdom in me

ABSTRACT

Agriculture is and will remain the largest employer of workforce and a source of livelihood for the masses. Indus Basin Irrigation System is the world largest irrigation system but on the other hand, it is the least efficient irrigation system (36%). Annually 24 Million Acre Feet water is lost in the field due to inefficient irrigation techniques i.e., flood irrigation and basin irrigation etc. The major audience of this research are small farmers. A Portable Hybrid High-Efficiency Irrigation Systems (HEIS) was purposed and experimentation was conducted on an available farm near Fateh Jang. Results shows that purposed irrigation system is feasible for 33.71% of majority farmers in Pakistan who own less than 2 acers land who can't afford costly HEIS. The current research envisage demonstrating a portable and hybrid HIES comprising of drip irrigation for orchards and sprinkler irrigation for row crops. The designed and manufactured system was cheap and a well efficient technique to irrigation the Alley cropping. Evapotranspiration(ET) based irrigation system was designed for calculating crop water requirement. Experimental ET calculated by Pan Evaporation has closest values to Penman Equation based on NASA Satellite collected data. The water use efficiency(WEU) of the proposed Hybrid HEIS is 64% in comparison to flood irrigation system. The on field demonstrated portable system work efficiently for irrigating one after another field which makes this system cost effective and in-reach of the local agriculturalists who could not afford expensive HEIS. Integrating Hybrid HEIS with alley cropping was a new concept and dire need of the hour which covers all aspects of irrigating the row crops and trees/orchards as well as it offered beneficial outcomes in terms of efficiency of land and water use, profit, productivity, food security and have positive impact on global environment.

CONTENTS

LIST OF FIGURES

List of Tables

CHAPTER 1: INTRODUCTION

1.1: Pakistan as Agricultural Country

Arable land and water are two principal natural resources for a country. According to world bank in 2016, agricultural land area for Pakistan was 368,440 square kilometers which is about 46% of the land of entire country [1]. Pakistan's agricultural sector also plays central role by contributing 18.9% in GDP and absorbs 42.3% of labor force [2, 3]. Roots of agriculture goes well beyond in history of this area which was visible in Mehrgarh by 8000–6000 BCE and sophisticated irrigation systems of Indus valley civilization around 4500 BCE [4]. This clearly shows the agricultural potential of the country.

1.2: Role of Agriculture in economy

Pakistan is a predominantly an agricultural country as this sector contributed 18.9% in 2017-18 financial years' GDP. Agriculture is also an important source of foreign exchange as Pakistan is a net food exporter country. Remarkable agricultural growth of 3.81% was recorded in year 2017-18, surpassed the target of 3.5% and also previous years' growth of 2.07% [5]. Around 63% of Pakistan's population is directly or indirectly involved with agriculture for livelihood [3]. Agriculture is also the primary supplier of raw products to downstream industry and contributes to exports. It also has linkages many other unnoticed statistics of economy.

1.3: Climate change

Climate is conductive in growth and development. Most of the areas receive plentiful of sunlight and rain which makes Pakistan favourable for growing abundant crop types. But Pakistan is most venerable country to climate changes and is ranked 12th among countries of the world [6, 7]. And these adversely affects agricultural production due to temperatures, changes on rain patterns, floods and negative effect on land and water resources [8, 9]. Adaption may be essential for subsistence and food security due to climate variability.

1.4: Water crisis

Agriculture sector, the backbone of Pakistan's economy also dominates in water consumption. Available water in terms of MAF of Pakistan from years range 1960 to 2015 is shown in the table figure 1.1 [10].

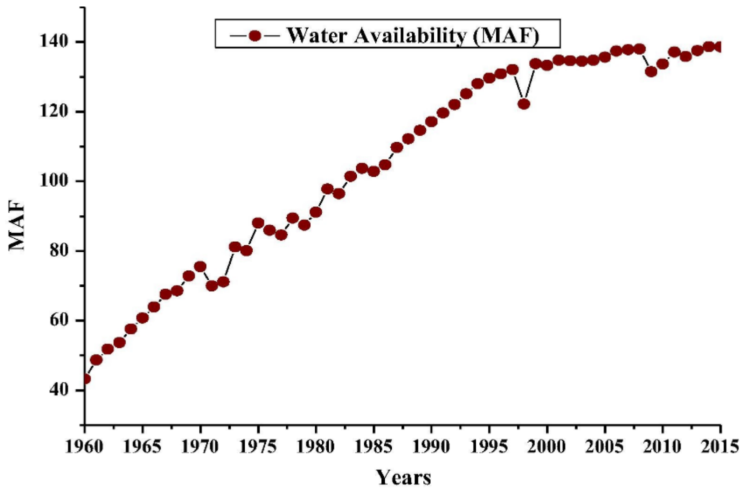

Figure 1.1: Water Availability (1960 to 2015)

Total agricultural production of Irrigated land yields more than 90% and consumes more than 93% of fresh water resources of Pakistan [10, 11]. Population growth and per capita water availability is under 800 m^3 for Pakistan, a huge stress on water available per person, as shown in figure 1.2 [10].

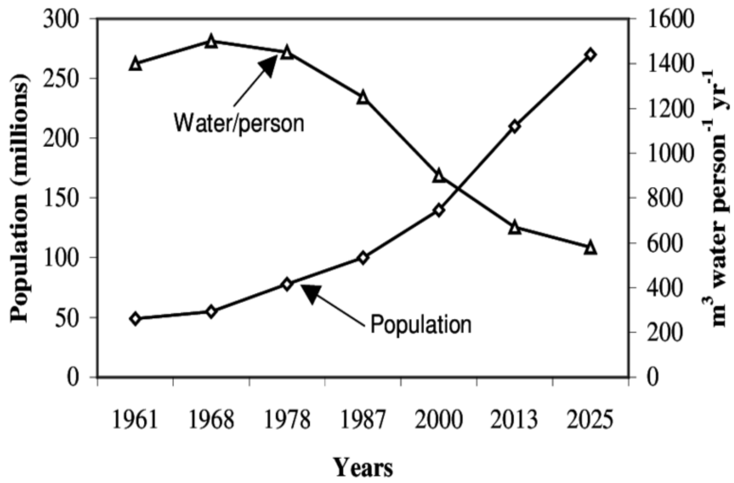

Figure 1.2: Pakistan's Population vs water availability per capita

1.5: Agricultural Land Distribution

Land is either owned or rented for agricultural purposes in Pakistan. A 2006 study by Gustavo Anríquez and Alberto Valdés classifies small land holders possessing up to 4 acers of land [12]. Agricultural land shrinks with time as because of the distribution within successors. This definition should be revised over a period a time as distribution of land between successors yields more and more small farms. According to revised definition of small land holders/tenants, they owns about 2.2 acers of farms [13]. In Pakistan, more than 56% of households have either no agricultural lands i.e. tenants or categorized as small farmers [12]. So this research is specific to small land holders/tenants, who represents the majority from the class.

1.6: Modern Irrigation Systems

High efficiency irrigation systems (HEIS) includes Drip, Sprinkle, Pivot, and many other irrigation types. These systems have specific limitations according to farm size and land conditions, and are applicable primarily to family owner-cultivators (possessing 7.5 to 25 acers) [13]. These systems have considerable installation and operating costs, which is difficult for a small land holder to bear. Basic aim of this study is to devise an irrigation system affordable for smaller famers i.e. audience of this research.

Small farms tend to sow crops with high crop intensity and crop yield to get maximum out of the available land. A tendency to sow mostly vegetables or some of the Rabi or kharif crop between orchards have been seen in Pakistan. This is referred as Alley cropping as show in figure 1.3.

Figure 1.3: Alley Cropping

Alley cropping, an agroforestry practice, allow cultivation of vegetables and agricultural crops during early years of tree growth [14]. Its beneficial agricultural approach to generate short term incomes from annual crops or vegetables and provides medium to long term products from shrubs or trees [15]. Land equivalent ratio (LER) for alley cropping is greater than 1 [16-18]. Although alley cropping yield reduced crop productivity by 17.4% to 22.8% with trees but increases tree yield by 32.7% and LER of 1.76 to 2.60 is obtained [19]. Greater LER means more crop yields which in return bore more profit for small farmer.

1.7: Current Scenario in Pakistan

When irrigation systems of Pakistan's alley cropped farms are reviewed, the row crops are irrigated using any of the available HEIS. Whereas, vegetables or annual crops between rows of shrubs or trees are flood irrigated. Using flood irrigation which is about 41% efficient, for vegetables or crops defies using HEIS (75% to 90% efficient (FAO)) for rows of shrubs or trees. Besides efficiency, flood irrigation lead to many other problems like tail water germinates weed seeds, higher labour costs, weed removal, excessive water requirements, leaching and many more. These factors decrease agricultural productivity and profitability. The solution for these problems resides in the expensive systems which are being utilized by the family owner-cultivators but are not feasible for small farms and affordable for small farmer. So, there is a need for devising a new irrigation technique which can be implemented on small farm area and affordable for small farmer.

Keeping above scenario under consideration there is a need of new irrigation technique for Small farmers with small arable land to improve utilization of land, lower irrigation costs. By the purposed irrigation system, LER can be improved. Greater LER means more food per unit area of land. So, it will be helpful for addressing food security issues while consuming lesser water resources so it can also solve water scarcity issues. We refer to this irrigation technique as HYBRID irrigation which is the more efficient and improved version of HEIS for alley cropping.

Existing irrigation system have lower LER as well as other problems like decreased irrigation efficiency, tail water germinates weed seeds, higher labour costs, weed removal, excessive water requirements, leaching and many more. Apart from the water depletion, the energy costs involved in transferring water and "lifting" it to irrigation systems via pumps is high. These factors decrease agricultural productivity and profitability. To overcome this problem, we are proposing a complete system for water distribution which is portable. The portable system will reduce the cost significantly as a farmer will not be required to buy the system for the whole field, instead the system for a portion of the farm will be procured, which will be utilized for the whole farm on modular basis. This is a very attractive system for the small and medium farmers who cannot afford the complete hybrid micro-irrigation system which utilizes minimum water and energy, as well as uniform distribution of the water resulting in the better yield with low energy requirement and lesser water.

1.8: Perks of Purposed Irrigation System

The following problems of the irrigation system will be catered in this research using the micro-irrigation system.

- The system will be low cost as for a small/medium farmer, the system will be procured for a small portion of the field, making it feasible for the small/medium farmer with maximum benefits at an affordable price.
- The water delivery system will be based on the hybrid micro-irrigation system (which is the combination of different technologies) required much lesser water and energy as compared to the flood irrigation.
- The distribution of the water will be uniform throughout the field.
- The pump required for this system will be portable and at-least 1/3 times smaller than the already instead pumps.
- This system can also be used by companies and self-entrepreneurs as a rental system for distribution of the water and fertilizer with added benefits of low running cost.
- Alley cropping also addresses the problem of leaching and sub surface contamination of water and soil [20].
- The subsidies provided by the Government of Pakistan for implementation of this system makes it very attractive and feasible for the farmers.

Also in this project we are getting valuable technical support for the agricultural irrigation system from Mr. Muhammad Mudassar Maqsood, he is the associate coordinator for the Indus Basin Initiative of the International Centre for Integrated Mountain Development (ICIMOD) at the National Agriculture Research Center, Islamabad, Pakistan. Being an agriculture and water resources engineer, we are getting value input from him regarding the system, also we are in contact with the University of Arid Agriculture, Rawalpindi for the support regarding the agriculture side when needed.

1.9: Research Objectives

For conducting a very specific and detailed research, research objectives were defined as the beginning as well-defined objectives narrows and focuses the research and ensures that the findings address the requirement of the audience (Small farmers and self-entrepreneurs).

- Comparison of Evapotranspiration obtained from different method and identify the significance of using these values.
- Development of a prototype farm with all the instrumentations and components for conducting experimentation.
- Calculation of water consumption using HEIS and conventional irrigation system for Alley Cropping
- Comparison of water saved using Hybrid HEIS and traditional irrigation systems

CHAPTER 2: LITRATURE REVIEW

2.1: Agricultural Water Consumption

Water shortage may affect up to two thirds of the world's population over the next several decades [21-28]. Maintaining ecological flows to sustain ecosystem services is essential but will be challenging in the face of growing pressure. Water scarcity is global and can aggravate in the future. Since it is impossible to create water resources in addition to those provided by nature, some authors emphasized the efficient use of water resources to minimize undesirable and preventable water losses during storage, transportation, application and use [29]. Pakistan's agricultural sector uses much more water than the world's average water consumption, which clearly reveals the unjust allocation of water to this sector [30, 31]. Total water consumption by different sectors is depicted in figure 2.1 [32].

