4

Research Advances in Sustainable Micro Irrigation

Management, Performance, and Applications of Micro Irrigation Systems

Megh R. Goyal, PhD, PE
Senior Editor-in-Chief

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MANAGEMENT, PERFORMANCE, AND APPLICATIONS OF MICRO IRRIGATION SYSTEMS

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VOLUME 4

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Edited by

Megh R. Goyal, PhD, PE

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LIST OF ABBREVIATIONS

Θ_w	dry weight basis
AAP	Apple Academic Press Inc.
Ac	application cost of fertilizers, LE/fed
Agg.%	aggregation percent
ASABE	American Society of Agricultural and Biological Engineers
Bp	the brake power, kW
CGDD	cumulative growing degree days
CLAC	Central Laboratory for Agricultural Climate, Egypt
CU	coefficient of uniformity
D	depreciation rate, LE/year
DIS	drip irrigation system
DOY	day of the year
DU	distribution uniformity
E	expectancy life, year
E.C.	energy costs, LE/year
EPAN	pan evaporation
ET	evapotranspiration
ETc	Crop evapotranspiration
F.C	annual fixed cost, LE/year
FAO	Food and Agricultural Organization, Rome
FC	field capacity
Fed	feddan = 0.42 ha = 4200 m2
Fr	fertilization cost, LE/fed
FUE	fertilizers use efficiency
GPIS	gated pipe irrigation system
gpm	Gallons per minute
I	interest, LE/year = [(I.C. + Sv) × I.R.]/2
I.C.	initial cost of irrigation system, LE
I.R.	interest rate per year, %
ICAR	Indian Council of Agriculture Research
IR	water intake rate into the soil
ISAE	Indian Society of Agricultural Engineers
kc	Crop coefficient
Kg	kilograms
Kp	Pan coefficient
Ks	Hydraulic conductivity
L	labor cost, LE/h
L.C.	annual labor cost, LE/year
LAI	leaf area index

LEPA	Low energy pressure irrigation system
LHBIS	low head bubbler irrigation system
lps	Liters per second
MAD	maximum allowable depletion
MSL	mean sea level
MWD	mean weight diameter
N	number of labors per faddan
O.C.	annual operating costs, LE/year
P	labor cost, LE/h
P	Pesticides price, LE/kg
Pc	pest control cost, LE/fed
PE	Polyethylene
PET	potential evapotranspiration
pH	acidity/alkalinity measurement scale
PM	Penman-Monteith
ppb	one part per billion
ppm	one part per million
Pr	cost of electrical power, LE/kW.h
psi	Pounds per square inch
PVC	poly vinyl chloride
PWP	permanent wilting point
R&M	repair and maintenance costs, LE/year
RA	Extraterrestrial radiation
RH	relative humidity
RMAX	maximum relative humidity
RMIN	minimum relative humidity
RMSE	root mean squared error
RS	solar radiation
SAR	Sodium absorption rate
SDI	subsurface drip irrigation
SRW	simulated rain water
Sv	salvage value after depreciation, LE
SW	Saline water
SWB	soil water balance
T1	annual irrigation time, h/year
T2	annual operating time, h
T3	time used, h/fed.
T4	taxes and overhead ratio, LE/year
TE	transpiration efficiency
TEW	total evaporable water
TMAX	maximum temperature
TMIN	minimum temperature
TR	temperature range
TSS	total soluble solids
TUE	transpiration use efficiency

USDA	US Department of Agriculture
USDA-SCS	US Department of Agriculture-Soil Conservation Service
Wc	weed control cost, LE/fed
Wf	amount of fertilizers, kg/fed
Wp	amount of pesticides, kg/fed
WSEE	weighed standard error of estimate
WUE	water use efficiency
WUSE	water use efficiency
WUTE	water utilization efficiency

LIST OF SYMBOLS

A	cross sectional flow area (L^{2})
AL	average life of wells
AW	available water ($\ominus_{w}\%$)
c	maximum leaf/stem water potential measured during the study
C	concentration of chlorine wanted, ppm
Cp	specific heat capacity of air, in J/(g·°C)
CV	coefficient of variation
D	accumulative intake rate (mm/min)
d	depth of effective root zone
D	depth of irrigation water in mm
Δ	slope of the vapor pressure curve (kPa°C^{-1})
e	vapor pressure, in kPa
e_{a}	actual vapor pressure (kPa)
E	evapotranspiration rate, in g/(m2·s)
Ecp	cumulative class-A pan evaporation for two consecutive days (mm)
eff	irrigation system efficiency
E_{i}	irrigation efficiency of drip system
E_{p}	Pan evaporation as measured by Class-A pan evaporimeter (mm/day)
Es	Saturation vapor pressure, in kPa
E_{pan}	Class A pan evaporation
ER	cumulative effective rainfall for corresponding two days (mm)
e_{s}	saturation vapor pressure (kPa)
$e_{s}–e_{a}$	vapor pressure deficit (kPa)
ET	evapotranspiration rate, in mm/year
ETa	reference ET, in the same water evaporation units as Ra
ETc	crop-evapotranspiration (mm/day)
ET_{o}	the reference evapotranspiration obtained using the Penman-Monteith method, (mm/day)
ET_{pan}	the pan evaporation-derived evapotranspiration
EU	emission uniformity
F	flow rate of the system (GPM)
F.C.	Field capacity (v/v,%)
G	soil heat flux at land surface, in W/m^{2}
H	the plant canopy height in meter
h	the soil water pressure head (L)
I	the infiltration rate at time t (mm/min)
IR	injection rate, GPH
IRR	irrigation
K	the unsaturated hydraulic conductivity (LT^{-1})

K_c	crop coefficient
Kc	crop-coefficient for bearing 'Kinnow' plant
Kp	Pan factor
K_p	Pan coefficient
L	length of the sample
l	shape parameter
m	rain gauge mean reading (mm)
n	number of states
n	number of emitters
n	number of rain gauges
N	the value of the same parameter after filtration
N_0	the value of specific quality parameter of unfiltered wastewater
P	percentage of chlorine in the solution*
Pa	atmospheric pressure, in Pa
P.W.P.	permanent wilting point ($\ominus_w$%)
PERC	percolation below the root zone
$\mathbf{p}_{ij}$	probability that an area under the classification '**i**' during the current year changes into the classification '**j**' next year
Q	flow rate in gallons per minute
q	the mean emitter discharges of each lateral (lh^{-1})
	the mean emitter discharge for all of the emitters
q_{lq}	the average emitter discharge from the lower quartile of sampled emitters
Q_{avg}	overall average of emitter discharge (l/h)
q_{ini}	mean discharge of new emitters at the same operating pressure of 98.06 kPa (lh^{-1})
Q_q	average low-quarter emitter discharge (l/h)
R	rainfall
R.S.M.	required soil moisture
r_a	aerodynamic resistance ($s\ m^{-1}$)
Ra	extraterrestrial radiation, in the same water evaporation units as ETa
R_e	effective rainfall depth (mm)
R_i	individual rain gauge reading in mm
R_n	net radiation at the crop surface ($MJ\ m^{-2}day^{-1}$)
Rs	incoming solar radiation on land surface, in the same water evaporation units as ETa
RO	surface runoff
r_s	the bulk surface resistance ($s\ m^{-1}$)
S	the sink term accounting for root water uptake (T^{-1})
Se	the effective saturation
S_p	plant-to-plant spacing (m)
S_r	row-to-row spacing (m)
SU	statistical uniformity (%)
S_ψ	water stress integral (MPa day)
t	the time that water is on the surface of the soil (min)

T	time in hours
V	volume of water required (liter/day/plant)
V_{id}	irrigation volume applied in each irrigation (liter tree^{-1})
V_{pc}	the plant canopy volume (m^3)
W	the canopy width
W_p	fractional wetted area
X(t)	state of the system at the year ‘**t**’
z	the vertical coordinate positive downwards (L)
α	it is related to the inverse of a characteristic pore radius (L^{-1})
γ	the psychrometric constant (kPa°C^{-1})
θ	volumetric soil water content (L^{3}L^{-3})
$\theta(h)$	the soil water retention (L^{3}L^{-3}),
θr	the residual water content (L^{3}L^{-3})
θ_s	the saturated water content (L^{3}L^{-3})
θ_v	the vertically averaged volumetric soil moisture content
θ_{vol}	a volumetric moisture content (cm^3/cm^3)
λ	latent heat of vaporization (MJ kg^{-1})
λE	latent heat flux, in W/mo
ρa	mean air density at constant pressure (kg m^{-3})
ρ_b	the bulk density (gm/cm^3)
$\psi_{i,\,i+1}$	average midday leaf/stem water potential for any interval i and i+1 (MPa)

PREFACE

Due to increased agricultural production, irrigated land has increased in the arid and sub-humid zones around the world. Agriculture has started to compete for the water use with industries, municipalities, and other sectors. This increasing demand along with increases in water and energy costs have made it necessary to develop new technologies for the adequate management of water. The intelligent use of water for crops requires understanding of evapotranspiration processes and use of efficient irrigation methods.

An article was published on the importance of micro irrigation in India, on the weblink: http://newIndianexpress.com/cities/bangalore/Micro-irrigation-to-be-promoted/2013/08/17/. Every day, similar news appears all around the world, indicating that government agencies at central/state/local levels, research and educational institutions, industry, sellers and others are aware of the urgent need to adopt micro irrigation technology that can have an irrigation efficiency up to 90%, compared to 30-40% for the conventional irrigation systems. I share with the readers comments on "Scaling-up Micro-irrigation Systems in Madagascar (SCAMPIS)" by Andriamalina R. Fenomanantsoa (Project Coordinator at Agriculturalists and Veterinaries without Frontiers in Madagascar) at the "International Annual UN-Water Zaragoza Conference 8-10 January 2013, Water Cooperation: Making it Happen!" The full version of his interview appears at http://www.un.org/waterforlifedecade/water_cooperation_2013/madagascar.shtml.

Andriamalina mentions, "*Madagascar is a dominantly rural population (70%) and a high-potential agricultural country that knows a situation of poverty and extreme food insecurity due to a lack of policies frameworks for the agricultural sector. This rural poverty may be amplified by the chronic decrease of water reserve, which is further aggravated by the models of water use practiced by the most of farmers (manual watering, crop flooding and irrigation line). The strategy of SCAMPIS has been the creation and strengthening of the supply chain of materials adapted to the local context. This strategy has mobilized several actors from the public and private sectors. Indeed, near to the marketing actions, some measures have been implemented in order to facilitate the access for producers to the materials. Approximately 9,500 families had access to the technologies through the supply chain (3 small manufacturers, and 60 resellers of equipments) and other stakeholders (NGOs, projects, economical operators).*"

Micro irrigation is sustainable and is one of the best management practices. I attended the 17th Punjab Science Congress on February 14–16, 2014 at Punjab Technical University in Jalandhar. I was shocked to know that the underground water table has lowered to a critical level in Punjab. My father-in-law in Dhuri told me that his "*family bought the 0.10 acres of land in the city for US$100.00 in 1942 AD because the water table was at 2 feet depth. In 2012, it was sold for US$200,000 because the water table had dropped to greater than 100 feet. This has been due to luxury use of water by wheat-paddy farmers*." The water crisis is similar in other countries, including Puerto

Rico, where I live. We can therefore conclude that the problem of water scarcity is rampant globally, creating the urgent need for water conservation. The use of micro irrigation systems is expected to result in water savings and increased crop yields in terms of volume and quality. The other important benefits of using micro irrigation systems include expansion in the area under irrigation, water conservation, optimum use of fertilizers and chemicals through water, and decreased labor costs, among others. The worldwide population is increasing at a rapid rate, and it is imperative that the food supply keeps pace with this increasing population.