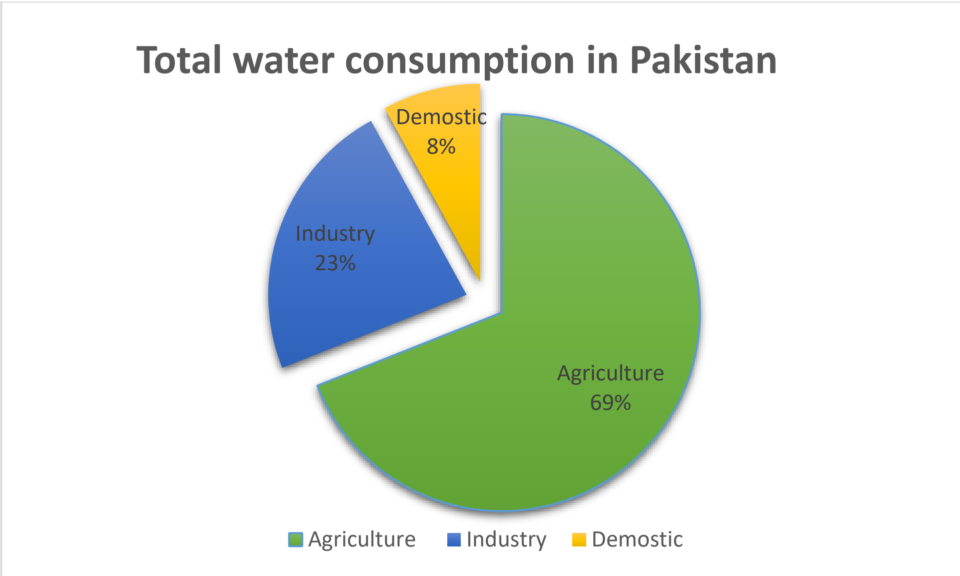

Figure 2.1: Total Water Consumption in Pakistan

2.2: Water Resources and Losses in Pakistan

Agricultural production depends on adequate availability of irrigation water supplies. With population growth, urbanization, industrialization and climate changes, the agricultural sector will encounter a variety of challenges in the near future [33, 34]. Pakistan's agricultural land lies in the arid to semi-arid region. The average rainfall ranges between 328 mm in southern regions to 2000 mm in northern areas [35]. So, to accommodate water and irrigational needs, the country has largest contiguous irrigation system comprising of Tarbela, Mangla and Chashm reservoirs. There are 23 barrages/headworks, 12 inter river linked canals, 45 canals commands covering more than 60,800 kilometers and this canal network providing water to over 140,000 watercourse [36]. Area irrigated by canal commands is about 16 million hectares (Mha) and 4 Mha is rainfed. Rivers are the major sources of irrigation water supply system, melting glaciers forms about 70% of these rivers and remaining comes from monsoon rainfalls. Although Pakistan has a marvelous gravity flow system which does not require any other energy source for flow, the irrigation efficiency is very low which is about 40% due to water losses during application and operational processes [37]. Major water losses take place during delivery to fields from headworks on river through canals and water courses and from the fields which are being irrigated. For enhancing efficiency of irrigation system and minimizing these losses, we must monitor and utilize efficient and latest irrigation methods such as drip and sprinkler irrigation. Per year profitability and per unit land productivity can be increased by using farming techniques such as Alley cropping.

2.3: Literature Review on HEIS and Alley cropping

There is a broad literature on land and water productivity and the effects of different irrigation systems and practices on agricultural productivity. This chapter includes some selected studies, firstly covering International perspective and Pakistani background from the literature on HEIS (drip and sprinkler irrigation) and second part including use of HEIS in alley cropping.

For applying water efficiently, there are number of techniques which possesses such a potential. However, each method performs best under specific agricultural conditions. For instance, sprinkler irrigation is suitable for undulating terrain, as it is difficult to irrigate fields through gravity. Similarly for point irrigation i.e. especially for orchards, drip irrigation is highly suitable [38]. Drip and sprinkle irrigation are the forms of pressurized high efficiency irrigation techniques. Pakistan has been categorized as water deficit country as irrigation water is becoming scarce and has approached to about 1000 m^3/capita [39]. Current pace and projection show that water availability will reach 915 m^3/capita in 2020 [40]. As certain from above facts and figures, irrigation land and water productivity and efficiency is the direst need of the hour, which reportedly is as low as 0.1 kg/m^3 [41].

The study investigated the significant conservation of water resources using drip and sprinkler irrigation systems in water limited areas of India [42]. The study showed that water loss was reduced by drip irrigation when water was dripped directly into the soil at the crop roots, which led to significant water savings. Research has also shown that drip irrigation is best for row crops. Compared to conventional irrigation methods, the use of the drip irrigation allowed to save water from 25% to 60% and increases yield by 60%.

A study was conducted on field trials to assess the impact of various irrigation methods on yields of cotton under southern Punjab (Pakistan) climatic conditions [43]. The study showed that the drip irrigation significantly enhanced the yield of cotton compared to furrow irrigation. The maximum water utilization efficiency of 7.9 kg/ha/mm and a water saving of approximately 54% were recorded in the drip irrigation system compared to the furrow irrigation system.

According to a research conducted in North China Plain by Zhang, the crop yield and WUE (water use efficiency) was observed in a wheat field which was irrigated by sprinklers and surface irrigation methods [44]. Results suggested better crop yield with high WUE of wheat fields under sprinkler irrigation.

A study for investigating the impact of various drip and furrow irrigation methods on WUE in western Iran was conducted [45]. The results showed that water consumption in furrow irrigation was almost 1.8 times more than in drip irrigation. They also found that grain yields using drip irrigation setup were 188 kg/ha higher than furrow irrigation. The water efficiency in the drip irrigation system (1.39 kg/ha/mm) was even higher than in a conventional furrow irrigation. (0.492 kg/ha/mm).

A study by Narayana Moorthy was done to examine the effects of drip irrigation systems on cotton and the potential economic benefits for farmers in three case studies [46]. 50% reduction in irrigation costs due to drip irrigation was observed while reporting 45% water savings compared to conventional irrigation methods. The study also measured 114% higher productivity than conventional irrigation.

The results of two-year study conducted on cotton field in Uzbekistan showed that ET-based scheduling method can achieve significant water savings of 25–34% without a significant change in yield [47]. This increased water productivity by 34-50%. If this method is widely used by water user associations (WUAs), large quantity of water can be saved that can be directed towards horizontal expansion of irrigated agriculture or for other purposes, such as supporting ecosystem services.

International Commission on Irrigation and Drainage (ICID) published irrigation report of 45 countries including China, USA, Mexico, India, Italy, Brazil, Spain, Korea, Iran, South Africa and Middle East, where the largest areas were under drip irrigation systems [48, 49]. According to the FAO Aquastat website(2008-2012), only 15 countries practiced drip irrigation (localized irrigation) out of 199 countries around the world, which has increased to 85 countries [49, 50]. The global Aquastat data in figure 2.2 also showed that about 86% of the area is surface irrigated, 11% with sprinkler and 3% with drip irrigation [51]. These figures depicts that changes in the agricultural production system have aimed WUE and significantly enhancing food security preferably by HEIS [52]. So, it is important to recognize the consequences of HEIS on productivity, profitability, water saving and water use efficiency.

Alley cropping is an agroforestry technique to increase land productivity, combines the production of crops (including trees/orchards) and forest plants and/or animals simultaneously or sequentially on the same land and uses farming management techniques compatible with cultural practices of the local population [53, 54]. The motive of this research blends alley cropping (traditional agricultural practices) with the modern irrigation system (HEIS). For obtaining optimum results, every corner of agricultural process is stretched for maximizing profitability, productivity, water use efficiency and food security. Forthcoming discussion is based on alley cropping technique using any of HEIS.

A research on Alley cropped hedgerow fruit trees was conducted using drip irrigation system [55]. It turned out that fruit trees withered, and some died without drip irrigation. The height and plant canopy of fruit trees with drip irrigation grew better. The vegetative growth of mango, lemon, star apple, guava and sapodilla with drip irrigation was 32, 80, 38, 55 and 20% higher than without irrigation. Drip irrigation of fruit trees during the dry season with rainwater collected during the rainy season could be the best strategy to reduce fruit tree damage and increase the growth rate, which will lead to an increase in WUE and productivity, quantity and quality of fruits. This research presents sustainable management and can contribute to alley cropped rainfed agricultural areas especially Rawalpindi, its surrounding area and other rainfed regions of Pakistan.

Ecological and economic benefits of alley cropping are well known. Integrating alley cropping technique with HEIS can even yield higher profitability, water use efficiency, productivity and ensures food security in forthcoming decades. A somewhat similar study was conducted by intercropping tomato and coriander by Marouelli in Brazil [56]. The objective was to assess the impact of both sprinkler and drip irrigation systems on production of tomato, when cultivated both as a single crop and intercropped with coriander. It was observed that better productivity of coriander was achieved by sprinkling. Tomato plants show 47% higher water productivity index under drip irrigation than that from sprinkler irrigation. Pests and diseases were also controlled by use of sprinkler irrigation in the tomato plants. Intercropping coriander with tomato reduces the damage caused by borer insects to the tomato fruits, being a promising strategy for the ecological management for pest and disease control in agricultural production systems.

It has been suggested that inclusion of a tree component in the agricultural system, in bunds and borders (sequentially with crops) or in intercropped agroforestry configuration, can led to increase land productivity and at the same time diversify agricultural enterprise and improve the economic security of small farmers [57-60]. Due to constantly low grain prices, which are associated with the subsequent abundant harvesting from these intensively cultivated fields, alley cropping is becoming increasingly attractive to farmers.

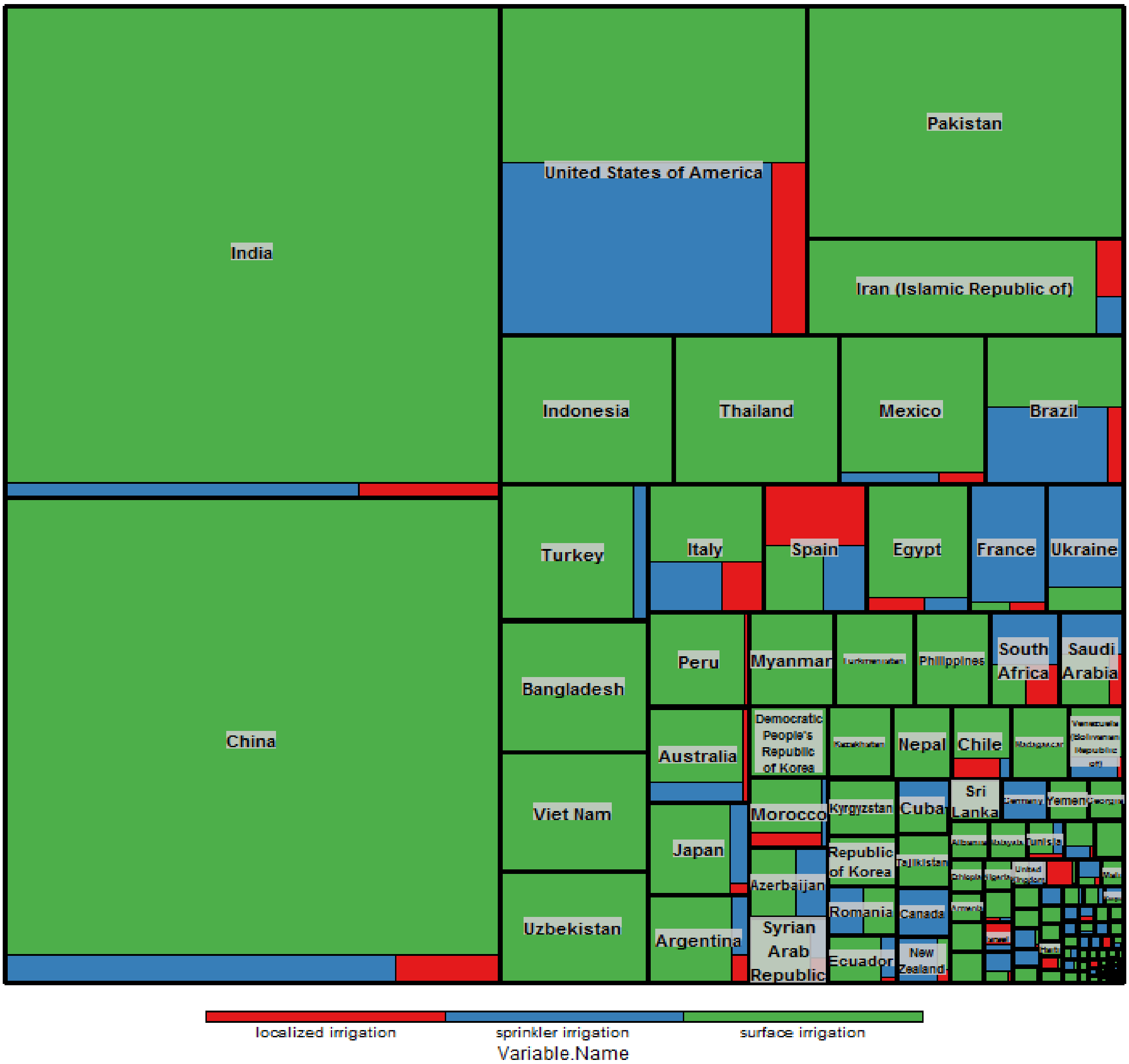

Figure 2.2: Distribution of area equipped for different irrigation by technology within each country and globally [51]

A review of experiments showed that pine and eucalyptus plantations reduce runoff by an average of 40 mm by 10% increase in forest cover as compared to grassland [61]. Shrubs and hardwood offer reduction in runoffs by 10 mm and 25 mm. This depicts vitality of orchards in alley cropping especially in rainfed (Islamabad and surrounding regions) and hilly northern areas of Pakistan. The hydrological effects of afforestation are generally recognized to be positive as it helps in reducing runoff and erosion, reducing sediment loads and improving water quality, improving the microclimate and control of nutrient flows [62].

Indian forest department has positively experimented growing wheat, mustard and sugarcane as co-crops with trees in various configurations [63]. Alley cropping provided farmers with a significant additional income per hectare and created employment [64, 65]. In addition, large amount of wood produced annually by this technique helped to meet growing demands of wood in plywood, pulp, and match industries, which generated additional employment opportunities in the region [66]. These results reckons that alley cropping is economically viable and more profitable than many of the crop rotations [65, 66]. Nearly all studies on alley cropping show an improvement over monoculture [64, 67, 68]. Singh and Sharma conducted studies on bund planting with similar outcomes [69].

Diversification of agricultural production with trees/orchards in cropping system by converting agricultural land into alley cropping systems, or by planting bunds and boundaries can improve livelihoods, increase economic security and productivity for small farmers. Growing trees on a farm directly reduces the burden on forests, biodiversity, wildlife and reducing carbon from atmosphere. Approaches to meet the ever-growing demand for shelter, fiber and food within scarce and limited land and water resources should be reliable with the global intention to preserve biodiversity of Earth [62]. The key to maintain forest ecosystems in tropical and densely populated developing countries like Pakistan, is to meet basic needs as described above by growing trees/orchards outside forests, i.e., on-farm.

It can be concluded from above cited literature the integrating different HEIS with alley cropping is a new concept and dire need of the hour which covers all aspects of irrigating the row crops and trees/orchards as well as it offers beneficial aspects in terms of efficiency of land and water use, profit, productivity, food security and have positive impact on global environment.

CHAPTER 3: EXPERIMENTATION

3.1: List of Equipment

Different type of equipment was used for the experimentation and can be categorized into the irrigating equipment and data collection equipment. The details and specification of the equipment will be discussed later in the experimentation section. The list of equipment that are used for the experimentation are given bellow.

1. Portable test stand
2. Water Pump
3. LDPE pipe
4. Adjustable water emitters
5. Sprinklers
6. Water meter
7. Elbows and joints

3.2: Experimentation Field and Layout

An area of 1 kanal (75 ft x 75ft) was selected in already available field near Fateh Jang, Rawalpindi, Pakistan. Previously, 12ft x 12ft farm was selected in NUST premises for experimentational purpose. But selecting a small farm do not validate the actual amount of water required for the field. Field parameters for conducting experimentation are as below:

Working area for HEIS irrigation	75ft x 75ft
Max # of Emitters	36
Max # of Sprinkles	50
Pipe diameter	1’’
Portable trolley	Roller type(Iron made)
Water meter	2.5 m3/hr

Table 3.1: Hybrid HEIS Field parameters

Working area for Flood irrigation	75ft x 75ft
Channel diameter	2 ft
Max flow rate	16 LPS (liter/second)

Table 3.2: Flood irrigation Field parameters

2 plots of same sizes were used for conducting experiments at the same time because of time conservation and providing similar climatic conditions for validating results. Google Earth image i.e., figure 3.1 shows the basic layout of the field. Green bordered area is irrigated using Hybrid HEIS and Yellow bordered area is flood irrigated. Water pump station and water channel is highlighted in blue. Purple lines are the 6 LDPE drip emitters pipes and the white lines represents sprinkler irrigation for Hybrid HEIS.

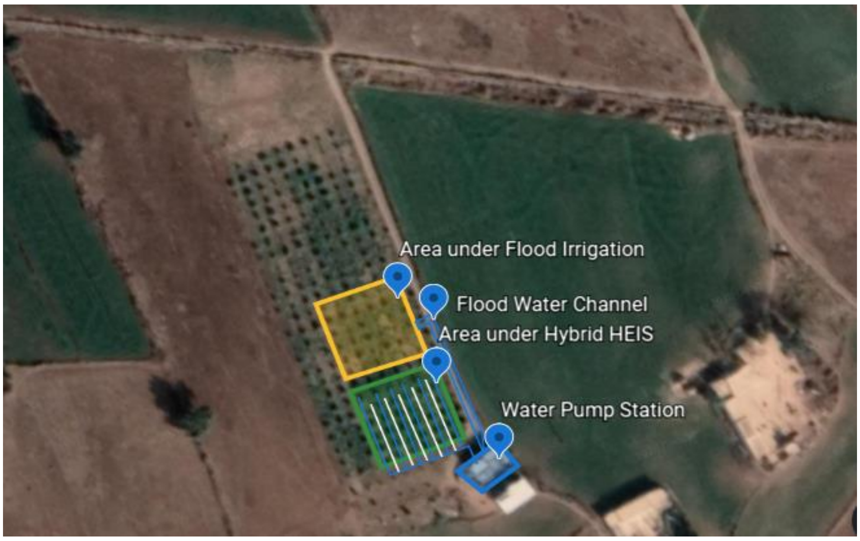

Figure 3.1: Field Map

3.2.1: Field Layout:

The available farm had an area of 13.15 kanals (Kanal is traditional unit of land area used in Pakistan and India which is under use even before British Empire). To standardize the calculations and results, an area of 1 kanal was selected for implementing purposed irrigation system. Two fields were developed at the same time for experimentation purposes to provide both areas of land the same atmospheric and climatic conditions for validation of results. Flood irrigation was already in practice and no new development or equipment was required for that part of experimentation. Software based Field layout for area under Hybrid HEIS was done for calculating the number of sprinklers, emitters, length of LDPE pipe and joints required for irrigation purposes. Same water pump was used for both irrigation setups. Hybrid HEIS field layout is shown in the figure 3.2.

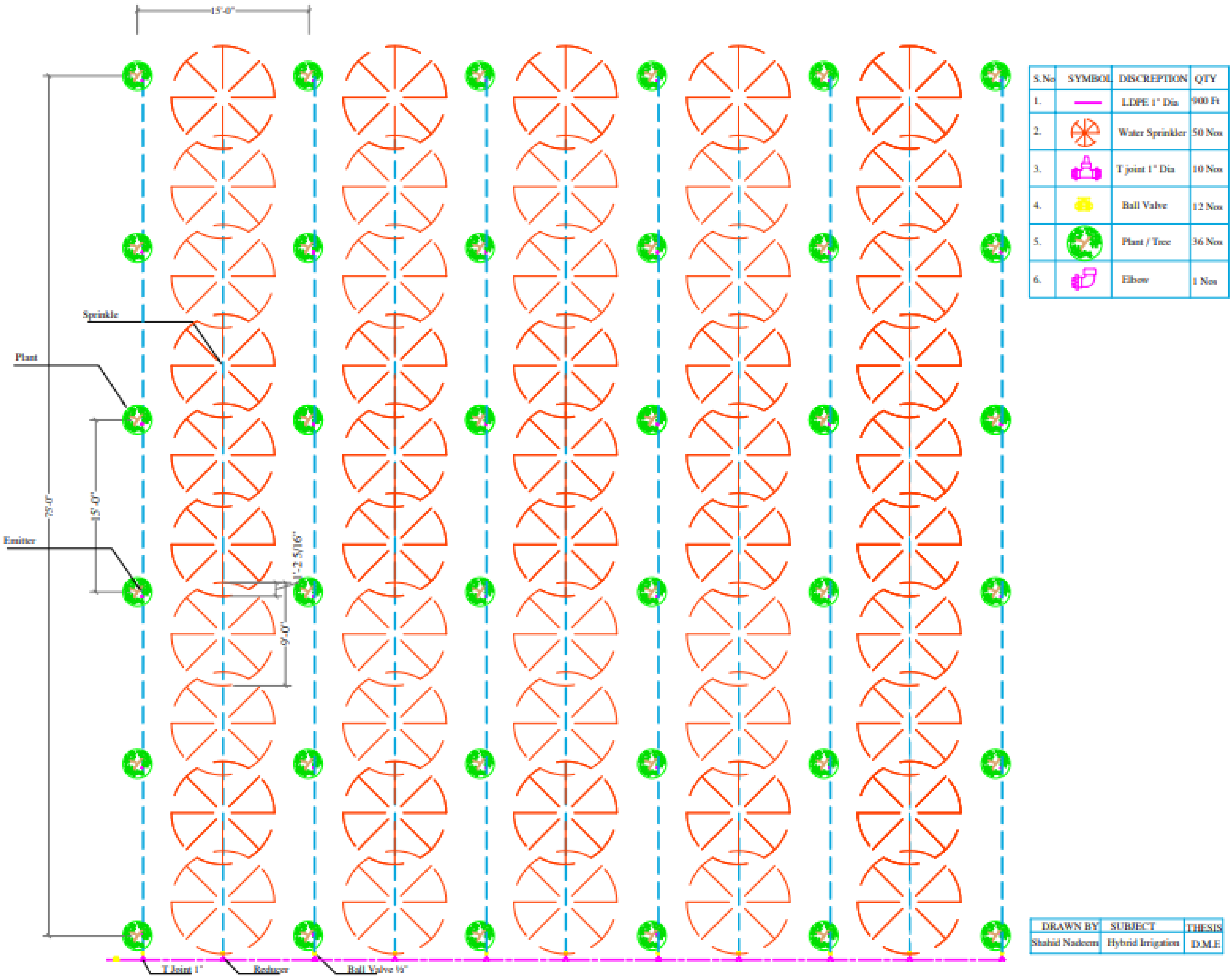

Figure 3.2: Hybrid HEIS Field layout

There were 6 rows and 6 columns (Total 36 in number) of lemon plants in an area of 75 ft^2. Each plant was at an equidistance of 15 feet from each other. 3 columns of Alley cropped vegetables were grown between two consecutive columns citrus plants.

In the selected farm of 75 feet by 75 feet, there were 6 rows and each row had 6 trees/orchards. In total, 36 trees/orchards were to be irrigated. To reduce system cost it was decided to use one emitter/dripper per plant with greater flowrate to address its water requirement. This also impacts selection of pipe diameter for water delivery, but the cost of water emitter was more significant than the cost of pipe with larger diameter.

3 consecutive vegetable rows between the 2 rows pf plants were irrigated using one water pipeline and there were ten sprinklers installed on each pipeline. Number of sprinklers were determined by field layout designed above. Selection of sprinklers was done based on quantity of water required and ability to work under low pressure. Selected sprinklers covered an area of 9 feet when deployed on site. The overlapping of each sprinkler was about 1.2 feet for proper irrigation and coverage of land where vegetables were grown.

3.3: Water Requirement Calculation

Due to the difficulty of obtaining precise measurements on site, forecasting methods are used for crop water requirements. The methods often must be applied under very different climatic and agronomic conditions from those in which they were originally developed. Testing method accuracy under new conditions is laborious, time consuming and costly. Methods used in this research for calculating water requirements are based on guidelines and the recommendations formulated by FAO to calculate Crop water requirements of crops under various climatic and agronomic conditions [70].