Micro irrigation, also known as trickle irrigation or drip irrigation or localized irrigation or high frequency or pressurized irrigation, is an irrigation method that saves water and fertilizer by allowing water to drip slowly to the roots of plants, either onto the soil surface or directly onto the root zone, through a network of valves, pipes, tubing, and emitters. It is done through narrow tubes that deliver water directly to the base of the plant. It is a system of crop irrigation involving the controlled delivery of water directly to individual plants and can be installed on the soil surface or subsurface. Micro irrigation systems are often used in farms and large gardens but are equally effective in the home garden or even for houseplants or lawns. They are easily customizable and can be set up even by inexperienced gardeners. Putting a drip system into the garden is a great do-it-yourself project that will ultimately save time and help the plants grow. It is equally used in landscaping and in green cities.

The mission of this compendium is to serve as a reference manual for graduate and undergraduate students of agricultural, biological, and civil engineering and horticulture, soil science, crop science, and agronomy. I hope that it will be a valuable reference for professionals who work with micro irrigation and water management; for professional training institutes, technical agricultural centers, irrigation centers, agricultural extension service; and other agencies that work with micro irrigation programs.

After my first textbook *Drip/Trickle or Micro Irrigation Management* by Apple Academic Press Inc., was published, and response from international readers, I was motivated to bring out for the world community this multi-volume series, Research Advances in Sustainable Micro Irrigation. This book series will complement other books on micro irrigation that are currently available on the market, and my intention is not to replace any one of these. This book series is unique because it is complete and simple, a one-stop collection, with worldwide applicability to irrigation management in agriculture. Its coverage of the field of micro irrigation includes historical review; current status and potential; basic principles and applications; research results for vegetable/row/tree crops; research studies from Chile, Colombia, Egypt, India, Mexico, Puerto Rico, Saudi Arabia, South Africa, Spain, Sweden, Turkey, and U.S.A.; research results on simulation of micro irrigation and wetting patterns; development of software for micro irrigation design; micro irrigation for small farms and marginal farmers; studies related to agronomical crops in arid, humid, semiarid, and tropical climates; and methods and techniques that can be easily applied to other locations (not included in this book).

This book offers basic principles, knowledge, and techniques of micro irrigation management that are necessary to understand before designing, developing, and evaluating an agricultural irrigation management system. This book is a must for those interested in irrigation planning and management, namely, researchers, scientists, educators, and students.

Volume 1 in this book series is titled *Sustainable Micro Irrigation: Principles and Practices*, and includes 16 chapters. Volume 2 is titled *Research Advances and Applications in Subsurface Micro Irrigation and Surface Micro Irrigation*, and includes 16 chapters. Volume 3 is titled *Sustainable Micro Irrigation Management for Trees and Vines*, and that includes 14 chapters.

The contributions by the authors of this book series have been most valuable in the compilation of this multi-volume compendium. Their names are mentioned in each chapter and in the list of contributors. These books would not have been written without the valuable cooperation of these investigators, many of whom are renowned scientists who have worked in the field of micro irrigation throughout their professional careers.

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We request the reader to offer us your constructive suggestions that may help to improve the next edition. The reader can order a copy of this book for the library, the institute or for a gift from http://appleacademicpress.com.

I express my deep admiration to my family for their understanding and collaboration during the preparation of this multi-volume book series. With my whole heart and best affection, I dedicate this book series to Jack Keller, who has been my master since 1979. He helped me to trickle on to add my drop to the ocean of service to the world of humanity. Without his advice and patience, I would not have been a "*Father of Irrigation Engineering of 20th Century in Puerto Rico,"* with zeal for service to others. My salutes to him for his irrigation legacy. As an educator, I offer a piece of advice to one and all in the world: "*Permit that our almighty God, our Creator and excellent Teacher, irrigate the life with His Grace of rain trickle by trickle, because our life must continue trickling on.*"

—Megh R. Goyal, PhD, PE, Senior Editor-in-Chief
June 30, 2014

Paul Polak (outofpovertyteam@gmail.com) sent me an email on December 19, 2013 indicating that "*I have sad news. My close friend and soul brother, Jack Keller, died suddenly in the middle of an animated political discussion at a social gathering before an IDE board meeting. Jack was a deeply spiritual person (Bahai's Faith). He was a world-class irrigation engineer who was not afraid of getting his shoes dirty. Our collaboration on SunWater to create a radically affordable solar pump system represents the way he lived all his life: dream big, make it happen, and die trying.*"

Rick Allan at the University of Idaho adds, *"Jack always impressed me by his ability (and desire) to take a visual snapshot of the world around him and 'parse' it into recognizable and solvable components. For example, his decoupling of irrigation efficiency into three or four component terms, or the balancing of costs for pipe size* *with costs for energy and distribution uniformity (economic pipe sizing). Through all of this, Jack could easily crack his famous grin and smile, showing his substantial enjoyment of 'playing in the water' (or playing in the mathematics) and figuring out solutions that benefited many, many people. I was most impressed when, in his seventies, Jack launched on his 15-year journey to bring small scale, economic drip, sprinkler, and treadle pumping systems into the hands of small farmers in Asia and Africa, thus enabling them to produce higher value crops, put cash into their pockets, and sending their children to school. I believe that Jack, alone, is responsible for tens of thousands of children being in school and advancing their educations, who otherwise would have been trapped in subsistence agriculture. Jack has left a huge, memorable irrigation legacy. The World will not be the same."*

—Megh R. Goyal, PhD, PE, Senior Editor-in-Chief
June 30, 2014

FOREWORD

With only a small portion of cultivated area under irrigation and with the scope to the additional area, which can be brought under irrigation, it is clear that the most critical input for agriculture today is water. It is important that all available supplies of water should be used intelligently to the best possible advantage. Recent research around the world has shown that the yields per unit quantity of water can be increased if the fields are properly leveled, the water requirements of the crops as well as the characteristics of the soil are known, and the correct methods of irrigation are followed. Significant gains can also be made if the cropping patterns are changed so as to minimize storage during the hot summer months when evaporation losses are high, if seepage losses during conveyance are reduced, and if water is applied at critical times when it is most useful for plant growth.

Irrigation is mentioned in the Holy Bible and in the old documents of Syria, Persia, India, China, Java, and Italy. The importance of irrigation in our times has been defined appropriately by N.D Gulati: "In many countries irrigation is an old art, as much as the civilization, but for humanity it is a science, the one to survive." The need for additional food for the world's population has spurred rapid development of irrigated land throughout the world. Vitally important in arid regions, irrigation is also an important improvement in many circumstances in humid regions. Unfortunately, often less than half the water applied is used by the crop – irrigation water may be lost through runoff, which may also cause damaging soil erosion, deep percolation beyond that required for leaching to maintain a favorable salt balance. New irrigation systems, design and selection techniques are continually being developed and examined in an effort to obtain high practically attainable efficiency of water application.

The main objective of irrigation is to provide plants with sufficient water to prevent stress that may reduce the yield. The frequency and quantity of water depends upon local climatic conditions, crop and stage of growth, and soil-moisture-plant characteristics. Need for irrigation can be determined in several ways that do not require knowledge of evapotranspiration (ET) rates. One way is to observe crop indicators such as change of color or leaf angle, but this information may appear too late to avoid reduction in the crop yield or quality. Other similar methods of scheduling include determination of the plant water stress, soil moisture status, or soil water potential. Methods of estimating crop water requirements using ET and combined with soil characteristics have the advantage of not only being useful in determining when to irrigate, but also enables us to know the quantity of water needed. ET estimates have not been made for the developing countries though basic information on weather data is available. This has contributed to one of the existing problems that the vegetable crops are over irrigated and tree crops are under irrigated.

Water supply in the world is dwindling because of luxury use of sources; competition for domestic, municipal, and industrial demands; declining water quality; and losses through seepage, runoff, and evaporation. Water rather than land is one of the limiting factors in our goal for self-sufficiency in agriculture. Intelligent use of water will avoid problem of sea water seeping into aquifers. Introduction of new irrigation methods has encouraged marginal farmers to adopt these methods without taking into consideration economic benefits of conventional, overhead, and drip irrigation systems. What is important is "net in the pocket" under limited available resources. Irrigation of crops in tropics requires appropriately tailored working principles for the effective use of all resources peculiar to the local conditions. Irrigation methods include border-, furrow-, subsurface-, sprinkler-, sprinkler, micro, and drip/trickle, and xylem irrigation.

Drip irrigation is an application of water in combination with fertilizers within the vicinity of plant root in predetermined quantities at a specified time interval. The application of water is by means of drippers, which are located at desired spacing on a lateral line. The emitted water moves due to an unsaturated soil. Thus, favorable conditions of soil moisture in the root zone are maintained. This causes an optimum development of the crop. Drip/micro or trickle irrigation is convenient for vineyards, tree orchards, and row crops. The principal limitation is the high initial cost of the system that can be very high for crops with very narrow planting distances. Forage crops may not be irrigated economically with drip irrigation. Drip irrigation is adaptable for almost all soils. In very fine textured soils, the intensity of water application can cause problems of aeration. In heavy soils, the lateral movement of the water is limited, thus more emitters per plant are needed to wet the desired area. With adequate design, use of pressure compensating drippers and pressure regulating valves, drip irrigation can be adapted to almost any topography. In some areas, drip irrigation is used successfully on steep slopes. In subsurface drip irrigation, laterals with drippers are buried at about 45 cm depth, with an objective to avoid the costs of transportation, installation, and dismantling of the system at the end of a crop. When it is located permanently, it does not harm the crop and solve the problem of installation and annual or periodic movement of the laterals. A carefully installed system can last for about 10 years.

The publication of this book series and this volume is an indication that things are beginning to change, that we are beginning to realize the importance of water conservation to minimize the hunger. It is hoped that the publisher will produce similar materials in other languages.

In providing this resource in micro irrigation, Megh Raj Goyal, as well as the Apple Academic Press, is rendering an important service to the farmers, and above all to the poor marginal farmers. Dr. Goyal, Father of Irrigation Engineering in Puerto Rico, has done an unselfish job in the presentation of this compendium that is simple and thorough. I have known Megh Raj since 1973 when we were working together at Haryana Agricultural University on an ICAR research project in "Cotton Mechanization in India."

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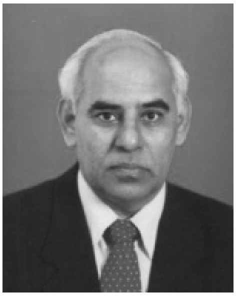

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Megh R. Goyal received his BSc degree in Engineering in 1971 from Punjab Agricultural University, Ludhiana, India; his MSc degree in 1977 and PhD degree in 1979 from the Ohio State University, Columbus; his Master of Divinity degree in 2001 from Puerto Rico Evangelical Seminary, Hato Rey, Puerto Rico, USA. He spent a one-year sabbatical leave in 2002–2003 at Biomedical Engineering Department, Florida International University, Miami, USA.

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He was the first agricultural engineer to receive the professional license in Agricultural Engineering in 1986 from the College of Engineers and Surveyors of Puerto Rico. On September 16, 2005, he was proclaimed as “Father of Irrigation Engineering in Puerto Rico for the twentieth century” by the ASABE, Puerto Rico Section, for his pioneer work on micro irrigation, evapotranspiration, agroclimatology, and soil and water engineering. During his professional career of 45 years, he has received awards such as Scientist of the Year, Blue Ribbon Extension Award, Research Paper Award, Nolan Mitchell Young Extension Worker Award, Agricultural Engineer of the Year, Citations by Mayors of Juana Diaz and Ponce, Membership Grand Prize for ASAE Campaign, Felix Castro Rodriguez Academic Excellence, Rashtrya Ratan Award and Bharat Excellence Award and Gold Medal, Domingo Marrero Navarro Prize, Adopted son of Moca, Irrigation Protagonist of UPRM, Man of Drip Irrigation by Mayor of Municipalities of Mayaguez/Caguas/Ponce and Senate/Secretary of Agriculture of ELA, Puerto Rico.

He has authored more than 200 journal articles and textbooks including *Elements of Agroclimatology* (Spanish) by UNISARC, Colombia; two *Bibliographies on Drip Irrigation*. Apple Academic Press Inc. (AAP) has published his books, namely, *Biofluid Dynamics of Human Body*, *Management of Drip/Trickle or Micro Irrigation*, *Evapotranspiration: Principles and Applications for Water Management*, and *Biomechanics of Artificial Organs and Prostheses*.” With this volume, AAP will publish 10-volume set on *Research Advances in Sustainable Micro Irrigation*. Readers may contact him at: goyalmegh@gmail.com.

WARNING/DISCLAIMER

The goal of this compendium is to guide the world community on how to manage the "Management, Performance, and Applications of Micro Irrigation Systems" system efficiently for economical crop production. The reader must be aware that the dedication, commitment, honesty, and sincerity are most important factors in a dynamic manner for a complete success. It is not a one-time reading of this compendium. Read and follow every time, it is needed. To err is human. However, we must do our best. Always, there is a space for learning new experiences.

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PART I

PERFORMANCE OF MICRO IRRIGATION SYSTEMS

CHAPTER 1

ADOPTION OF MICRO IRRIGATION IN INDIA: FACTORS AND POLICIES

D. SURESH KUMAR

CONTENTS

In this chapter: Rs. = An Indian currency = US $0.01669.

1.1 INTRODUCTION

Water is becoming increasingly scarce resource that is limiting agricultural development in many developing and developed economies across the world. A study by the International Water Management Institute (IWMI) shows that around 50% of the increase in demand for water by the year 2025 can be met by increasing the effectiveness of irrigation [18]. In India, almost all the easily possible and economically viable irrigation water potential has already been developed, but the demand for water for different sectors has been growing continuously [17, 22]. Moreover, the water use efficiency in the agricultural sector, which still consumes over 80% of water, is only in the range of 30–40% in India, indicating that there is considerable scope for improving the water use efficiency.

The review of past studies lucidly shows that the solution to the problem of growing groundwater scarcity and persistent groundwater resource degradation across regions are two folds: Firstly, the supply side management practices like watershed development, water resources development through major, medium and minor irrigation projects. The second is thorough the demand management by efficient use of the available water both in the short-run and long-run perspectives. This includes drip irrigation and other improved water management practices. Recognizing the importance of sustainable water use efficiency in agriculture, a number of demand management strategies (like water pricing, water users association, turnover system, etc.) have been introduced since the late seventies to increase the water use efficiency especially in the use of surface irrigation water.

One of the demand management mechanisms is the adoption of micro irrigation such as drip and sprinkler method of irrigation. Evidences show that many researchers attempted to study the impact of drip irrigation [1, 2, 4, 8, 11, 14–16]. The water use efficiency increases up to 100% in a properly designed and managed drip irrigation system [3, 19]. Drip method of irrigation helps to reduce the over exploitation of groundwater that partly occurs because of inefficient use of water under surface method of irrigation. Environmental problems associated with the surface method of irrigation like water logging and salinity are also completely absent under drip method of irrigation [14]. In addition, drip method helps in achieving saving in irrigation water, increased water use efficiency, decreased tillage requirement, higher quality products, increased crop yields and higher fertilizer use efficiency [11, 16, 20].

Though the potential benefits generated by the drip irrigation methods are apparent, the adoption of drip irrigation is yet to be widely promoted across regions, states and elsewhere. Kumar [5] found that the most ideal policy environment for promotion of micro irrigation technologies in well-irrigated areas would be pro-rata pricing of electricity, while this would create direct incentive for efficient water use. Adoption of micro irrigation systems is likely to pick up fast in arid and semi arid, well-irrigated areas, where farmers have independent irrigation sources, and where groundwater is scarce. Further, high average land holdings, large size of individual plots, and a cropping system dominated by widely spaced row crops, which are also high-valued, would provide the ideal environment for the same [6].

The huge initial investment, small size of holding, lack of technical support, cropping pattern, access to water and socioeconomic conditions of farmers, etc., [11] are major factors influencing adoption of drip irrigation. In some cases, even after the adoption of drip irrigation, the farmers, particularly, the small farmers found to discontinue drip irrigation for several reasons such as lack of maintenance, irrelevant cultural background, and unreliable water supply [4]. Though there are many studies attempted to identify factors limiting the adoption of drip irrigation, still, it is not clear where should we promote micro irrigation.

In this context, the drip irrigation has received much attention from policy makers and others for its perceived ability to contribute significantly to groundwater resources development, agricultural productivity, economic growth, and environmental sustainability. Yet in many parts of the country and elsewhere, they have yet to be widely adopted. Also, it is crucial to determine/locate the areas where the micro irrigation should be encouraged and promoted.

Keeping these issues in view, this chapter addresses following important issues:

(i) What changes the drip irrigation brings to the farming system?
(ii) Whether the adoption of drip irrigation is motivated by the cropping pattern or the cropping pattern is followed by drip adoption?
(iii) What factors limit/enhance the adoption of drip irrigation systems? and
(iv) What policy action must be taken at different levels to speed up the adoption of drip irrigation and groundwater development?

1.2 METHODOLOGY

1.2.1 THE LOCATION AND DATA

The study was conducted in the Coimbatore district of Tamil Nadu, India where groundwater resource degradation is alarming. Two blocks were selected so as to represent drip adoption and control. From the selected blocks, two revenue villages were selected purposively where the adoption of drip irrigation is widespread. Farm households in the selected villages constituted the sample units. To examine the adoption and impact of drip irrigation on resource use, agricultural production and farm income, 25 drip-adopting farmers were selected in each village and correspondingly 25 nondrip adopters were selected in control villages.

To select the drip adopters, the list of farmers from the Department of Agricultural Engineering was collected. Also, we enumerated the list of farmers adopting drip irrigation after discussions with the villagers and private firms dealing drip irrigation systems. Thus, a sample of 100 farmers was studied. For the purpose of the study, interview schedules were formulated and pretested. The needed information from the respondent group was gathered personally administering the interview schedule. The primary information collected from the farm households included details on well investment, groundwater use, extraction and management, crop production including input use and output realized, farm income, adoption of drip irrigation, and investment on drip irrigation. This also included asset position, education and other socioeconomic conditions.

1.2.2 QUANTIFICATION OF BENEFITS AND DOUBLE-DIFFERENCE METHODOLOGY

Farm level data were collected for both drip adopters and nonadopters before and after drip irrigation technology. This enables the use of the double-difference method to study the impacts due to adoption of drip irrigation. The framework was adopted from the program evaluation by Maluccio and Flores [9].

In Table 1, the columns distinguish between the groups between drip adopters and nondrip adopters and the rows distinguish between before and after the drip adoption. This is best explained in the Fig. 1.

TABLE 1 Double-difference method.

Particulars	Drip Adopters	Non-adopters	Difference across groups
After drip adoption	D1	C1	D1-C1
Before drip adoption	D0	C0	D0-CO
Difference across time	D1-D0	C1-C0	Double difference (D1-C1)-(D0-C0)

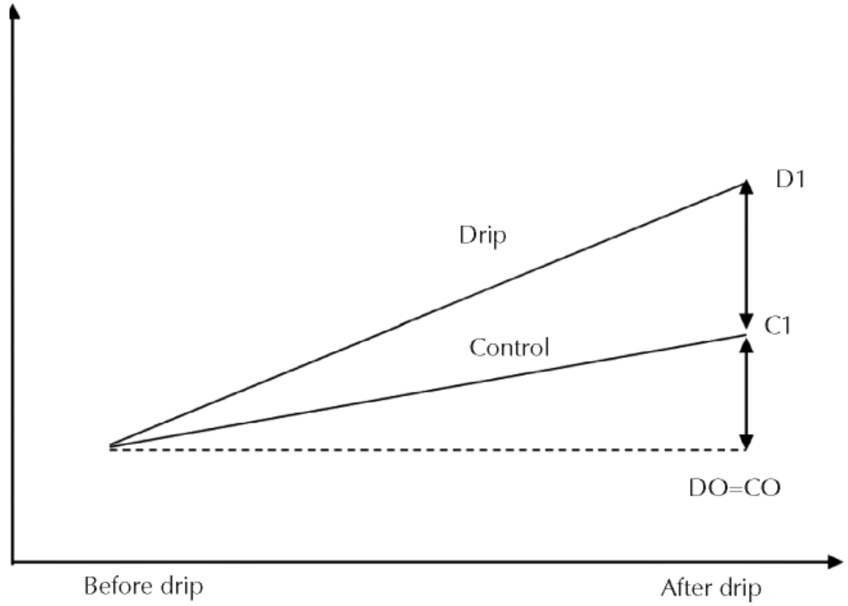

FIGURE 1 Illustration of impact of drip adoption by double difference method.

1.2.3 ADOPTION OF DRIP IRRIGATION

A key concern for policy makers is making the farm households adopting micro irrigation technologies in order to manage the growing groundwater scarcity. Thus, an important research question is what factors influence the decision of farm households to adopt drip irrigation. For this purpose, area under drip irrigation installed by the farm households was considered as the dependent variable. It is expected that the adoption of drip irrigation by the farm households influenced by different physical, socioeconomic, institutional and household specific factors.

The dependent variable adoption of drip irrigation would be zero for those households who do not adopt drip irrigation. If the dependent variable is censored, values in a certain range may all be recorded as single value. Given that our dependent variable is censored at zero, a Tobit estimation rather than OLS is appropriate [7, 21]. In such a case, Tobit estimators may be used. Thus, the functional form of the model specified in the present study with a Tobit model, with an error term (Ui) which is independently, normally distributed with zero mean and constant covariance, is given by Eq. (1).

$$\begin{aligned} DA^{*}i &= Xi\ b + Ui \text{ For } i = 1.n \\ DAi &= T^{*}i \text{ if } Xi\ b + Ui > 0 \\ &= 0 \text{ if } Xi\ b + Ui <= 0 \end{aligned} \tag{1}$$

In Eq. (1): DAi = Area under drip irrigation in hectares; Xi = Vector of independent variables; b = Vector of unknown coefficients; and n = Number of observations. In the functional relationship defined by Eq. (1), the DAi is the endogenous variable which is expected to influence by other exogenous variables viz., age of the farmer in years (AGE), educational level of the farmer in years of schooling (EDUCATION), farm size in hectares (FSIZE), proportion of wider spaced crop (WIDERCROP), participation in nonfarm income activities (NONFARM) and percentage of area irrigated by wells (AWELLS).

Economic implications can be drawn by using the results of the empirical model. Following a Tobit decomposition framework suggested by McDonald and Moffitt [10], the effects of the changes in the explanatory variables on the probability of adoption of drip irrigation and intensity of adoption could be obtained.