The effect of climate on crop water requirement is determined by the evapotranspiration (ET_O). ET_O is expressed in mm per day and represents the average value of water required in a period. The four methods are presented for calculating ET_O as prescribed by FAO, The Blaney-Criddle method, radiation, Penman and Pan Evaporation. First, the choice of method should be based on the type of climate data available and the precision required to determine the water requirements. The climatic data required for the different methods are:

Method	Temp-erature	Humidity	Wind	Sunshine	Radiation	Evaporation	Environ-ment
Blaney-Criddle	Ø	ǂ	ǂ	ǂ			ǂ
Radiation	Ø	ǂ	ǂ	Ø	ф		ǂ
Penmen	Ø	Ø	Ø	Ø	ф		ǂ
Pan Evaporation		ǂ	ǂ			Ø	Ø
ǂ = Estimated data		Ø = Measured data, if available				ф = if available, not essential	

Table 3.3: Methods for calculating ET_O

One objective of this research was to calculate ET_O by all these methods. Results of ET_O calculated by NASA (The National Aeronautics and Space Administration) satellite data using Blaney-Criddle, Radiation and Penmen method will be compared by the method with past ten years of experimentally calculated data (courtesy of Engr. Muhammad Mudassar Maqsood ICIMod, Pakistan) i.e., pan evaporation. So, to fulfil the research objective, this section of report will be detailed and all terminology will be discussed in depth for better understanding of the audience.

3.3.1: Blaney-Criddle Method

This method is recommended for areas where only air temperature climatic data is available. The relationship, which is the average value for a given month, is expressed as follows:

$$ET_O = c\,[p\,(0.46\,T + 8)]\ \text{mm/day}$$

where: ETo = evapotranspiration in mm/day for the month considered,

T = average daily temperature in ^{O}C during that month,

p = average daily percentage of total daytime hours derived from Table 3.4 for a given month and latitude.

c = adjustment factor which depends on the sunshine hours, minimum relative humidity, and daytime wind estimates.

Latitude North South.1/	Jan July	Feb Aug	Mar Sept	Apr Oct	May Nov	Jun Dec	Jul Jan	Aug Feb	Sep Mar	Oct Apr	Nov May	Dec Jun
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	. 17	.13
58	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.1 7
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
5o	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.2J	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.26	.24	21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

1/ southern latitudes: apply 6-month difference as shown.

Table 3.4: Average daily percentage of total daytime hours

Using general information and references on humidity, sunshine and wind [71]:

	Rhmin	n/N	U daytime	Block Fig. 3.3	Line Fig. 3.3
Oct-March	medium	medium	light/mod	V	1-2
April-May	low/med	high/med	moderate	IV-V, I &II	2
June-July	medium	high/med	moderate	II & V	2
Aug-Sept	medium	high/med	light/mod	II & V	1-2

Table 3.5: Parameters for calculating ET_O by Blaney-Criddle Method

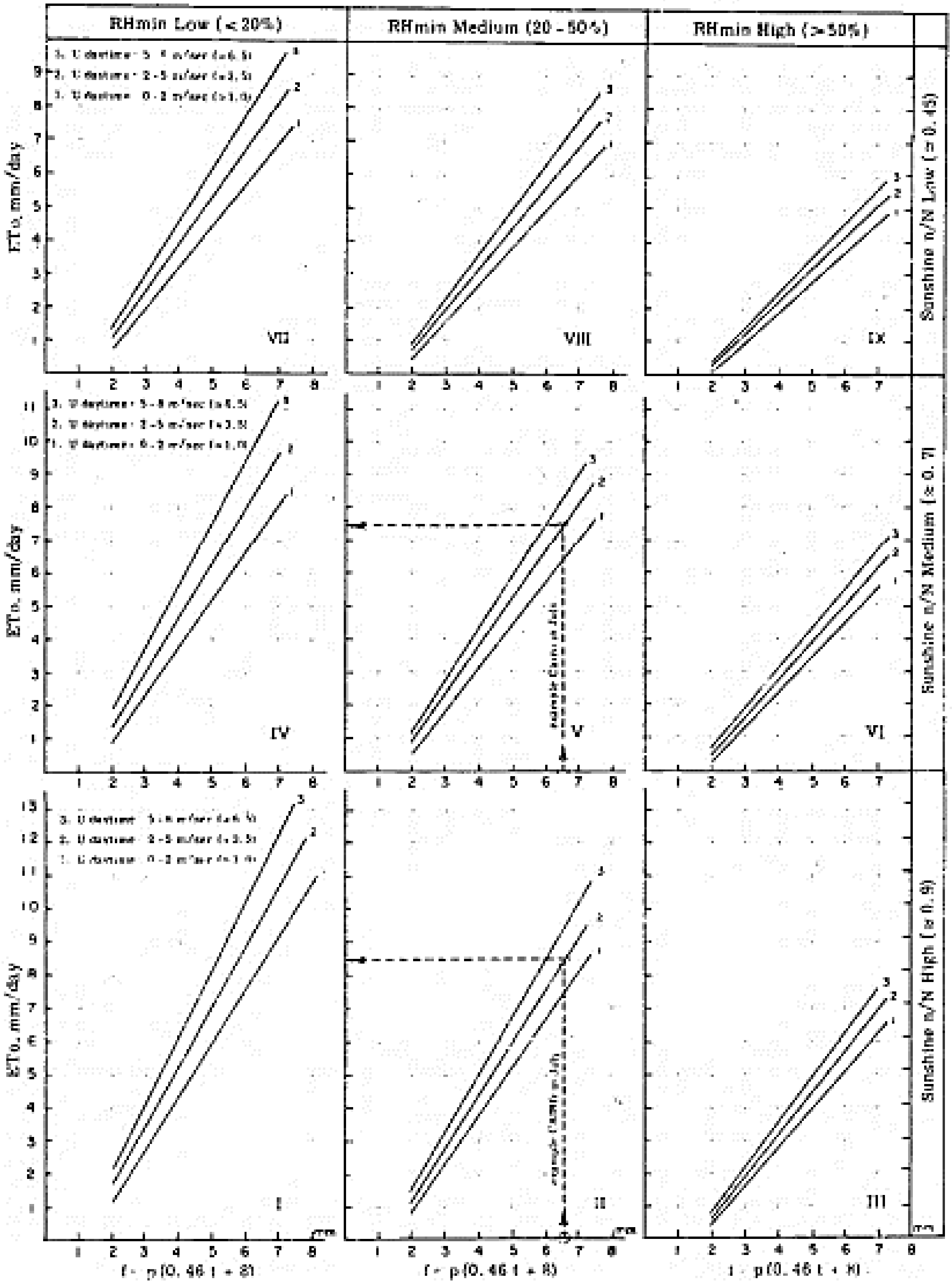

Figure 3.3: Prediction of ETo from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and daytime wind.

Daily average temperature (T) for the past 38 years from 1981 to 2019 was used from online available NASA's meteorological data for calculating ET_O [72].

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp.	1981-2019 (NASA)	10.7	13.0	18.3	24.6	31.1	35.3	34.0	31.8	29.3	24.1	17.9	12.8
p =	From table 3.4	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.22
p(.46 T+8) =		3.02	3.50	4.43	5.61	6.92	7.76	7.49	6.79	6.02	4.85	3.80	3.11
ET_O	From table 3.5 & fig. 3.3	2.10	2.83	3.85	6.53	9.10	9.35	9.10	7.81	6.70	4.30	3.00	2.30

Table 3.6: Calculation of ET_O by Blaney-Criddle method

3.3.2: Radiation Method

The radiation method is an adaptation of the Makkink formula (1957). It is recommended for areas where measured radiation, sunshine and air temperature are available climate data, but no measured humidity and wind levels are available. Though, Knowledge of general levels of wind intensity and air humidity is required. These should be estimated using extrapolations from nearby areas or local sources or published weather reports. The radiation method should be more reliable than the Blaney-Criddle approach presented.

To calculate solar radiation (Rs) from sunshine duration or cloudiness data, to determine the weighting factor (W) from temperature and altitude data and to select the appropriate adjustment as given by the relationship between W.Rs and ETo in Figure 2 for different mean humidity and daytime wind conditions.

The recommended relationship (which is the average over the specified period) is expressed as follows:

$$ETo = c\,(W.\,Rs)\ \text{mm/day}$$

where: ETo = evapotranspiration of the reference crop in mm/day
Rs = solar radiation with equivalent evaporation in mm/day
W = weighting factor, depends on altitude and temperature
c = adjustment factor, depends on wind conditions and average humidity

Latitude (Northern Hemisphere)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
50°	3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2
48	4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7
46	4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3
44	5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7
42	5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2
40	6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7
38	6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1
36	7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6
34	7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2
32	8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8
30	8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9,5	8.3
28	9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8
26	9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3
24	10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7
22	10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2
20	11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7
18	11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1
16	12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6
14	12.6	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0
12	12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5
10	13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9
8	13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3
6	13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7
4	14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15,1	14.5	14.1
2	14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4
0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 3.7: Extra Terrestrial Radiation (Ra) expressed in equivalent evaporitic in mm/day

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
Altitude (m)																				
0	.43	.46	.49	.52	.55	.58	.61	.64	.66	.68	.71	.73	.75	.77	.78	.80	.82	.83	.84	.85
500	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.88	.88	.89
4000	.55	.58	.61	.64	.66	.69	.71	.73	.76	.78	.79	.81	.83	.84	.85	.86	.88	.89	.90	.90

Table 3.8: Values of Weighting Factor (W) for the Effect of Radiation on ETo at Different Temperatures and Altitudes

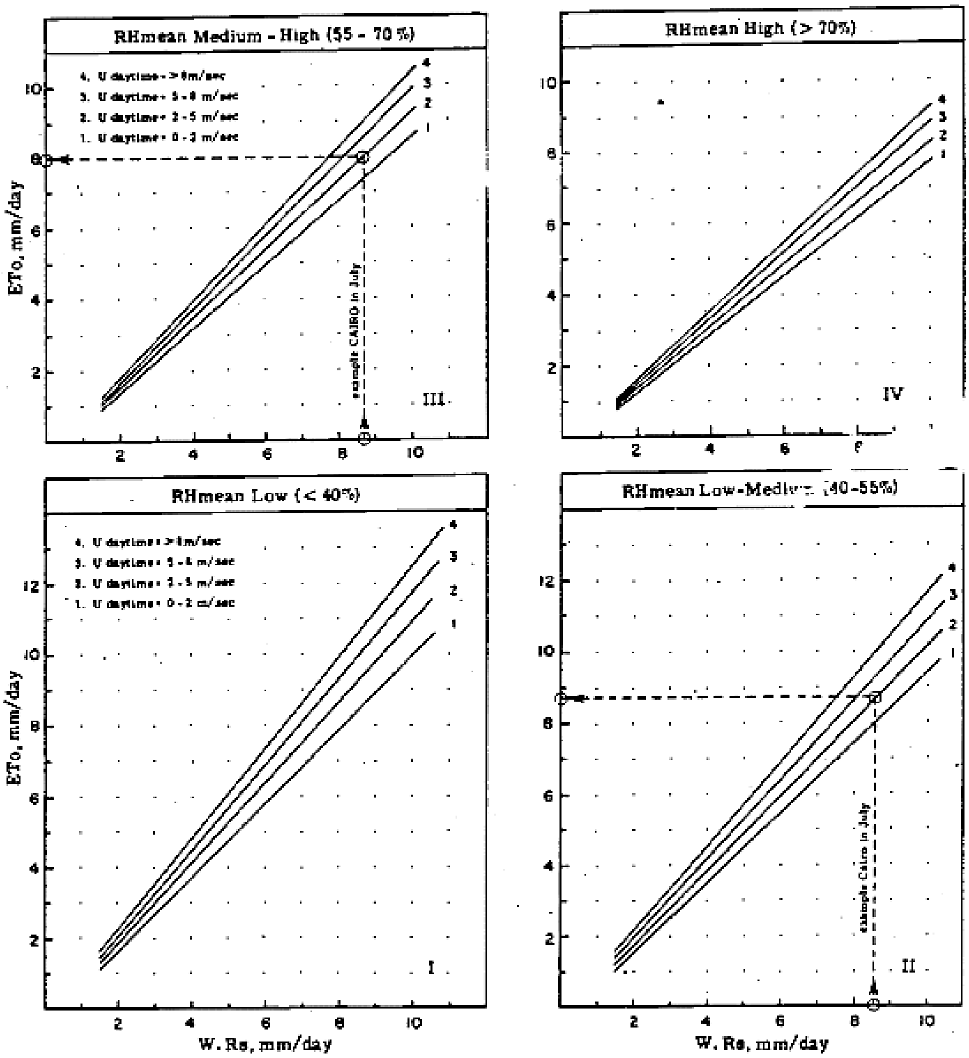

Figure 3.4: Prediction of ETo from W. Rs for different conditions of mean relative humidity and daytime wind.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp.	1981-2019 (NASA [72])	10.7	13.0	18.3	24.6	31.1	35.3	34.0	31.8	29.3	24.1	17.9	12.8
n/N	World Data [73]	0.66	0.61	0.78	0.91	0.89	0.84	0.83	0.85	0.85	0.62	0.63	1.25
Ra =	From table 3.7	8.15	10.0	12.6	14.9	16.8	16.8	16.8	15.5	13.5	11.0	8.81	7.57
Rs =	= [0.25 + 0.5(n/N)] *Ra	4.72	5.55	8.07	10.5	11.7	11.2	11.2	10.5	9.10	6.18	4.99	6.62
W =	From table 3.8	0.57	0.60	0.67	0.74	0.80	0.83	0.82	0.81	0.78	0.74	0.67	0.60
W. Rs =		2.70	3.36	5.38	7.73	9.36	9.36	9.19	8.48	7.11	4.55	3.33	3.99
ET_O	From table 3.5 & fig. 3.4	2.05	2.8	4.75	7.4	9.3	9.05	8.6	7.75	6.4	3.8	2.75	3

Table 3.9: Calculation of ET_O by Radiation method

n= mean sunshine hours, N = maximum sunshine hours, Ra = The amount of radiation received at the top of the atmosphere.

3.3.3: Penman Method

The Penman method (1948) is proposed for areas where measured data on wind and sunshine duration, humidity, temperature, and radiation are available; It should give the most satisfactory results compared to the other methods presented above.

Penman's equation consisted of two terms, the energy (radiation) and the term aerodynamics (wind and humidity) term. In calm weather, the aerodynamic term is generally less important than the other one. In windy conditions, and especially in the more arid regions, the aerodynamic term becomes relatively important. The method uses average daily climatic data, since daytime and night-time weather conditions significantly affect the evapotranspiration. Calculation techniques and tables are provided here to facilitate the necessary calculations.

The equation used for calculating ETo is:

$$ETo = c\,[W.Rn + (1-W).f(u).(ea-ed)]$$

where: ETo is evapotranspiration of the reference crop in mm/day
W = weighting factor (temperature-related)
Rn = net radiation in equivalent evaporation in mm/day
f(u) = wind related function
(ea-ed) is difference between the saturation vapour pressure and actual vapour pressure at average air temperature, both in mbar
c = adjustment factor to compensate for the effect of night and day weather conditions

Temperature ^{O}C	0	1	2	3	4	5	6	7	8	9
ea (bar)	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10	10.7	11.5
Temperature ^{O}C	10	11	12	13	14	15	16	17	18	19
ea (bar)	12.3	13.1	14	15	16.1	17	18.2	19.4	20.6	22
Temperature ^{O}C	20	21	22	23	24	25	26	27	28	29
ea (bar)	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7	37.8	40.1
Temperature ^{O}C	30	31	32	33	34	35	36	37	38	39
ea (bar)	42.4	44.6	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

Table 3.10: Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in ^{0}C

Temperature ^{O}C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
1-W at Altitude (m)																				
0	.57	.54	.51	.48	.45	.42	.39	.36	.34	.32	.29	.27	.25	.23	.22	.20	.19	.17	.16	.15
500	56	.52	.49	.46	.43	.40	.38	.35	.33	.30	.28	.26	.24	.22	.21	.19	.18	.16	.15	.14
1000	.54	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.20	.18	.17	.15	.14	.13
2000	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12
3000	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11
4000	.46	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11	.10

Table 3.11: Values of Weighting Factor (1-W) for the Effect of Wind and humidity on ETo at Different Temperatures and Altitudes

Temp ^{O}C	2	4	6	8	10	12	14	16	18
f(T)	11.4	11.7	12	12.4	12.7	13.1	13.5	13.8	14.2
Temp ^{O}C	20	22	24	26	28	30	32	34	36
f(T)	14.6	15	15.4	15.9	16.3	16.7	17.2	17.7	18.

Table 3.12: Effect of Temperature f(T) on Longwave Radiation (Rnl)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp	1981-2019 (NASA)	10.7	13.0	18.3	24.6	31.1	35.3	34.0	31.8	29.3	24.1	17.9	12.8
ea =	From table 3.10	12.7	15	20.7	30.9	45	57	53.5	47.3	40.6	30	20.4	14.8
RH mean	1981-2019 (NASA)	45.7	48.4	46.8	38.9	25.9	24.2	43.9	53.6	45.0	32.3	31.0	37.5
ed=	ea* (RH mean/100)	5.81	7.26	9.69	12.0	11.6	13.8	23.5	25.3	18.3	9.70	6.34	5.56
ea-ed =		6.89	7.74	11.0	18.8	33.3	43.1	29.9	21.9	22.2	20.3	14.0	9.24
U=	1981-2019 (NASA)	105	116	119	126	136	136	150	128	98.9	91.8	100	104
f(u) =	0.27(1+ U/100)	0.56	0.58	0.59	0.61	0.64	0.64	0.68	0.62	0.54	0.52	0.54	0.55
1-W	From table 3.11	0.43	0.40	0.33	0.30	0.27	0.23	0.18	0.22	0.24	0.24	0.25	0.39
(1- W) * f(u)(ea-ed) =		1.64	1.79	2.18	3.46	5.81	6.30	3.73	2.93	2.86	2.56	1.93	2.01
Ra =	From table 3.7	8.05	9.95	12.5	14.8	16.5	17.0	16.8	15.5	13.4	10.9	8.69	7.43
n/N	World Data	0.66	0.61	0.78	0.91	0.89	0.84	0.83	0.85	0.85	0.62	0.63	1.25
Rs =	= [0.25 + 0.5(n/N)] *Ra	4.67	5.5	8.01	10.4	11.4	11.4	11.2	10.5	9.06	6.12	4.92	6.49
α =	For crops	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rns=(1-α) *Rs		2.33	2.75	4.01	5.23	5.75	5.73	5.61	5.25	4.53	3.06	2.46	3.25
f(T) =	From table 3.12	12.9	13.3	14.3	15.5	16.9	17.9	17.7	17.1	16.5	15.4	14.1	13.2
f(ed) =	0.34 - 0.044√ed	0.23	0.22	0.2	0.19	0.19	0.18	0.13	0.12	0.15	0.2	0.23	0.24
f(n/N) =	0.1+0.9(n/N)	0.69	0.64	0.80	0.92	0.90	0.86	0.85	0.87	0.86	0.66	0.67	1.22
Ran =	f(T)*f(ed)* f(n/N)	2.09	1.90	2.32	2.66	2.90	2.71	1.91	1.75	2.15	2.05	2.17	3.82
Rn =	Rns-Rnl	0.24	0.85	1.69	2,57	2.85	3.02	3.70	3.50	2.38	1.01	0.30	-0.6
Wo =	From table 3.8	0.43	0.40	0.33	0.27	0.20	0.17	0.18	0.19	0.21	0.26	0.35	0.40
Wo.Rn=		0.1	0.34	0.56	0.69	0.58	0.52	0.68	0.68	0.50	0.27	0.10	-.24
[(1-W)(f(u)(ea -ed)] + [W_o*R_n]		1.74	2.13	2.74	4.15	6.39	6.82	4.41	3.61	3.35	2.83	2.03	1.78
c =	Weather based	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
ET_O		1.88	2.30	2.96	4.48	6.91	7.37	4.77	3.90	3.63	3.06	2.20	1.92

Table 3.13: Calculation of ET_O by Penman method

U= Avg. Wing Speed (km/day)

3.3.4: Pan Evaporation Method

Evaporation pans helps assessing the integrated effects of temperature, wind, radiation and humidity on evaporation from open water surface. In the same way, a plant responds to the same climatic variables, but numerous key factors can lead to significant differences in water loss. Solar radiation reflection from water surface is only 5 to 8 percent, and for most crops it ranges between 20 to 25 percent. The heat storage in the pan causes almost the same evaporation during day and night, whereas most vegetative surfaces transpire only during the day. The difference may be caused in water losses from crops and pans because of the above-mentioned factors and differences in humidity, temperature and turbulence of the air above the surfaces. Pan Evaporation method gives experimentally measured values of ET_O and is the best method for calculating evapotranspiration if feasible.

Evapotranspiration of a reference plant (ET_O) can be obtained by:

$$ET_O = K_P . E_{PAN}$$

where: E_{PAN} = pan evaporation in mm/day and represents the daily average of the period

K_P = pan coefficient

Average Pan Evaporation with 5 Years of Time Intervals i.e., 1988-1992, 1993-1997, 1997-2002, 2002-2007, 2007-2012 and 2012-2017 were used for calculating ET_O. The data of pan evaporation ($E_{PAN)}$ is courtesy of Engr. Muhammad Mudassar Maqsood from ICI-Mod, Pakistan. And the maximum value of pan coefficient i.e., 1 was selected based on dry and hot weather conditions of the farm.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
E_{PAN} =		1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49
K_P =		1	1	1	1	1	1	1	1	1	1	1	1
ET_O		1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49

Table 3.14: Calculation of ET_O by Pan Evaporation method

Four different methods for calculating evapotranspiration has been discussed in detail. Comparison of these methods will be done in Chapter 4 i.e., Results and Discussion. Now calculation regarding daily water consumption by Hybrid HEIS and flood irrigation will be discussed below. ET_O by pan evaporation will be used as it gives experimentally calculated values and these results using these values would be closer to the experimental values.

Fully grown lemon with 10 feet canopy were used as orchards/trees and spinach was used as vegetables for calculating water consumption of the field. In agriculture, water is applied after a set interval of time rather than irrigating the fields on daily basis. Already practiced irrigation interval of 5 days was used for calculating irrigation time. Efficiency of sprinklers and emitters which is around 75% and 90%(FAO) respectively, was also considered while calculating the time required for irrigation.

For Vegetables		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_O =		1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49
Daily water required	=29.39* 0.95* ET_O (Liters)	49.8	57.5	75.7	118	188	192.7	113.9	98.5	97.5	76.5	51.1	41.6
Irrigation Interval= 5 days													
Total discharge (L)		249	287	378	590	940	963.5	569.2	492	487	382	255	208
Sprinkler Discharge = 150 LPH (liters/hour) & Sprinklers Efficiency = 75%													
Time for irrigation (Hrs)	=0.75* (total discharge /sprinkler discharge)	1.24	1.43	1.89	2.95	4.70	4.817	2.846	2.46	2.43	1.91	1.27	1.04

Table 3.15: Quantity of Water and time Required by sprinklers for vegetables

For Orchards/trees		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_O =		1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49
Daily water required	=3.53* 0.75* ET_O (Liters)	4.73	5.47	7.19	11.2	17.8	18.29	10.8	9.35	9.26	7.26	4.85	3.96
Irrigation Interval= 5 days													
Total discharge (L)		23.6	27.3	35.9	56.0	89.2	91.46	54.03	46.7	46.3	36.3	24.2	19.7
Emitters Discharge = 16 LPH (liters/hour) & Emitters Efficiency = 90%													
Time for irrigation (Hrs)	=0.90* (total discharge /emitter discharge)	1.33	1.54	2.02	3.15	5.02	5.14	3.04	2.63	2.60	2.04	1.37	1.11

Table 3.16: Quantity of Water Required by emitters for Orchards/trees

For Hybrid HEIS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Discharge for 50 sprinklers (Liters)	2492	2879	3787	5900	9402	9635	5692	4927	4878	3826	2556	2084
Total Discharge for 36 emitters (Liters)	170.3	196.7	258.8	403.2	642.5	658.4	389	336.7	333.3	261.5	174.7	142.4
Total Discharge for Hybrid HEIS (sprinkler + emitters)	2662	3075	4046	6303	10044	10293	6081	5264	5211	4088	2731	2226.8

Table 3.17: Quantity of Water Required for Hybrid HEIS

For irrigating the field for a year under the given weather conditions, the purposed Hybrid HEIS consumes about 62,031 liters or 62.03 m^3 of water. The maximum quantity of water required for irrigation per interval is 1054.96 liters in June. Calculations of required pipe diameter and power of electric motor is based on this value of water required as it is the highest value among all other months.