The basic relationship between the expected value of all observations, E(DA), the expected value conditional upon being above the limit, E(DA*), and the probability of being above the limit, F(*z*), is defined by Eq. (2).

$$E(DA) = E(DA^{*}).F(z) \tag{2}$$

The effect of a given change in the level of the explanatory variables on the dependent variables (the Eq. (3)) can be obtained by decomposing the Eq. (2).

$$\frac{\partial E(DA)}{\partial X_i} = F(z)\left(\frac{\partial E(DA^{*})}{\partial X_i}\right) + E(DA^{*})\left(\frac{\partial F(z)}{\partial X_i}\right) \tag{3}$$

Thus, the total elasticity of change in the level of the explanatory variable consists of two effects: (i) change in DA of those above the limit (i.e., elasticity of intensity of drip adoption, for those households who already an adopter) and (ii) the change in the probability of being above the limit (i.e., probability of drip adoption).

1.3 STATUS OF MICRO IRRIGATION IN TAMIL NADU

Tamil Nadu state ranks seventh in India in terms of area under micro irrigation. During 2008, a total area of 158,521 ha was practiced under micro irrigation in the Tamil Nadu state. Of the total area under micro irrigation, the drip accounted for 82.85% (131,335 ha) and sprinkler for 17.15% (27,186 ha). In all India, the area under drip irrigation was 36.82% and under sprinkler was 63.18%. It is clear that the drip method of irrigation is more popular among the farmers in Tamil Nadu when compared to sprinkler method of irrigation. It is seen that the Tamil Nadu state has only 9.2% of the total drip area in India, where as the sprinkler irrigation accounts for only 1.1% of total area in the country. The area under micro irrigation accounts 4.1% of the total area under irrigation in the country. The area under micro irrigation is very low in Tamil Nadu when compared to the national level area. The net sown area of the state is 5,126,000 ha, whereas the gross cropped area is 5,842,000 ha. The area under micro irrigation accounts for only 3.1% of the net sown area of the state, whereas it accounts for 5.49% of the net irrigated area and 4.79% of the gross irrigated area. Thus, there is a huge potential to increase the area under micro irrigation in the state.

1.3.1 THE STUDY AREA (THE COIMBATORE DISTRICT OF TAMIL NADU STATE)

In the study area, that is, the Coimbatore district of Tamil Nadu state, agriculture depends largely on minor irrigation projects and other sources such as wells, rain-fed tanks, etc. The chief source of irrigation in the district is through wells. The average well-failure rate is 47% for open-wells and 9% for bore-wells. There are six different soil types viz., red calcareous soil, black soil, red noncalcareous soil, alluvial and colluvial soil, brown soil and forest soil. The mean annual rainfall for the 45 years (between 1961 and 2005) is worked out to be 687.1 mm and the coefficient of variation is worked out to be 28.21%. The distribution of rainfall across seasons indicates that the mean rainfall ranged from 16 mm during winter to 348 mm during northeast monsoons. The groundwater potential in January 2003 indicated that the total groundwater recharge was 880.97 million cubic meter (MCM), net groundwater availability (90% of total groundwater recharge) was 792.87 MCM, domestic and industrial draft was 40.57 MCM, irrigation draft was 779.13 MCM and the stage of groundwater development was 103%.

The level of groundwater development exceeds 100% of the utilizable groundwater recharge in 11 blocks, between 90 and 100% in four blocks and between 70 and 90% in another four blocks. The stages of groundwater development in the study blocks, viz. Anamalai and Madathukulam blocks was 51% and 56%, respectively. Increasing private investment on wells is visualized over the years as groundwater irrigation assumes importance. Farmers in this district rely heavily on groundwater for irrigation.

Dependence on groundwater for irrigation is a common phenomenon in both the study blocks. The source wise area irrigated indicates that the groundwater irrigation accounts 52.29% in Annamalai block and 35.85% in Madathukulam block. The increasing trend in groundwater irrigation further confirms that heavy dependence on this for irrigation. This confirms the importance of groundwater for agricultural crop production, that is, the area irrigated by different abstraction structures is much more than that of the surface water sources. The irrigation system often suffers due to inadequate supply of surface water and depends upon groundwater sources as an alternative to supplement to surface water to stabilize the irrigation.

1.4 RESULTS FROM FIELD STUDIES

1.4.1 GENERAL CHARACTERISTICS OF THE FARM HOUSEHOLDS

The general characteristics of the sample farm households were analyzed to observe any significant changes in land holdings, cropped area, irrigated area due to the introduction of drip irrigation. For this purpose, the drip adopters were compared with the control households. It was observed that the average size of holding among the drip adopters was significantly larger than the nonadopters in control village. Since drip method of irrigation involves huge initial investment, large farmers adopt widely when compared to small and marginal farmers (Table 2).

It is argued that drip irrigation increases cropped area and area under irrigation as it is a viable water saving technology. Our study confirms the earlier findings that the drip irrigation technology increased the net sown area, net irrigated area and there-by helps in achieving higher cropping intensity and irrigation intensity. For instance, the net sown area is increased from 13.27 hectares to 14.49 hectares whereas the gross cropped area increased from 13.71 hectares to 14.91 hectares (Table 2). Similarly the net irrigated area and gross irrigated area also increased after drip adoption. During the survey, we found that drip irrigation technology resulted in significant impacts. Being an efficient water saving technology, it helps in expanding the irrigated area and saving water.

The details regarding before drip adoption was collected based on the recall basis. For control villages, the reference period for the preadoption was considered to be 10 years before, that is, 1995.

TABLE 2 General Characteristics of sample households, 2007–2008.

Particulars	Drip adopters		Non-adopters	
	Before	After	Before	After
Number of farm households	50		50	
Number of workers in the household (Number)	2.0	2.0	2.52	2.52
Farm size (Hectares)	16.54***	16.54	5.06	5.06
Net sown area (Hectares)	13.27***	14.49	4.66	4.66
Gross cropped area (Hectares)	13.71***	14.91	4.66	4.66
Cropping intensity (%)[a]	102.04**	101.82	100.00	100.00
Net irrigated area (Hectares)	13.17***	14.41	4.57	4.57
Gross irrigated area (Hectares)	13.67***	14.85	4.57	4.57
Irrigation intensity (%)[b]	102.30	101.88	100.00	100.00
Percentage of area irrigated by wells to the total cropped area (%)	99.82	99.74	97.53	97.53

TABLE 2 *(Continued)*

Particulars	Drip adopters		Non-adopters	
	Before	After	Before	After
Percentage of area irrigated under drip to gross irrigated area (%)	96.94			

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

[a]Cropping intensity is defined as the ratio of gross cropped area to net sown area and expressed as percentage.

[b]Irrigation intensity is the ratio of gross irrigated area to net irrigated area and expressed as percentage.

1.4.2 CROPPING PATTERN

An attempt was made to find whether drip irrigation had induced a certain new cropping system or the crops had followed drip technology as a response to the growing water scarcity? The cropping pattern, that is, proportion of area under different crops, is a good indicator of the development of resource endowments and agricultural production. It is expected that drip method of irrigation helps in the development of water resource potential and also helps the farmers to get more crop and income per drop of water.

The longitudinal analysis of cropping pattern across farm households and villages revealed that the adoption of drip irrigation is motivated my many factors. The two major constraints limiting agricultural production are human labor and water scarcity. These made the farmers to alter their cropping pattern towards less labor and water intensive crops. Resource poor farmers go in for rainfed crops. However, the big farmers who have capital access adopt various water management and coping strategies. One of the important coping strategies or rather efficient water management technologies is adoption of drip irrigation. Thus, in regions where there is severe water and labor scarcity, first there is a shift from labor and water intensive crops such as vegetables, sugarcane, cotton, paddy to less labor intensive crops such as coconut, takes place and followed by drip adoption. As drip irrigation saves human labor substantially by reduction in operations such as irrigation and weeding, water-loving crops such as banana and grapes are planted followed by drip irrigation. Significant changes in cropping pattern are observed. It is evident that over a period of time, the water and labor intensive crops like paddy, sugarcane and vegetables area were significantly reduced in drip village. However, the area under coconut has increased from 45% to 88% over time (Table 3). Increase in area under coconut is also seen among the nonadopters in the control village implying changes in the cropping pattern. Thus, the micro irrigation could be promoted in regions with high water and labor scarcity. As cropping pattern decides the adoption and suitability of drip irrigation, widespread adoption of micro irrigation could be promoted in the regions where shift towards crops like coconut, banana are common.

TABLE 3 Drip irrigation and cropping pattern changes (percent), 2007–2008.

Crops	Drip adopters		Non-adopters	
	Before	After	Before	After
Banana	9.54	1.89	34.24	—
Coconut	45.04	88.63	—	64.2
Cotton	—	—	2.67	—
Maize	—	0.87	3.82	2.2
Paddy	6.47	1.02	35.41	13.5
Sugarcane	5.7	—	22.08	17.85
Turmeric	6.71	0.21	—	1.67
Vegetables including tomato	26.54	7.38	1.78	0.58

1.4.3 IRRIGATION INVESTMENTS AND DISTRIBUTION OF PUMP HORSE POWER

Growing groundwater scarcity coupled with cheaper power supply resulted in further degradation of the groundwater resource in the water scarce regions like Coimbatore.

Pro-rata system (PR) has been commonly used in most of the Indian states till last seventies. In this method, farmers have to pay electricity cost based on the consumption of electricity in kWh. Tariff rate sometime vary with farmers' category and horsepower of pump-sets. In this method, farmers who use more electricity will have to pay more cost for electricity and vice-versa.

After eighties, many Indian states started to introduce **flat rate system** (FR) for agriculture. In this FR, tariff charges will be fixed based on the HP of pump-sets and not by the quantity of electricity consumption. Pump-set owning farmers can consume electricity as much as they need. Farmers need not pay tariff for every month. Normally it will be remitted once in three months/six months. Studies found that flat rate tariff policy has strong equity and poverty alleviation benefits. It reduces the working costs of State Electricity Boards that spend considerable amount of money for meter reading, etc. It also allows the bore well owning farmers to sell water in a low price for the poor nonbore well farmers.

It is argued that cheaper pricing policies of electricity and shifting of tariff from pro-rata to flat rate have reduced the marginal costs of water as well as electricity to zero. As a result farmers use both groundwater and electricity inefficiently. The effect of such cheaper electricity has resulted in negative externalities such as over pumping, changes in crop pattern towards more water intensive crops, well deepening, increase in well investments, pumping costs, well failure and abandonment and out migration which are increasing at a much faster rate. To cope up with the degradation of groundwater resource, farmers make huge investments on groundwater extraction. They include investment on drilling new bore wells or dug wells, deepening of existing wells, construction of intermediate storage structures and micro irrigation technologies like drip irrigation, sprinkler irrigation and so on. Thus, the investment on irrigation structures assumes crucial to study. The total amortized cost of irrigation investment is worked out as the sum of amortized cost on wells, electric motor and equipments, surface storage tanks and drip irrigation equipments.

The amortization of irrigation structures is calculated using Eqs. (4) and (5). The discount rate of 5% is used in amortization reflecting long-term sustainable rate. Similarly investment on conveyance, pump-set, electrical installation, and surface storage tanks and drip irrigation structures were amortized, where AL is average life of wells and it is assumed to be 30 years based on the average life of well life in the study area. Similarly, the average life of bore-wells is assumed as 20 years, electrical motors 15 years, surface storage tanks 25 years and drip irrigation equipments 10 years.

$$\text{Amortized cost of well} = [(\text{Compounded cost of well})\times(1+i)^{AL} \times i] \div [(1+i)^{AL}-1] \quad (4)$$

where: AL = Average life of wells; and

$$\text{Compounded cost of well} = (\text{Initial investment on well}) \times (1+i)^{(2008-\text{year of construction})} \quad (5)$$

The analysis on well and irrigation investments revealed that the total fixed cost on wells and other irrigation structures is worked out to high among the drip adopters than the nonadopters in the control village. For instance, the total amortized cost is worked out to Rs. 9,325.91 per hectare for drip adopters and Rs. 5,788 per hectare for the control village. It is 61% higher than the control village (Table 4). The increased investment on fixed irrigation investments is mainly due to additional investment on drip equipments.