Discharge (Q) (liters)	Pumping time (T)	Flow rate (LPS)	Diameter of pipe (mm)	Reynold number	Frictional factor	Frictional head loss	Head loss due to bends and valves	Total dynamic head	Power (watt)
		(Q/T)	D = √(LPS X10-3X4/3.14 16)	Re = (ρ.v.D)/ ɥ	f =1.325/([ln[e/3.7D +5.74/[Re]^.9] ^2)	$\frac{f.L.v^2}{2.g.D}$	[(Nb*ξb *v2)/ 2g] + [(Nv*ξv *v2)/ 2g]		[LPS*10-3 * g* ρ *TDH] / η
10293	5.14	0.56	26.61	33349.5	0.023619	12.41	0.73	55.81	1522.7

Table 3.18: Mechanical parameters for Hybrid HEIS

Water required and other parameters for flood irrigation are calculated using same methodology as above. Irrigation interval of 4 days was selected on experience basis of local landlords rather than 5 days as in case of Hybrid HEIS due to the fact that water losses from open field were higher and field required more water to grow to its full potential.

For Flood irrigation		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_O =		1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49
Daily water required	=29.36* 3.4*ET_O (Liters)	178	206	271	422	673	689.6	407.4	352	349	273	183	149
For 1 kanal		3175	3667	4825	7517	11978	12275	7252	6277	6214	4875	3257	2655
Total discharge (L)	= water req*1.66	5270	6088	8011	12479	19884	20377	12038	10421	10316	8093	5407	4408

Table 3.19: Quantity of Water Required for Flood irrigation

The mechanical parameters were not calculated for flood irrigation as it was open channel flow. And water pump of 10 HP was already installed on the experimentation farm. The water pump had a flow rate of 16LPS(40m^3/hr) with a head of 45 meters.

3.4: Irrigation Equipment

Irrigation systems comprises of various valves, fittings, pipes, and other equipment depending on type of system and its installation. Most systems have the same assembly, so relatively small equipment can meet the needs of the entire region. This equipment can be divided into following sections:

• Water-lifting devices • Emitters and Sprinklers, • Water meter • Pipes and Connector fittings.

3.4.1: Water Lifting pump

An automatic irrigation pump i.e., Leo APm150 of 2 HP was installed for hybrid HEIS irrigation as per calculated mechanical parameters. The maximum head for the pump flow rate was 90 meters and maximum flow rate of 70 liters per minute (LPM) could be obtained from pump. This head and flow rate was more than required as per calculations but water was to be lifted from 45 meter below ground and the tested flow rate of 35 LPM was obtained which was just around the flow as required by the Hybrid HEIS. As discussed earlier, water pump used for flood irrigation was already installed on the farm. For the same reason flow rate and pump power required for flood irrigation were not discussed. The already installed pump was a 10HP with experimentally calculated flow rate of 16 LPS or 57.6 m^3/hr. This pump could lift to 50 meters. The same pump was used for irrigating the experimental farm.

3.4.1: Emitters and Sprinklers

Each lemon plant was irrigated using variable flow emitter/dripper which have a flow rate of 14-18 LPH (liters per hour). Reason for choosing variable emitters was the controllable flow rate. These emitters were tested onsite before irrigation and had an experimental flow rate of 16 LPH when opened fully. Vegetable rows were irrigated using sprinklers. A sprinkler has an experimental flow rate of 140-160 LPH and it covered a diameter of 9 feet on experimental field. Field layout was designed after testing the diameter of water sprinklered area. Sprinklers were overlapped for about 14 inches so that they irrigate maximum area of land for adequate water supply to vegetables. Each sprinkler row had 10 sprinklers for covering the area between two consecutive orchard rows as shown in field layout section i.e., Figure 3.2. The emitters and sprinklers used in experimentation are shown in figure 3.5

Figure 3.5: Emitters and Sprinklers in action

3.4.2: Water meter

A locally available water meter was used to calculate amount of water consumed during Hybrid HEIS irrigation process. This water meter had a flow rate of 2.5 m^3/hr (2500 L/hr) and was as accurate as it can measure 0.1 liter. This meter had a higher nominal pressure of 10 bars and could operate on the pressure as low as 1 bar. Water consumed for flood irrigation was calculated just by channel discharge i.e., 57.6 m^3/hr of installed water pump and multiplying this flow rate with time of irrigation of the field.

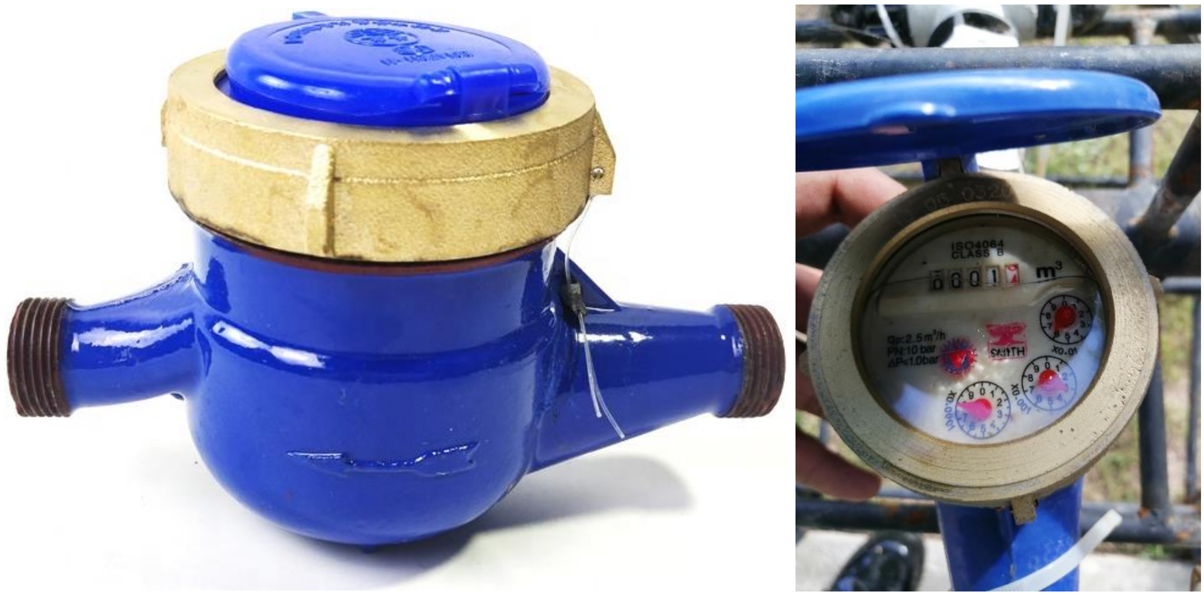

Figure 3.6: Water meter

3.4.3: LDPE pipe and connector

LDPE pipe also known as soft polyethylene was selected for its properties of rolling, proven success in pressure piped irrigation techniques and are the predominant kind of pipes in micro-irrigation systems. Ease of pipe rolling was necessary as the system had to roll back the entire pipe network for making it portable. A diameter of 25mm LDPE pipe was selected for experimentation. According to calculated parameter a 26.5 mm pipe was required but available LDPE pipe size are 25mm or 32mm. Compression type Polypropylene (PP) pipe connector fittings were used. They can be easily assembled and disassembled without cutting the pipe. They are more expensive than other connectors, but last longer and can be used in a variety of installations.

Figure 3.7: LDPE pipe in Field

Figure 3.8: PP pipe Connector

3.5: Design and Manufacturing of Portable Hybrid HEIS

As referenced above that Agricultural land shrinks with time as because of the distribution within successors. Land is either owned or rented for agricultural purposes in Pakistan. A 2006 study by Gustavo Anríquez and Alberto Valdés classifies small land holders possessing up to 4 acers of land[15]. This definition should be revised over a period a time as distribution of land between successors yields more and more small farms. According to revised definition of small land holders/tenants, they owns about 2.2 acers of farms[16,17]. So this research is specific to small land holders/tenants, who represents the majority from the class. To overcome the problem of irrigation using expensive and fixed HEIS, we are proposing a complete system for water distribution which is portable. The portable system will reduce the cost significantly as a farmer will not be required to buy the system for the whole field, instead the system for a portion of the farm will be procured, which will be utilized for the whole farm on modular basis. This is a very attractive system for the small and medium farmers who cannot afford the complete hybrid micro-irrigation system which utilizes minimum water and energy, as well as uniform distribution of the water resulting in the better yield, LER, WUE along with low energy requirement and lesser water.

Basic approaches for designing and manufacturing the system was that this portable system should mount all the working equipment for easy transport and equipment should not require assembling and disassembly when ever it is moved from one part of the farm to another. So this portable Hybrid HEIS should mount water meter, fold drip tapes/pipes with emitters and sprinkles. Cost of this portable system was a major focus so manufacturing should be out of the locally available inexpensive light weight material. The total weight of pipe to be folded on portable stand for 1 kanal field was about 8 kg and the measured weight of sprinklers and emitters was 2.5 kg. The Moment arm for rolling the pipe was calculated which came out to be 41 N.

3.5.1: Preliminary design

Preliminary design was made so that it had a main supporting structure, 6 rollers and a seven piece interconnecting shaft. Main support structure had to carry 6 rollers, shaft and weight of pipes and other irrigation equipment. One roller for folding an orchard emitter and a sprinkler pipe was pre-designed Rollers had two type of motion, i.e., rotating motion and liner motion. Rotating motion of roller was obtained using bearings and this helped in rolling the irrigation pipes. Linear motion was used for sliding the roller towards main support structure to make the assembly compact for transportation purposes. These rollers were interconnected via rotating shaft. This shaft consisted of seven pieces, joined via pin and cotter mechanism. This was done for detaching a 75 feet long shaft and making it easier for transportation purposes. Preliminary design is showing in figure 3.9(A), 3.9(B) and 3.9(C).

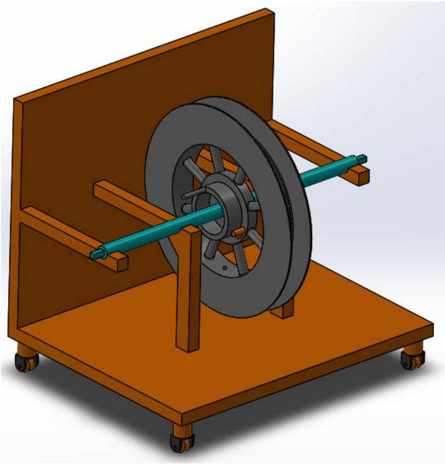

Figure 3.9 (A): Main support structure

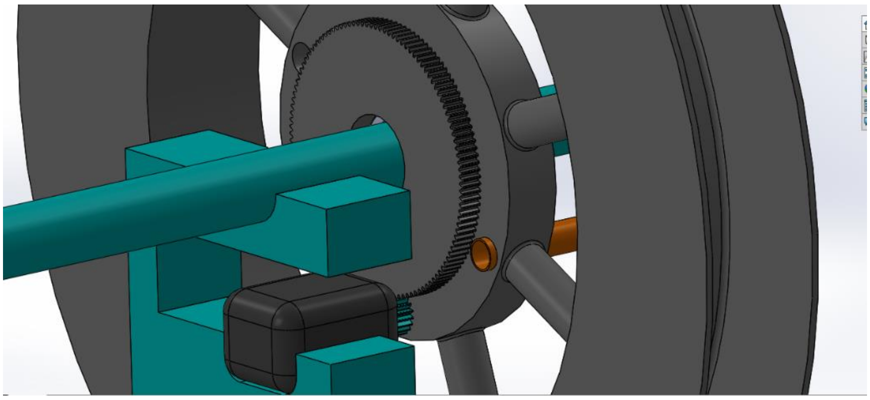

Figure 3.9 (B): Motor with gear arrangement for rotational purposes

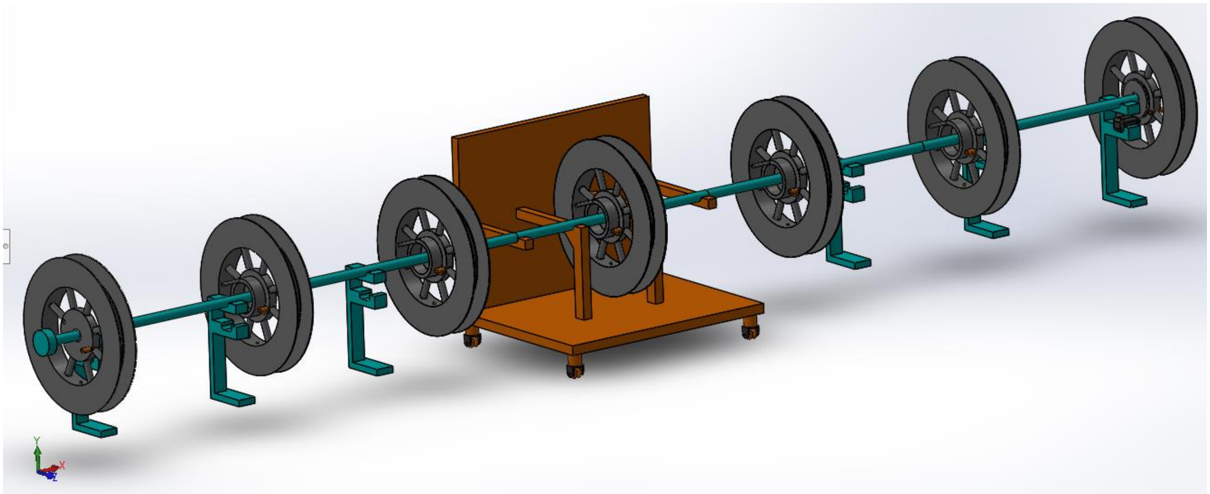

Figure 3.9 (C): Preliminary Design of Portable Hybrid HEIS

Cost, Manufacturing, Power to drive, and Weight of portable Hybrid HEIS stand was much more than the target. To carry a 10.5 kg pipe this stand was surely overdesigned. Hence many iterations were done in the designing phase to make it cost effective, reduce weight, easier transportation, manufacturing and making this system hand driven rather involving gears and motor driven system.