TABLE 4 Details of well and irrigation investment (Rupees/hectare of GCA) in the sample farms, 2007–2008.

Investment	Drip adopters	Non-adopters
Investment on wells	3672.75***	3324.99
	(39.38)	(57.44)
Investment on electric motors	2271.60	2306.65
	(24.36)	(39.85)
Investment on surface storage tanks	54.73***	157.07
	(0.59)	(2.71)
Investment on drip irrigation equipments	3326.83	
	(35.67)	
Total investment on irrigation structures	9325.91***	5788.71
	(100.00)	(100.00)
Distribution of horse power of pump		
HP/pump	5.23	6.29
HP/GCA	4.45	4.50
HP/GIA	4.45	4.65

Note: Figures in parentheses indicate percentage to total.

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

Of the total fixed investments, the investment on wells assumes major share. The percent share of wells to the total cost is 39.38% for drip adopters and 57.44% for control farmers. It is evident that the investment on wells is higher among the control farmers. The percent share of drip investments is worked out to 35.67% implying huge investment on drip irrigation.

Growing water scarcity coupled with low discharge rate forced the farmers to construct an intermediate water storage structures. These farm surface storage tanks help the farmers to store water and irrigate when and where needed. The water is pumped from very deep borewell and stored in these tanks and then used for irrigating crops. These storage structures are constructed by both the drip adopters and non-adopters. As the cost of construction of surface storage tank is very low (Rs. 30 to 42/M^3), it is becoming popular among the farmers. These structures account 0.6% to 2.71%.

1.4.4 CROP YIELD AND PRODUCTIVITY GAINS

Micro irrigation in general drip irrigation method in particular, primarily followed for increasing the water use efficiency. The yield of important crops grown in the sample farms is presented in Table 5. In the study area, the drip method of irrigation is followed widely in banana, coconut, and in few cases, drip adoption is followed in maize and turmeric. As the focus of this study is impact of drip irrigation, the yield of drip-adopted crops is compared with the flood method.

TABLE 5 Yield of selected crops (100 Kg/ha) in the study farms, 2007–2008.

Crops	Drip adopters	Non-adopters
Banana	605.6***	591.5
Coconut^Y	23012.8***	19213.5
Maize		33.4
Paddy	54.5	55.7
Sugarcane		110.7
Turmeric		50.3

Y = Number of nuts per hectare of coconut garden.

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

The yield of banana is worked out to 60,500 Kg/ha when compared to 59,100 Kg/ha in the control farmers, accounting 2.38% increase in yield under drip method over flood method of irrigation. Similarly, the coconut registered an increase in yield of 19.8% under drip over flood method of irrigation. The findings of the research in this chapter further confirm increased productivity could be achieved through drip method of irrigation and on line with the earlier studies [3, 12, 13]. This higher crop productivity under drip method of irrigation occurs mainly through higher water use efficiency. The drip method of irrigation, unlike flood method, supplies water continuously at regular intervals, and the crops cultivated under drip method does not face moisture stress, the major factor negatively affecting crop yield [19]. Thus, drip method of irrigation sufficiently contributing for achieving higher yield.

1.4.5 IMPACT OF DRIP IRRIGATION TECHNOLOGY ON AGRICULTURAL PRODUCTION

The economics of banana cultivation revealed that the cost of labor significantly reduced under drip method (Rs. 11,123/ha), which is 55.6% less than the control village (Rs. 25,075/ha). The drip method of irrigation saves significantly the human labor involved in crop production activities. It saves irrigation labor and weeding labor. On an average the human labor days used for weeding banana is 17 labor days/ha under drip method of irrigation where as it is 60 labor days/ha under flood method of irrigation. Thus, the drip method saves nearly 71% of weeding labor when compared to flood method of irrigation. Similarly, the drip method saves considerable labor for irrigation. The irrigation labor is worked out to 168 labor days/ha under flood method of irrigation where as it is 18 labor days under drip method of irrigation. As the drip method saves considerable human labor, the cost of cultivation is significantly less under drip method over the flood method (Table 6).

The reduction in cost towards human labor has significant bearing on the cost of cultivation. Though, the cost of installation of drip equipments and maintenance is incurred by the drip farms, the reduced cost of cultivation is observed by 25%. The gross margin per hectare is worked out to Rs. 189,259/ha in drip farms where as it is Rs. 159,478/ha in control village. It clearly shows that drip method of irrigation resulted in an increase of 18.67%. As the adoption of drip irrigation saves considerable water and energy, the water and energy productivity is significantly more in drip farms than the control village where the flood irrigation is followed. For instance, the water productivity is worked out to 7.1 kg/M^3 of water in drip farms and 2.8 kg/M^3 of water in control village. Significant difference in energy productivity is also noticed. The returns per unit of water and energy used show that drip farms have significantly higher returns over the control village. Thus one could conclude that the drip adoption would be a viable technology and generate significant bearing on the private profits.

TABLE 6 Economics of crop production (Rs. per ha) for Banana in sample farms, 2007–2008.

Particulars	Drip adopters	Non-adopters
Quantity of water pumped (M^3)	8506.3	21316.9
Quantity of energy consumed (kwh)	2670.9	7313.9
Cost of labor (Rs.)	11123.4***	25075.4
Capital (Rs.)	70678.3***	94752.2
Yield (quintals)	605.6	591.5
Gross income (Rs.)	259937.5	254230.8
Gross margin (Rs.)		
189259.2***		
159478.5		

TABLE 6 *(Continued)*

Particulars	Drip adopters	Non-adopters
Yield per unit of water (Kg/M^3)	7.1***	2.8
Yield per unit of energy (Kg/kwh)	22.5***	8.3
Returns per unit of water (Rs/M^3)	21.8***	7.6
Returns per unit of energy (Rs/kwh)	68.1***	22.9

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

The economics of coconut cultivation in drip and control village revealed that the cost saving due to reduction in labor is 63% (Table 7). Similarly, the cost of cultivation has considerably reduced under drip method registering a reduction of 9.1%. It is interesting to note that the drip method resulted in high water and energy productivity.

TABLE 7 Economics of crop production (Rs. per ha) for Coconut in sample farms, 2007–2008.

Particulars	Drip adopters	Non-adopters
Quantity of water pumped (M^3)	13185.5	21584.7
Quantity of energy consumed (kwh)	905.2	5774.9
Cost of labor (Rs.)	4670.1***	12463.5
Capital (Rs.)	29814.4***	32798.3
Yield ('00 nuts)	231.8***	199.4
Gross income (Rs.)	113737.3	85084.2
Gross margin (Rs.)	83922.8	66145.8
Yield per unit of water (nuts/M^3)	1.8***	1.0
Yield per unit of energy (nuts/kwh)	25.9***	3.8
Returns per unit of water (Rs/M^3)	6.5***	3.4
Returns per unit of energy (Rs/kwh)	95.5***	12.6

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

The analysis of economics of crop cultivation under drip and flood methods revealed that the drip method of irrigation has significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. The physical water and energy productivity is significantly high in drip method of irrigation over the flood method of irritation.

1.4.6 THE FACTORS THAT INFLUENCE THE ADOPTION OF DRIP IRRIGATION TECHNOLOGY?

In this section, the factors that influence the adoption of drip irrigation are identified. Estimation of the factors that determine adoption of drip irrigation is presented in Table 8. The sample includes 100 farmers both the drip adopters and nonadopters in the drip and control village, respectively. Given the significance of the coefficients obtained for the different variables hypothesized to determine adoption of drip method of irrigation, we have greater confidence in our results.

TABLE 8 Factors influencing adoption of drip irrigation technology, 2007–2008.

Variables	Regression Coefficient	Elasticity of Intensity of adoption	Elasticity of adoption
CONSTANT	–38.909		
	(–0.984)		
AGE	0.179*	1.5817	1.6015
	(1.967)		
EDUCATION	–0.0427		
	(–0.247)		
FISIZE	0.779***	1.4461	1.4642
	(7.636)		
WIDERCROP	0.179**	2.6576	2.6910
	(2.428)		
NONFARM	4.838***	0.4323	0.4377
(2.840)			
AWELLS	0.242		
	(0.612)		
Log-likelihood function	–185.00		
Number of observations	100		
Dependent variable	DAREA		
Model	TOBIT		

Note: *** significance at 1% level; ** significance at 5% level; * significance at 10% level.

Figures in parentheses indicate estimated ‘t’ ratios.

It can be observed that the variables AGE, FSIZE, WIDERCROP and NONFARM are found to be significant determinants of adoption of drip irrigation on the expected positive line in both the water scarce and surplus regions. These variables are robust in determining the adoption and extent of drip adoption across regions.

Age of head of the household or decision-making farmer influences the adoption of drip irrigation positively. The age, which reflects the experience in farming, has significant bearing on adoption of various agricultural crop production technologies. Experience improves awareness about the positive externalities generated by drip irrigation and motivates farmers to initiate action. Apparently, experience matters for adoption of drip technology. Our results confirm that the experience in farming significantly influences the drip adoption.

The size of the farm reflects the wealth status of the farmers, which is expected to influence drip irrigation positively as drip involves huge initial investment. We found that size of the farm exerts a significant and positive influence on adoption of drip irrigation. The reason for this may have to do with the fact that the wealthier people have adequate capital, which enables them to adopt any technology, particularly the drip technology. However, few small and marginal farmers also show inclination towards adoption of drip irrigation. But for want of initial investment they do not opt for drip irrigation.

Cropping pattern in any region has significant bearing on the adoption of drip technology. It is known that drip technology is more suitable when the cropping pattern is dominated by wider spaced crops such as banana, coconut, grapes and so on. Though we recommend the drip technology for the annual crops like vegetables, turmeric, sugarcane, maize, etc., drip method of irrigation is quickly adopted in regions where cropping pattern is dominated by horticultural crops like banana, grapes, etc. It is clear from the analysis that the proportion of wider spaced crop is found to significantly influence the drip adoption. In our study area, the farmers prefer to grow less labor-intensive crops like coconut and banana. This change in cropping pattern again motivates the farm households to adopt drip technology.

One can expect that participation in nonfarm income activities enable the households to generate addition income to manage both their households and make adequate investments on farm development. It is evident that the variable NONFARM is found to be significantly and positively influence the drip adoption.

The proportion of area under wider space crops has the highest impact on both the adoption and intensity of adoption followed by AGE, FSIZE and NONFARM. The total elasticity for the variable WIDERCROP is estimated to be 5.3486, which is divided into 2.6910 for adoption, and 2.6576 for intensity of adoption. This suggests that a 10% increase in area under wider spaced crop is expected to result in about 53% increase in adoption of drip technology and extent of drip irrigation. Thus alternative-cropping pattern would facilitate promoting drip irrigation in larger scale.

1.5 CONCLUSIONS AND POLICY SUGGESTIONS

This research has revealed that adoption of drip irrigation technology has increased the net sown area, net irrigated area and thereby has helped in achieving higher cropping intensity and irrigation intensity. It has been found that there is a significant shift towards crops such as coconut and banana from annual crops like vegetables, paddy, sugarcane and the like. The main reasons have been found as scarcity of human labor and water. As the cropping pattern decides the adoption and suitability of drip irrigation, widespread adoption of micro irrigation could be promoted in the regions where shift towards crops like coconut, banana are common. The analysis of economics of crop cultivation under drip and control has revealed that the drip method of irrigation has a significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. The physical water and energy productivity is significantly high in drip over the flood method of irrigation. The adoption of drip irrigation is significantly influenced by experience, farm size, proportion of wider spaced crops and participation in nonfarm income activities. Thus, our policy focus may be tilted towards the promotion of drip irrigation in those regions where scarcity of water and labor is alarming and where shift towards wider- spaced crops is taking place.