3.5.2: Final design

After many iterations, a simple design which was easy to manufacture, transport, operate and had low production, maintenance and running cost was purposed. A system 0.5 inch diameter iron rod was used for manufacturing the main supporting structure and roller. Bending a straight pipe and welding was used as manufacturing techniques. 36 inches main supporting structure was bend and two arms were welded on it. Roller was also mounted in the similar way and bending, cutting and then welding all pieces together. For carrying 10.5 kg load and producing a moment arm of 41 N for rolling a pipe of 900 feet (or 0.045 N/foot)structure analysis was not required as the structure had to carry pipe for one part of farm to another, where no high speed travelling or rolling is required nor variable loads to be applied on the system. In order to stay focused on main objectives the basic approach was adopted. Circular roller and trolly were constructed out of iron pipe for folding and carrying irrigation mechanism. Simpler construction techniques were used for manufacturing i.e., bending and welding. Iron pipe of 0.5 inches was bent as shown figure 3.10(A) and 3.10(B).

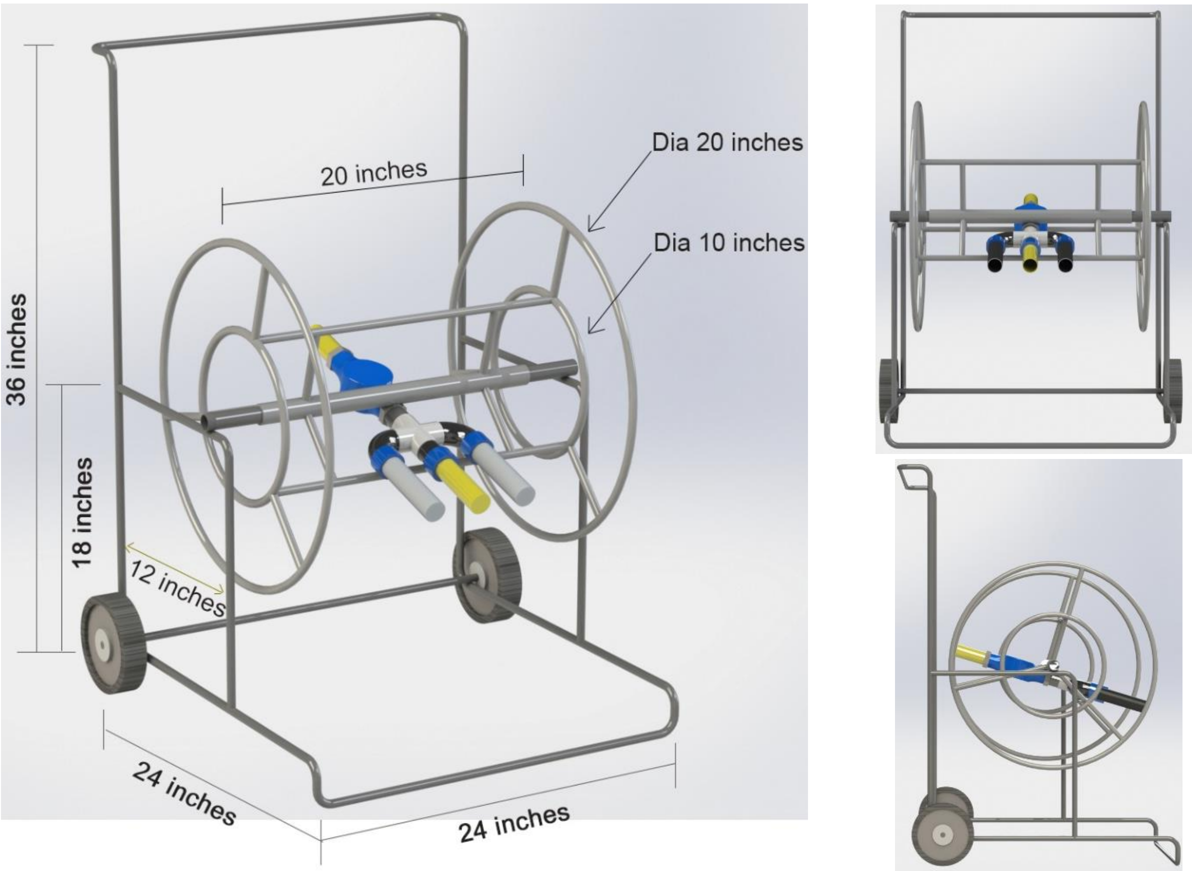

Figure 3.10(A): Final Portable Hybrid HEIS design

Figure 3.10(B): On-field Portable Hybrid HEIS

3.6: Cost Analysis

Cost analysis for manufacturing the Portable Hybrid HEIS was done.

Items	Quantity	Cost (PKR)
Iron pipe	20 ft	2000
Sprinklers	50 nos	15000
Emitter	36 nos	5400
LDPE pipe	900 ft	9000
Water Pump	1 nos	19000
Pipe for pump	145 ft	13000
Electrical installations	-	9800
Water meter	1 nos	2400
End plugs	11 nos	550
GTO	11 nos	550
Wheels	2 nos	900
PP. T-connector	8 nos	4000
PP. L-connector	2 nos	900
PP. Plus-connector	1 nos	550
Bending charges	-	3000
Cutting and welding charges	-	3800
Nuts and washers	4 nos	200
Black spray paint	3 nos	1050
Total	-	91100*

Table 3.20: Total Cost of Portable Hybrid HEIS

Items	Quantity	Cost (PKR)
Water Pump	1 nos	69000
Pipe for pump	145 ft	38900
Electrical installations	-	29000
Total	-	126900*

Table 3.21: Total Cost of Flood Irrigation

*it may be noted that installation of 10 HP pump also require a well and Transformer of its own for operational purposes, which costs around 7-9 lacs. Whereas if considered, boring cost for HEIS is around 1.5 lacs. Hence flood irrigation setup cost way much more than Portable Hybrid HEIS.

3.7: Experimentation

On-site experiments were conducted after selecting, manufacturing and integrating all equipment and portable stand. As depicted from the literature cited above maximum evapotranspiration occurs during day time i.e., in the noon to be more specific. So more quantity of water is required during this period of time. Hence considering the fact, experimentation was conducted somewhere near noon and afternoon for calculating the maximum quantity of water consumed by the orchards and mixed vegetables. This experimentation was conducted for a period of one year staring from June, 2019 to the end of May, 2020. Results from these experiments are discussed in forth coming section.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1: Evapotranspiration Comparison

One of the objective of this research was to find the best suited method for calculating evapotranspiration and eventually the water consumption by the Orchards and mixed vegetables. Four methods were discussed in detail in Chapter 3 showing all the steps to calculate ET_O. Three of these four methods (i.e., Blaney-Criddle, Radiation and Penman methods) depend on weather data (if available) and uses interpolations from different graphs and tables. Whereas Pan evaporation is on-site calculated experimental data. If we compare theoretical methods to each other, Blaney-Criddle method uses measured temperature data and estimated humidity, wind, sunshine and environment conditions for ET_O. Radiation method uses more measured factors of temperature, sunshine and radiation. Estimated data of humidity and wind is also taken into the account for calculation purposes. So it can be stated that results derived from Radiation method are more authentic than from Blaney-Criddle method. When Penman method is considered, measured values of temperature, humidity, wind and sunshine as well as estimated values of environmental and radiation are used for derivation of ET_O. Hence maximum number of environmental and on-site factors are considered in penman method so it can be stated that this method could produce more accurate results when compared to prior two methods (Blaney Criddle and Radiation). This statement can also be supported by the figures in table 4.1 where the values of ET_O by Penman equation are closer to the values of experimentally calculated Pan evaporation method.

Comparison of the prior three theoretical methods was done with past 30 years of experimentally calculated values of ET_O by Pan Evaporation.

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Blaney-Criddle	2.10	2.83	3.85	6.53	9.10	9.35	9.10	7.81	6.70	4.30	3.00	2.30
Radiation	2.05	2.8	4.75	7.4	9.3	9.05	8.6	7.75	6.4	3.8	2.75	3.0
Penman	1.88	2.30	2.96	4.48	6.91	7.37	4.77	3.90	3.63	3.06	2.20	1.92
Pan Evaporation	1.78	2.06	2.71	4.23	6.74	6.90	4.08	3.53	3.49	2.74	1.83	1.49

Table 4.1: Comparison of ET_O by different methods

Graph in shown in figure 4.1 to illustrate the comparison of ET_O values by these methods. This graph also shows that values of Penman are closest to Pan Evaporation method. From the discussion, table 4.1 and figure 4.1, we can conclude that if experimental data is not available one can apply Penman equation using NASA satellite measured data for calculating ET_O. Blaney-Criddle and Radiation gives much higher values of ET_O.

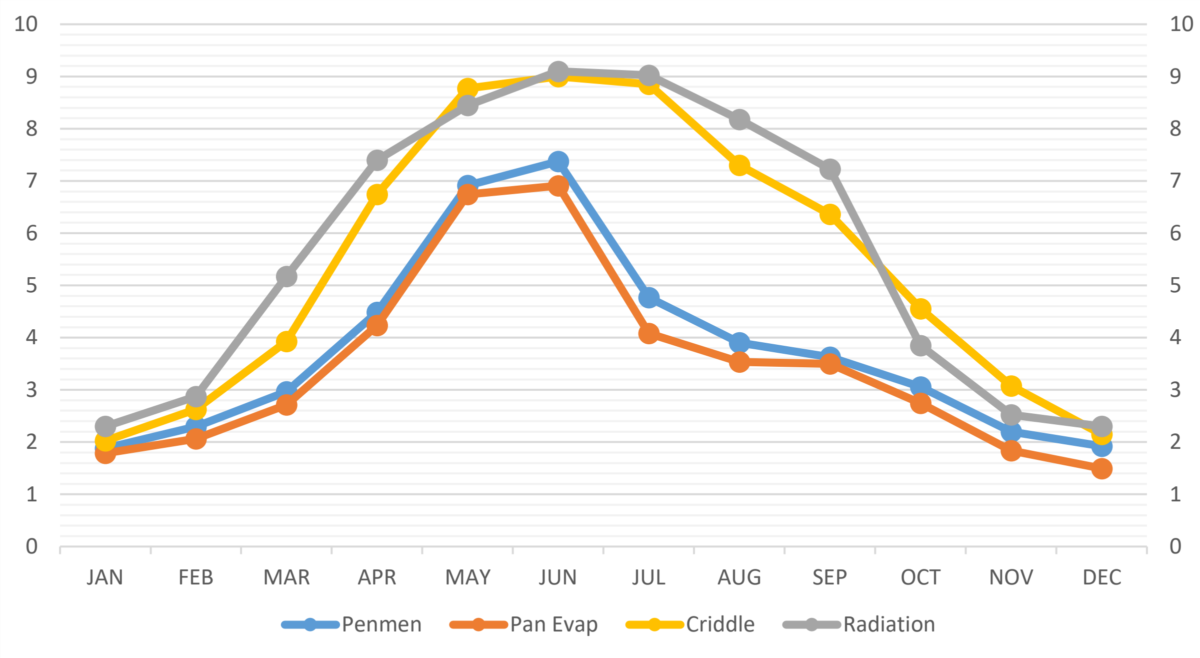

Figure 4.1: Comparison of ET_O by different methods

4.2: Water Consumption

Water was applied in 1 kanal field for a period of one year, i.e., from June, 2019 to May, 2020. Rain water was also taken into the account for measuring the exact amount of water available to the plants during the entire period of experimentation. Table 4.2 show collected rainwater data.