1.6 SUMMARY

Recognizing the importance of drip irrigation, this chapter has addressed the important issues such as (i) what factors limit/enhance the adoption of drip irrigation systems? and (ii) what policy action must be taken at different levels to speed up the adoption of drip irrigation and groundwater development?. The drip method of irrigation has been found to have a significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. The adoption of drip irrigation is significantly influenced by experience, farm size, proportion of wider spaced crops and participation in nonfarm income activities. Hence, the policy should be focused on promotion of drip irrigation in those regions where scarcity of water and labor is alarming and where shift towards wider-spaced crops is taking place.

KEYWORDS

- **Adoption**
- **Drip Irrigation**
- **Double-difference method**
- **Economics**
- **Factors influencing adoption**
- **India**
- **Indian National Committee on Irrigation and Drainage, INCID**
- **Kenya**
- **Micro irrigation**
- **Non-adopters**
- **Rs, Indian rupee = US$ 0.0167**
- **Tamil Nadu**
- **Wider-spaced crops**

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CHAPTER 2

IMPACT OF DRIP IRRIGATION ON FARMING SYSTEM: EVIDENCE FROM SOUTHERN INDIA

D. SURESH KUMAR and K. PALANISAMI

CONTENTS

In this chapter: Rs. 1.00 = one Indian rupee = US $0.0166972

2.1 INTRODUCTION

Developing infrastructure for the water resources and their management have been the common policy agenda in many developing economies, particularly in the arid and semiarid tropical countries like India. A study by the International Water Management Institute (IWMI) has shown that around 50% of the increase in demand for water by the year 2025 can be met by increasing the effectiveness of irrigation [16].

The review of past studies lucidly shows that the solution to the problem of growing groundwater scarcity and persistent groundwater resource degradation across regions is two fold. The first is the supply side management practices like watershed development, water resources development through major, medium and minor irrigation projects, etc. The second is thorough the demand management by efficient use of the available water both in the short-run and long-run perspectives. This includes drip irrigation and other improved water management practices. Recognizing the importance of sustainable water-use efficiency in agriculture, a number of demand management strategies (like water pricing, water users association, turnover system, etc.) have been introduced since the late-1970s to increase the water-use efficiency, especially in the use of surface irrigation water. One of the demand management mechanisms is the adoption of micro irrigation such as drip and sprinkler methods of irrigation. Evidences show that the water-use efficiency increases up to 100% in a properly designed and managed drip irrigation system [4, 17]. Drip method of irrigation helps to reduce the overexploitation of groundwater that partly occurs because of inefficient use of water under surface method of irrigation. Environmental problems associated with the surface method of irrigation like waterlogging and salinity are also completely absent under drip method of irrigation [11]. Drip method helps in achieving saving in irrigation water, increased water-use efficiency, decreased tillage requirement, higher quality products, increased crop yields and higher fertilizer-use efficiency [10, 15, 18].

Though the potential benefits generated by the drip irrigation methods are apparent, the adoption of drip irrigation is yet to be widely promoted across regions, states and elsewhere. It is found that the most ideal policy environment for promotion of micro irrigation technologies in the well-irrigated areas would be pro-rata pricing of electricity, which would create direct incentive for efficient water use [7]. Adoption of micro irrigation systems is likely to pick up fast in the arid and semi arid, well-irrigated areas, where farmers have independent irrigation sources, and where groundwater is scarce. Further, large size of farm and individual plots, and a cropping system dominated by widely spaced row crops, which are also high-valued, would provide the ideal environment for the same [6]. Evidences show that many researchers have attempted to study the impact of drip irrigation [2, 5, 9, 10, 12, 15] and have found that drip irrigation produces the desired positive impacts. It is evidenced that the drip irrigation technology is technically feasible, particularly when the farmers depend on groundwater sources [3]. Still, the studies on impacts of drip irrigation on the farming system as a whole are scanty and yet to be explored much.

In this context, the drip irrigation has received much attention from policy makers and others for its perceived ability to contribute significantly to groundwater resources development, agricultural productivity, economic growth, and environmental sustainability. Yet in many parts of the country and elsewhere, these have yet to be adopted widely. Keeping these issues in view, this chapter focuses on issues, such as:

(i) What changes the drip irrigation brings to the farming system?
(ii) Whether the adoption of drip irrigation is motivated by the cropping pattern or the cropping pattern is followed by drip adoption? and
(iii) What policy action must be taken at different levels to speed up the adoption of drip irrigation?

2.2 METHODOLOGY

2.2.1 SAMPLING FRAMEWORK

The study was conducted in the Coimbatore district of Tamil Nadu state where groundwater resource degradation is alarming. Two blocks were selected so as to represent drip adoption and control. From the selected blocks, two revenue villages were selected purposively where the adoption of drip irrigation is widespread. Farm households in the selected villages constituted the sample units. To examine the adoption and impact of drip irrigation on resource use, agricultural production and farm income, 25 drip-adopting farmers were selected in each village and correspondingly 25 nondrip adopters were selected in control villages. To select the drip adopters, the list of farmers from the Department of Agricultural Engineering was collected. Also, we enumerated the list of farmers adopting drip irrigation after discussions with the villagers and private firms dealing drip irrigation systems. Thus, a sample of 100 farmers was studied.

2.2.2 SAMPLING DATA

For the purpose of the study, both secondary and primary information was collected from different sources. The secondary information included trend in rainfall, growth in the number of wells, number of wells functioning and wells defunct, cropping pattern, crop yields, occupational structure and area irrigated. The general particulars of the area were collected from the Assistant Director of Statistics and Assistant Director of Agriculture of the respective regions. Interview schedules were formulated and pretested. The needed information from the respondent group was gathered personally administering the interview schedule. The primary information collected from the farm households included details on well investment, groundwater use, extraction and management, crop production including input use and output realized, farm income, adoption of drip irrigation, and investment on drip irrigation. This also included asset position, education and other socioeconomic conditions.

2.2.3 MARKOV CHAIN ANALYSIS

Our objective here was to study the changes that have occurred in the farming system, particularly through cropping pattern as a result of adoption of drip irrigation. In order to examine the changes in the cropping pattern, Markov chain analysis was performed.

Markov chain models are concerned with the problems of movement, both in terms of movement from one location to another and in terms of movement from one “state” to another. These models are used for describing and analyzing the nature of changes generated by the movement of such variables, in some cases these models may also be used to forecast future changes [1].

The changing cropping pattern was worked out assuming that it follows a first order Markov chain [8], as explained below.

A first order Markov chain is characterized by the transition probability matrix [Eq. (1)].

$$P = \begin{bmatrix} p_{11}\, p_{12} \cdots p_{1n} \\ p_{21}\, p_{22} \cdots p_{2n} \\ \cdots \qquad \cdots \\ p_{n1}\;\; p_{n2} \cdots p_{nn} \end{bmatrix} \tag{1}$$

where: $\mathbf{p}_{\mathbf{ij}}$ is the probability that an area under the classification '**i**' during the current year changes into the classification '**j**' next year and '**n**' is the number of states. Therefore, p_{ij} is defined by Eq. (2).

$$p_{ij} = \Pr\{X(t+1) = j \,/\, X(t) = i\} \tag{2}$$

where: **X(t)** = State of the system at the year '**t**.' It is clear that

$p_{ij}{}^{3}\, o, i, j = 1,2....,n$ and

$$\sum_{j=1}^{j=n} p_{ij} = 1\,,\ \mathrm{i} = 1{,}2\ldots{,}\mathrm{n} \tag{3}$$

The transition probability matrix for the study was 9 × 9 matrix resulting in 81 unknown probabilities $\mathbf{p}_{\mathbf{ij}}$, **i, j** = 1, 2, …, 9, which were estimated using farm level data. In this study, the structural change in cropping pattern after introduction of drip irrigation system was examined by using the Markov chain approach. The estimation of the transitional probability matrix (**P**) was central to this analysis. The element $\mathbf{P}_{\mathbf{ij}}$ of the matrix indicated the probability that the area would switch from the **i**th crop to **j**th crop over a period of time, that is, after the introduction of drip irrigation system. The diagonal elements ($\mathbf{P}_{\mathbf{ij}}$) indicated the probability that the area share of a crop would be retained in the successive time periods.

2.3 THE STUDY AREA

2.3.1 DRIP IRRIGATION IN TAMIL NADU

Tamil Nadu state stands seventh in the country in terms of area under micro irrigation. During 2008, a total area of 158,521 hectares was practiced under micro irrigation in the Tamil Nadu state. Of the total area under micro irrigation, the drip accounted for 82.85% (131,335 ha) and sprinkler for 17.15% (27,186 ha). At the national level, the area under drip irrigation was 36.82% and under sprinkler was 63.18% (Fig. 1). It is clear that the drip method of irrigation is more popular among the farmers in Tamil Nadu when compared to sprinkler method of irrigation. It is seen that the Tamil Nadu state has only 9.2 per of the total drip area in the country where as the sprinkler irrigation accounts for only 1.1% of total area in the country. The area under micro irrigation accounts 4.1% of the total area under irrigation in the country.

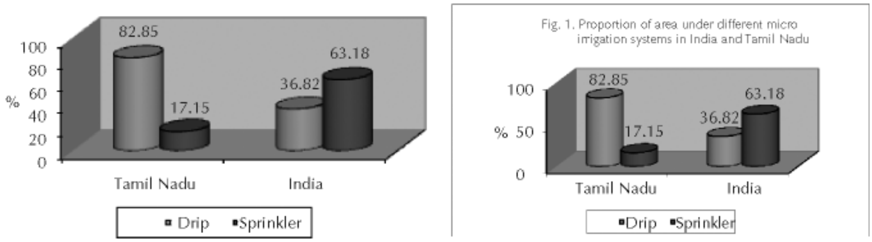

FIGURE 1 Proportion of area under different micro irrigation systems in India and Tamil Nadu.

The area under micro irrigation is very low in Tamil Nadu compared to the national level area. The net sown area in Tamil Nadu is 5,126,000 ha, whereas the gross cropped area is 5,842,000 ha. The area under micro irrigation accounts for only 3.1% of the net sown area in Tamil Nadu, whereas it accounts for 5.49% of the net irrigated area and 4.79% of the gross irrigated area. Thus, there is a huge potential to increase the area under micro irrigation in Tamil Nadu.

2.3.2 COIMBATORE DISTRICT OF TAMIL NADU STATE

The study area included the Coimbatore district of Tamil Nadu state, where the agriculture depends largely on minor irrigation projects and other sources such as wells, rain-fed tanks, etc. The chief source of irrigation in this district is through wells. The average well-failure rate is 47% for open-wells and 9% for bore-wells [14]. There are six different soil types viz.: red calcareous soil, black soil, red noncalcareous soil, alluvial and colluvial soil, brown soil and forest soil. The mean annual rainfall for the 45 years (between 1961 and 2005) is 687.1 mm and the with a coefficient of variation of 28.21%. The distribution of rainfall across the seasons indicates that the mean rainfall ranged from 16 mm during winter to 348 mm during north-east monsoons. The groundwater potential as on January 2003 indicated that the total groundwater recharge was 880.97 million cubic meter (MCM), net groundwater availability (90% of total groundwater recharge) was 792.87 MCM, domestic and industrial draft was 40.57 MCM, irrigation draft was 779.13 MCM and the stage of groundwater development was 103%.