Month	Rain fall (mm/m2)	Rain water per kanal (liters/day)
Jun-19	57.2	996.385
Jul-19	111.2	1874.54
Aug-19	257.8	4345.84
Sep-19	86.1	1499.8
Oct-19	73.5	1239.02
Nov-19	16.4	285.677
Dec-19	4.9	82.6013
Jan-20	52.5	885.014
Feb-20	50.2	904.603
Mar-20	218.6	3685.03
Apr-20	56.1	977.224
May-20	111.6	1881.29

Table 4.2: Rain water per kanal

The actual water consumption for flood irrigation is shown in table 4.3. The total water consumed by the flood irrigation was 128418.03 liters.

Orchard Under Flood Irrigation	Channel Discharge (LPS)	Time taken to irrigate 1 kanal (minutes)	Total water applied (Litres)	Irrigation Interval (days)	Daily Water Applied (litres/day) per Kanal (Alley cropping)	Total water applied (Litres/day) (rain + irrigation)
Jun-19	16	52	49920	4	12480	13476.3851
Jul-19	16	48	46080	4	11520	13394.5436
Aug-19	16	45	43200	4	10800	15145.83938
Sep-19	16	41	39360	4	9840	11339.80345
Oct-19	16	38	36480	5	7296	8535.019374
Nov-19	16	37	35520	5	7104	7389.676848
Dec-19	16	35	33600	5	6720	6802.601292
Jan-20	16	35	33600	5	6720	7605.013839
Feb-20	16	37	35520	5	7104	8008.603308
Mar-20	16	39	37440	4	9360	13045.02905
Apr-20	16	43	41280	4	10320	11297.22385
May-20	16	44	42240	4	10560	12441.28656
					Total	**128481.03**

Table 4.3: Actual Water Consumption by flood irrigation

The total water consumption by the Hybrid HEIS was 82397.42 liters. The actual water consumption for Hybrid HEIS is shown below. Table 4.4(A) shows actual water consumption by orchard under drip irrigation and table 4.4(B) shows actual water consumed by mixed vegetables under sprinkler irrigation. Combining the water consumption gives the total water consumed by Hybrid HEIS.

Orchard Under Drip	Average Calculated Discharge of Emitter (LPH)	Irrigation time (hr)	Irrigation Interval (days)	Daily Water Applied (litres)	Total plants/ kanal	Total water applied (litres/ rotation)	Total water applied (litres/ rotation) (rain + irrigation)
Jun-19	13.80	5.14	5.00	14.20	36.00	511.15	1507.54
Jul-19	13.60	3.04	5.00	8.27	36.00	297.61	2172.15
Aug-19	13.90	2.63	5.00	7.31	36.00	263.31	4609.15
Sep-19	14.20	2.60	5.00	7.40	36.00	266.28	1766.09
Oct-19	14.20	2.04	5.00	5.80	36.00	208.90	1447.92
Nov-19	14.40	1.37	5.00	3.93	36.00	141.54	427.21
Dec-19	14.40	1.11	5.00	3.21	36.00	115.39	197.99
Jan-20	14.30	1.33	5.00	3.81	36.00	137.01	1022.02
Feb-20	14.20	1.54	5.00	4.37	36.00	157.15	1061.76
Mar-20	14.00	2.02	5.00	5.66	36.00	203.86	3888.89
Apr-20	13.70	3.15	5.00	8.63	36.00	310.77	1287.99
May-20	13.50	5.02	5.00	13.55	36.00	487.95	2369.24
						Total	**21757.94**

Table 4.4(A): Actual Water Consumption by Orchard Under Drip

Vegetables Under Sprinkler	Average Calculated Discharge of Sprinkler (LPH)	Irrigation time (hr)	Irrigation Interval (days)	Daily Water Applied (litres)	Total sprinklers / kanal	Total water applied (litres/ day)	Total water applied (litres/ day) (rain + irrigation)
Jun-19	146.00	4.82	5.00	140.67	50.00	7033.65	8030.03
Jul-19	141.50	2.85	5.00	80.55	50.00	4027.35	5901.89
Aug-19	141.90	2.46	5.00	69.92	50.00	3496.12	7841.96
Sep-19	142.10	2.44	5.00	69.32	50.00	3465.82	4965.62
Oct-19	147.00	1.91	5.00	56.26	50.00	2812.77	4051.79
Nov-19	148.20	1.28	5.00	37.89	50.00	1894.56	2180.24
Dec-19	150.00	1.04	5.00	31.27	50.00	1563.30	1645.90
Jan-20	150.20	1.25	5.00	37.43	50.00	1871.71	2756.72
Feb-20	148.30	1.44	5.00	42.69	50.00	2134.67	3039.27
Mar-20	144.90	1.89	5.00	54.89	50.00	2744.34	6429.37
Apr-20	143.20	2.95	5.00	84.50	50.00	4224.91	5202.13
May-20	142.80	4.70	5.00	134.26	50.00	6713.24	8594.53
						Total	**60639.48**

Table 4.4(B): Actual Water Consumption by Vegetables Under Sprinkler

A comparison of water consumption for each month using Flood irrigation and Hybrid HEIS is shown in the table 4.5. This table also depicts the total water save per month using Hybrid HEIS.

Total Annual Water Usage	Total water applied Flood Irrigation(Liters)	Total water applied HEIS for Alley Cropping(Litres)	Water Saving per kanal (liters)
Jun-19	13476.39	9538	3939
Jul-19	13394.54	8074	5320
Aug-19	15145.84	12451	2695
Sep-19	11339.8	6732	4608
Oct-19	8535.019	5500	3035
Nov-19	7389.677	2607	4782
Dec-19	6802.601	1844	4959
Jan-20	7605.014	3779	3826
Feb-20	8008.603	4101	3908
Mar-20	13045.03	10318	2727
Apr-20	11297.22	6490	4807
May-20	12441.29	10964	1478
Total	**128481.03**	**82397.42**	**46083.61**

Table 4.5: Water Consumption Comparison

Graphical comparison of water consumption is shown in figure 4.2. The graph shows almost the linear behaviour of the water consumed for a month with respect to each other. This means the water consumption for each month was approximately equal for both of the selected experimental fields but the significant amount of water saved is due to the utilization of efficient irrigation techniques.

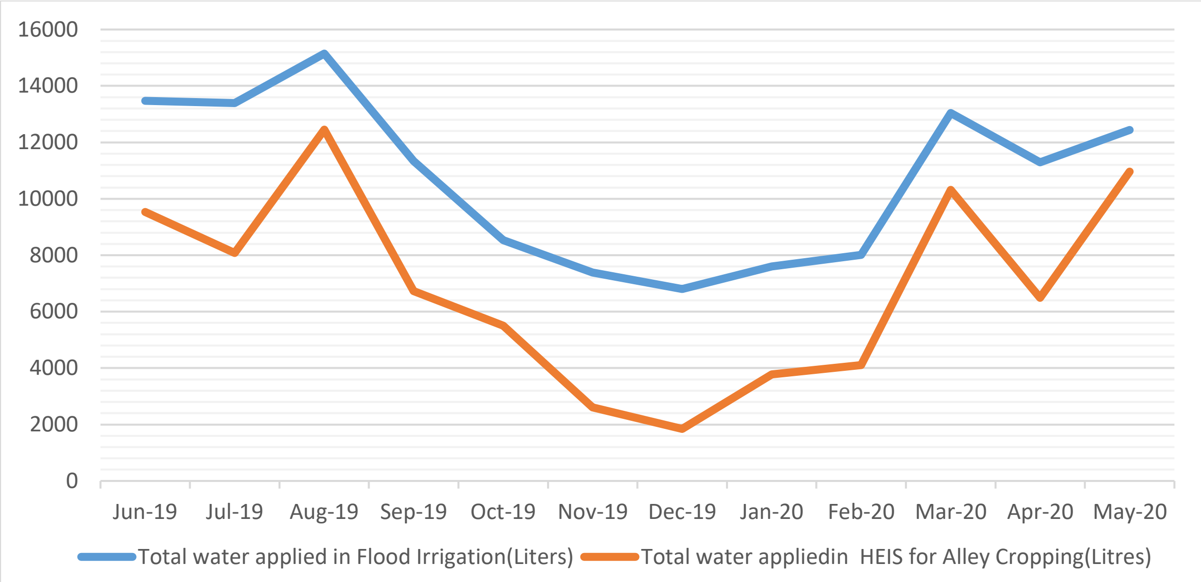

Figure 4.2: Water Consumption Comparison

4.3: Water Saved

After implementing the purposed irrigation system, annual saving of 46083.61 liters was achieved. The Hybrid HEIS leads to higher WEU than flood irrigation because there is lower evaporation of water from soil and water surface accumulated in the field. Total water use (TWU) is low due to the fact the HEIS system have low wetted fraction than flood irrigation where entire area is wetted. There are some water losses in Hybrid HEIS system. An entire study to investigate these losses is required for measuring the losses involved.

4.4: Perks of the Portable Hybrid HEIS

Following are advantages of experimented Hybrid HEIS over the flood irrigation technique.

- As cited in literature, this is a very attractive system for the small and medium farmers, as it utilizes minimum water and energy, as well as uniform distribution of the water resulting in the better yield, LER, WUE along with low energy requirement and lesser water.
- It is completely easy to set up, rolling it back and irrigate another field. The roll back ability of the system also help in ploughing the farm without risks of damaging the irrigation lines.
- Significant quantity of water is saved and low operation and labour costs are required. The comparison of water has been done in this study. Operational cost was not an object of the study but it is quite evident that irrigation a field with 10 HP pump requires a lot more power than irrigating the same size of farm with a 2 HP pump. This system controls the amount of weed growth due to no tail and overapplication of water hence extra labour costs are involved for removal of weeds [74]. Controlling weeds in the field also improves the yields of agricultural products in the farm.
- Water distribution throughout the field is equal. But this is not true in case of flood irrigation.
- Water supplied to each irrigation line can be controlled.

- Levelling of soil and bunding are critical during flood irrigation. While in Hybrid HEIS each emitter and sprinkler works as separate entity for applying water, therefore surface levelling and bunding can be neglected.
- Soil degrading such as leaching are avoided using the purposed system but flood irrigation have worst impacts on soil quality [75].
- Initial HEIS system cost can be reduced by using the Portable system which was also added in this project to facilitate small farmers to address the problem.
- Food security can also be addressed using this system as the productive and yield per unit land is increased.

4.6: Disadvantages of Hybrid HEIS

- Maintanance is required from time to time.
- Clogging occurs in the system if not properly maintained.

CHAPTER 5: CONCLUSION

Experimentation of the Purposed Portable Hybrid HEIS conducted on an available farm near Fateh Jang which was a promising and economical irrigational setup for the majority of small farmers which are about 66.29% of the total population dependent on agriculture in Pakistan. Significant quantity of water was saved and low operational and labour costs were required. The comparison of water consumption has been done with flood irrigation in this study. This system controls the amount of weed growth due to no tail and over application of water hence no extra labour costs are involved for removal of weeds. This improves the yields and productivity of agricultural products in the farm. This study is a milestone for the farmers who own less than 2 acers land who can't afford costly HEIS. The current research envisage demonstrating a portable and hybrid HIES comprising of drip irrigation for orchards and sprinkler irrigation for row crops. The designed and manufactured system was cheap and a well efficient technique to irrigation the Alley cropping. Evapotranspiration(ET) based irrigation system was designed for calculating crop water requirement. Four different methods were used for calculations of ET. Experimental ET calculated by Pan Evaporation has closest values to Penman Equation based on NASA Satellite collected data. Hence Penman equation can be used if Pan Evaporation experimental data is not available for calculating ET. The water use efficiency(WEU) of the proposed Hybrid HEIS is 33.71% in comparison to flood irrigation system. The on field demonstrated portable system work efficiently for irrigating one after another field which makes this system cost effective and in-reach of the local agriculturalists. The ploughing of land was also easier as the system was portable and could be roll out of the field hence making it more user friendly. Integrating Portable Hybrid HEIS with alley cropping was a new concept and dire need of the hour which covers all aspects of irrigating the row crops and trees/orchards as well as it offered beneficial outcomes in terms of efficiency of land and water use, profit, productivity, food security and have positive impact on global environment.

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