The level of groundwater development exceeds 100% of the utilizable groundwater recharge in 11 blocks, between 90 and 100% in four blocks and between 70 and 90% in another four blocks. The stages of groundwater development in the study blocks was 169% for Thondamuthur block and 173% for Annur block, respectively. This indicates the problem of groundwater in the region. Increasing private investment on wells is visualized over the years, as groundwater irrigation assumes importance. Farmers in this district rely heavily on groundwater for irrigation. The source-wise area irrigated indicates that the groundwater accounts for 88.7% and 52% of the total area irrigated in the Thondamuthur and Annur blocks, respectively. The increasing trend in groundwater irrigation further confirms a heavy dependence on it for irrigation.

2.4 RESULTS AND DISCUSSION

2.4.1 FARM LEVEL IMPACTS OF DRIP IRRIGATION

In this section, our aim was to observe the significant changes in landholdings, cropped area, and irrigated area due to the introduction of drip irrigation. For this purpose, the drip-adopters were compared with control households. The average size of holding among the drip-adopters was significantly large as compared to control villages. Since drip method of irrigation involves huge initial investment, large farmers adopt it widely as compared to small and marginal farmers (Table 1). The details before the drip adoption were collected based on the recall basis. For the control villages, the reference period for the preadoption was considered to be 10 years before, that is, 1995.

TABLE 1 General characteristics of sample households in Tamil Nadu, 2007–2008.

General characteristics for cropping system	Drip villages		Control villages	
	Before	After	Before	After
Number of workers in the household (No.)	2.7	2.7	1.92	1.92
Farm size (ha)	5.52	5.41	2.23	2.28
Net sown area (ha)	4.51	5.31	1.41	1.35
Gross cropped area (ha)	4.77	6.36	1.46	1.39
Cropping intensity (%)[a]	105.57	124.34	103.54	102.96
Net irrigated area (ha)	3.65	4.97	1.27	1.22
Gross irrigated area (ha)	3.84	6.26	1.28	1.22
Irrigation intensity (%)[b]	104.88	130.16	100.18	100.00
Percentage of area irrigated by wells to the total cropped area (%)	82.0	98.03	94.65	94.26
Percentage of area irrigated under drip to gross cropped area (%)	67.14		—	—
Percentage of area irrigated under drip to gross irrigated area (%)	68.57		—	—

Notes:

***, ** and * indicate values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

[a] Cropping intensity is defined as the ratio of gross cropped area to net sown area and is expressed as a percentage.

[b] Irrigation intensity is the ratio of gross irrigated area to net irrigated area and is expressed as a percentage.

It is argued that drip irrigation increases cropped area and area under irrigation as it is a viable water-saving technology. Our study confirms the earlier findings that the drip irrigation technology increases the net sown area and net irrigated area and thereby helps in achieving higher cropping intensity and irrigation intensity. For instance, in the villages with drip irrigation, the net sown area has increased from 4.51 ha to 5.31 ha, whereas the gross cropped area has increased from 4.77 ha to 6.36 ha. A similar positive trend was seen in the net irrigated area and gross irrigated area. During the survey, it was found that drip irrigation technology has resulted in significant impacts. Being an efficient water-saving technology, it has helped in expanding the irrigated area and saving of water.

The percentage of area irrigated by wells to the total cropped area has significantly increased in the drip villages among drip adopters. It is concluded that the percentage of area irrigated by wells to gross cropped area has increased from 82.0% to 98.03% due to the intervention of drip irrigation. It is lucid from the analysis that drip irrigation technology has resulted significant positive impacts in the farming system.

2.4.2 CROPPING PATTERN

An attempt was made to investigate whether drip irrigation had induced a certain new cropping system or the crops had followed drip technology as a response to the growing water scarcity? The cropping pattern, that is, proportion of area under different crops, is a good indicator of the development of resource endowments and agricultural production. It is expected that drip irrigation helps in the development of water resource potential and also helps the farmers to get more crop and income per drop of water.

The longitudinal analysis of cropping pattern across farm households and villages has revealed that the adoption of drip irrigation is motivated by many factors. The two major constraints limiting agricultural production are: human labor and water scarcity. These two factors had compelled the farmers to alter their cropping pattern towards less labor and water- intensive crops. The resource poor farmers were going in for rain-fed crops like sorghum, maize, etc. However, the big farmers with access to capital were adopting various water management and cropping strategies. Drip irrigation being one of the important water management technologies, was being adopted. Thus, in regions where there was severe water and labor scarcity, first there was a shift from labor and water-intensive crops such as vegetables, sugarcane, cotton, paddy, etc. to less labor-intensive crops such as coconut, and it was being followed by drip adoption. As drip irrigation saves human labor substantially by reduction in operations such as irrigation and weeding, water-loving crops such as banana and grapes were being planted following drip irrigation.

TABLE 2 Drip irrigation and cropping pattern changes (%) in study farms in Tamil Nadu, 2007–2008.

Crops	Drip villages		Control villages	
	Before	After	Before	After
Banana	15.13	16.31	24.91	24.45
Coconut	4.68	22.52	8.25	8.02
Cotton	3.19	0.0	.	.
Grapes	18.82	24.05	.	.

TABLE 2 *(Continued)*

Crops	Drip villages		Control villages	
	Before	After	Before	After
Ragi	4.19	0.0	.	.
Sorghum	14.78	2.5	20.36	19.77
Sugarcane	.	.	11.85	11.17
Turmeric	0.0	7.1		2.47
Vegetables including tomato	30.73	21.52	27.74	27.74

A significant shift towards crops such as coconut, grapes was commonly observed in the drip villages (Table 2). The main reasons were scarcity human labor and water. For this reason, a reduction in area under vegetables was also observed. Thus, the micro irrigation could be promoted in the regions with high scarcity of water and labor. As a cropping pattern decides the adoption and suitability of drip irrigation, widespread adoption of micro irrigation could be promoted in the regions where shift towards crops like coconut and banana is common.

2.4.3 TRANSITION PROBABILITY AND STEADY STATE PROBABILITY OF CHANGES IN CROPPING PATTERN

Significant changes in the cropping pattern were observed in the study area. As the changes in cropping pattern favor the adoption of drip irrigation technologies, we were also interested in studying the type of transition that has taken place in the cropping pattern. For this, employing Markov chain analysis, the transition and steady state probabilities were computed and have been presented in Table 3. Markov analysis is a way of analyzing the current movement of variable in an effort to predict its future movement. In the transition probability matrix, the rows identify the current state of the cropping pattern being studied and the columns identify the alternatives to which the cropping pattern could move. Here, the row probabilities are associated with crops retention and move to other crops (i.e., shift to other crops), while the column probabilities are associated with crops retention and move towards the crop (i.e., shift towards the crops, gain to the particular crop). The transition probability presented in the Table 3 depicts the cropping pattern changes over time.

The diagonal elements represent probability of retaining the same crop in future. For instance, the probability of retaining banana crop was worked out to be 57%. Similarly, for coconut the probability of retention was 75%. The analysis shows that the probability of shifting of the area under maize to banana was 18%, to coconut was 18%, to tomato was 15%, to grapes was 13% and to other crops was 4%. The probability of retention of maize crop was 29%. Similarly, the vegetables have shown retention probability of only 24%. The probability of shifting area of vegetables to banana was 12%, to coconut was 20%, and to grapes was 12%. What will happen in the future if this pattern of changes in the cropping pattern occurs? If this kind of transition continues, around 32% of the cropped area will assume area under coconut and grapes will assume 44% of the total cropped area. This ensures better scope for a wider adoption of drip irrigation in the region. The Markov analysis has lucidly shown that the existing trend in cropping pattern changes will result in a new cropping pattern, which will favor wider adoption of drip method of irrigation in the future.

TABLE 3 Transition probability and steady state probability of changes in cropping pattern in Tamil Nadu.

Crops	Sorghum	Banana	Coconut	Maize	Tomato	Grapes	Vegetables	Others
Sorghum	0.03	0.17	0.24	0.06	0.19	0.23	0.02	0.06
Banana	0.01	0.57	0.22	0.02	0.06	0.06	0.02	0.04
Coconut	0.04	0.07	0.75	0.01	0.04	0.09	0.00	0.00
Maize	0.04	0.18	0.18	0.29	0.15	0.13	0.00	0.04
Tomato	0.05	0.09	0.21	0.02	0.42	0.11	0.06	0.05
Grapes	0.01	0.01	0.07	0.00	0.02	0.87	0.01	0.01
Vegetables	0.03	0.12	0.20	0.06	0.18	0.12	0.24	0.05
Others	0.00	0.20	0.12	0.08	0.08	0.19	0.05	0.29
Fallow	0.06	0.14	0.26	0.08	0.20	0.14	0.04	0.08
Steady state probabilities	0.02	0.10	0.32	0.01	0.07	0.44	0.01	0.02

2.4.4 IMPACT OF DRIP IRRIGATION ON AGRICULTURAL PRODUCTION

To assess the impact of drip irrigation on agricultural production, the economics of drip irrigation were worked out for the major crops. The adoption of drip irrigation has significant positive impact on the cost of cultivation and cost of production and returns of the farmers. The economics of banana cultivation revealed that the cost of labor was significantly lower under the drip method (Rs 9,761/ha), which was 69% less than in the control villages (Rs 31,487/ha). The drip method significantly saves the human labor involved in crop production activities. It also saves irrigation labor and weeding labor. On an average, the human labor days used for weeding banana were 17 labor days/ha under drip method and 60 labor days/ha under flood method of irrigation. The drip method saved nearly 71% of weeding labor when compared to flood method of irrigation. The irrigation labor has been worked out to be 168 labor days/ha under flood method and 18 labor days/ha under drip method of irrigation. Due to this, the cost of cultivation was significantly less under drip over the flood method.

The reduction in cost on human labor has a significant bearing on the cost of cultivation. Though, the cost of installation of drip irrigation equipments and maintenance is incurred by the farmers, the cost of cultivation per hectare has been worked out to be Rs. 80,396/ha in drip farms, which is around 23% less than in the control villages (Rs. 109,685/ha). The gross margin per hectare has been found as Rs. 200,232/ha in drip and Rs. 163,048/ha in control farms. It clearly shows that drip method of irrigation has resulted in an increase of 22% of gross margin over the control. As the adoption of drip irrigation saves considerable water and energy, the water and energy productivity is significantly more in drip farms than the control villages where the flood irrigation is followed (Table 4). For instance, the water productivity has been worked out to be 7.4 kg/M^3 of water in drip farms and 4.9 kg/M^3 of water in control villages. Significant difference in energy productivity has also been noticed. The returns per unit of water and energy have shown that drip farms have significantly higher returns over the control. Thus, one could conclude that the drip adoption would be a viable technology with significant bearing on the private profits.

TABLE 4 Economics of crop production (per ha) for banana in sample farms in Tamil Nadu, 2007–2008.

Particulars	Drip villages	Control villages
Quantity of water applied (M^3)	8,979***	12,669
Quantity of energy consumed (kWh)	2,219***	8,294
Cost of labor (Rs.)	9,761***	31,487
Capital (Rs.)	80,369***	104,351
Yield (tons)	60.34***	57.79
Gross income (Rs.)	280,602***	267,400
Gross margin (Rs.)	200,232***	163,048
Yield per unit of water (kg/M^3)	7.4***	4.9
Yield per unit of energy (kg/kWh)	28.6***	7.2
Returns per unit of water (Rs/M^3)	23.8***	13.3
Returns per unit of energy (Rs/kWh)	92.3***	19.8

Notes:

***, ** and * indicate that values are significantly different at 1%, 5% and 10% levels, respectively, from the corresponding values of control village.

The economics of coconut cultivation in drip and control villages has revealed that the cost saving due to reduction in labor was 69% (Table 5) Similarly, the cost of cultivation was considerably lower under the drip method, registering a reduction of 15.5%.

TABLE 5 Economics of crop production (per ha) for coconut and grapes in sample farms in Tamil Nadu, 2007–2008.

Particulars	Coconut		Grapes	
	Drip villages	Control villages	Drip villages	Control villages
Quantity of water applied (M^3)	3096***	10855	5195***	6757
Quantity of energy consumed (kWh)	917***	7423	550***	3124
Cost of labor (Rs.)	3733***	12024	17324***	29433
Capital (Rs.)	27510***	32560	50690***	60124
Yield (‘00 nuts in coconut and tones in grapes)	227***	201	22.84***	19.45
Gross income (Rs.)	105443***	86419	246668***	233454
Gross margin (Rs.)	77933***	53859	195978***	173330
Yield per unit of water (nuts/ M^3or kg/M^3)	7.3***	1.9	4.7***	3.1
Yield per unit of energy (nuts/ kWh of kg/kWh)	28.6***	2.6	43.7***	6.2
Returns per unit of water (Rs/M^3)	25***	5	41***	27
Returns per unit of energy (Rs/kWh)			378***	55
98***				
7				

***, ** and * indicate that the values are significantly different at 1%, 5% and 10% levels from the corresponding values of control village.

The impact of drip irrigation on resource saving and productivity enhancing was highly significant in grapes. Since grape cultivation is sensitive to water stress and involves huge labor for irrigation, weeding, training and pruning, the drip could resulted in significant savings in water and labor, leading to reduction in cost of cultivation (Table 5).

In grape cultivation, the cost incurred on human labor was Rs. 17,324/ha in drip farms and Rs. 29,433/ha in control farms with an average reduction of 41% (Table 5). Also, there was a reduction in the cost of cultivation by 15.6% in drip farms over control farms. The gross margin across farms indicated that the drip farms achieved relatively higher returns with a given price of output when compared to control farms mainly due to difference in yield. The physical productivity of water and energy was significantly higher in drip than control farms.

The analysis of economics of crop cultivation under drip and flood methods of irrigation has revealed that the former has a significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. The physical water and energy productivity was significantly high in drip than flood method of irrigation. One could conclude that the drip has a significant bearing on the private costs and hence on profit of farmers.

2.5 CONCLUSIONS

The study has revealed that adoption of drip irrigation technology has increased the net sown area, net irrigated area and thereby has helped in achieving higher cropping intensity and irrigation intensity. It has been found that there is a significant shift towards crops such as coconut, grapes and banana from annual crops like vegetables, sugarcane and the like. The main reasons have been found as scarcity of human labor and water. As the cropping pattern decides the adoption and suitability of drip irrigation, widespread adoption of micro irrigation could be promoted in the regions where shift towards crops like coconut, banana and grapes are common. The analysis of economics of crop cultivation under drip and control has revealed that the drip method of irrigation has a significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. The physical water and energy productivity is significantly high in drip over the flood method of irrigation. One could conclude that the drip has a significant bearing on the private costs and benefits and hence on profit of farmers. Thus, our policy focus may be tilted towards the promotion of drip irrigation in those regions where scarcity of water and labor is alarming and where shift towards wider- spaced crops is taking place.

2.6 SUMMARY

The micro irrigation in general and drip irrigation in particular has received considerable attention from policy makers, researchers, economists, etc., for its perceived ability to contribute significantly to groundwater resources development, agricultural productivity, economic growth, and environmental sustainability. In this paper, the impact of drip irrigation has been studied on farming system in terms of cropping pattern, resources use and yield. The drip method of irrigation has been found to have a significant impact on resources saving, cost of cultivation, yield of crops and farm profitability. Hence, the policy should be focused on promotion of drip irrigation in those regions where scarcity of water and labor is alarming and where shift towards wider-spaced crops is taking place.

KEYWORDS

- **Coimbatore**
- **Drip irrigation**
- **Economics**
- **India**

- **Markov Chain Analysis**
- **Micro irrigation**
- **Rs, Indian rupee = US$0.0167**
- **Southern India**
- **Tamil Nadu**

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CHAPTER 3

RESEARCH ADVANCES IN MICRO IRRIGATION IN INDIA

R. K. SIVANAPPAN

CONTENTS

3.1 INTRODUCTION

Land and water are the basic needs of agriculture and economic development of any country. The demands for these resources are continuously increasing. It is possible to increase the intensity of cultivation up to 200–300% or more provided water is available as India is having sunshine throughout the year. Further large areas of waste/fallow lands are available and hence optimum use of the available water is very critical at this juncture.

Water is a vital resource for life, human/societal development and environmental sustainability. We must treat the water economic and socially good and that water management must aim for the most worthwhile use ensuring equity, concerns, adequate, efficiency and environmental sustainability. Water planners, managers, users and generally policy makers face many challenges: The need to meet the basic water requirements of present and future generations; maintain the renewable fresh water resources and develop public and private institutions capable of managing supply and demand resolving conflicts; and protecting watersheds and allocating scarce water resources.

Though water resources in India are good, but the utilizable water is about 110 M.H.M. (70 M.H.M from surface and 40 M.H.M from ground water). This utilizable water can irrigate about 130−140 M-ha. This is only about 50−60% of the gross cultivable area in the country. Further, agriculture draws about 85% of the total water used at present. It is estimated that the allocation will be reduced to 71% in the next 20−25 years, since the demand of water for industries and municipal purposes is expected to increase. Therefore, we must find ways and means to increase the area of irrigation and production to feed the growing population.

The investment per hectare for irrigation projects has been increasing enormously from Rs. 1500 during 1951–1956 to about Rs. 100,000 during 9th plan and Rs. 150,000 during 12th plan. Though we have increased the production by five fold in the last 60 years (from 50 million tons in 1951 to about 250 million tons at present),still the average production per Ha is less compared to many countries in the world, such as: Egypt. China, Taiwan, Japan, etc. The main reason for this is due to inadequate irrigation management, and not introducing pressure irrigation (Sprinkler and Drip irrigation)on a large scale. Therefore, it is necessary to economize the use of water and at the same time increase the productivity per unit area and per unit quantity of water.

The production of fruits/vegetables in India ranks 2nd in the world, but it is not sufficient for the minimum requirement of the population. Further, there is a good potential of exporting these products to get sufficient income to the farmers and foreign exchange to the country. We get highest rainfall in the world, that is, 12,000 mm at Chirapunji – India and at the same time less than 100 mm in Rajasthan and some other parts of the country. Further the rain falls only in 3 or 4 months times during the year. Even Chirapunji is facing drinking water problem before monsoon starts. Therefore, there is a need to harvest, conserve and use the water efficiently.

The food requirement in India will increase from 220 MT in 2000 A.D.to 450−500 M-tons in 2050 A.D. The present average production is about 2.2 tons per ha in irrigated areas and about 0.75 tons/ha in rain-fed areas. These values can be easily increased to 3.5 to 4.0 tons/ha and 1.5 to 2.0 tons/ha for irrigated and rain-fed lands, respectively. Also, the gross irrigated area can be increased to 150–160 M-ha for the required food production in 2050 A.D. The targets can be achieved by better water management, introducing controlled irrigation systems on a large scale in India in the coming years, by using micro irrigation system and use the sewage and effluent water (reuse) after reclamation.

3.2 MICRO IRRIGATION

Micro-irrigation is a new technology in the country compared to sprinkler irrigation but farmers are showing keen interest in introducing this water saving technology. Drip irrigation was introduced on large scale in Israel during the sixties and at present the entire area for all crops, micro irrigation is the only irrigation method practiced. The Israeli farmers grow flowers, fruits and vegetables using drip system. But the important factor is that the Government is helping the farmers by way of extension and marketing of the products. The flowers plucked in the morning can reach the markets in London, Paris, Stockholm in the noon or evening. In this way, the farmers are encouraged to go for this system of irrigation. It is estimated that about 6 to 7 M-ha is under Drip irrigation in the world. At present, the countries using this system are: U.S.A., Israel, France, Spain, Italy, Cyprus, Australia, South Africa, Egypt, India, China, Taiwan, Thailand, Brazil, Puerto Rico, etc., for about 60 different crops. In Israel, sewage water after reclamation is used to irrigate cotton crop by this method. The entire sugarcane crop is irrigated by drip (Biwall in Hawaii, U.S.A.) system. There are various methods of drip irrigation such as: Drip, Micro Sprayer, Micro sprinkler, Typhon, Bi-wall, Leakage pipes, etc.

In India, though Drip system is familiar with the farmers, the drip irrigated area is about 2.0 M-ha, which is very meager compared to the total irrigated area in the country (>100 M-ha). About 60 wide spaced crops are irrigated by this method. In the beginning, it was introduced in water scarcity areas for wide spaced crops like coconut, pomegranate, orange, grapes, etc. But now, farmers use this method even in places where sufficient water is available for irrigation and also for closely spaced row crops. If one asks a banana farmer in Jalgaon district of Maharashtra state – India, why he has gone for drip irrigation, his answer, is: Increased yield; Less inputs (Labor, fertilizers, chemicals, etc.); High quality of products; and finally saving of water.

Therefore, the farmers in India are also aware of the importance of this system just like any farmer in U.S.A. or in Israel, but the problem of introducing on large scale in India is the high investment cost of this system. The cost is Rs. 70,000–80,000 per ha for closely spaced crops: Vegetables, cotton, sugarcane, mulberry, etc. and this cost is prohibitive to small farmers in the country, though the economics will prove that this system is economically viable.

When National Commission on the use of Plastic in Agriculture (NCPA) requested me to prepare a perspective plan for drip and sprinkler irrigation during 1989–1990, I suggested about an area of one M-ha under drip irrigation by 2000 A.D. But the top officials in the Government of India were septic about the suggestion and informed that it is too ambitious, but I was able to convince them that the projection is very less taking into consideration the advantages of the system and the different crops grown and the large irrigated area in the country.

India has 37% of the total irrigated area of the world, compared to 25 to 30% for the drip irrigated area. The main reason for slow progress is due to high initial cost of installation. If the cost is brought down to Rs. 10,000 per acre (maximum, Rs. 25,000/ hectare), it is possible that many farmers including small farmers will go for drip irrigation without waiting for subsidy from the Government of India. Many organizations in India are now doing research trails to bring down the cost in the farmers field in the country.

Micro-irrigation can be practiced for all row crops and in all soils. In this method, the required quantity of water is given to each plant at the root zone through the network of pipes. Hence, the losses are minimum due to water conveyance and water distribution. Since the water based on evapotranspiration (ET) is delivered daily to the plants, soil moisture will be always available more or less near the field capacity. This implies that the roots can take moisture from the soil without any crop stress. This results in the uniform and optimum of a crop. In addition, crop fertilizer requirements can be met by fertigation, thus resulting in 30% savings of the nutrients without affecting the yield.

Micro-irrigation system is suited for undulated terrain, shallow soils and water scarcity areas. Saline/brackish water areas can also be used to some extent, since water is applied daily, which keeps the salt stress at minimum. These salts are pushed to the periphery of the moisture regime, which is away from the root zone of the crop. Therefore, crop growth is not affected due to salinity. The main advantages of micro irrigation compared to gravity irrigation system are: Increased water use efficiency (90–95%); Higher yield (40–100%); Decreased tillage requirements; High quality products; Higher fertilizer use efficiency (30% saving); Less weed growth (labor saving); All operations can be done at all times; and Less labor requirements.

3.3 RESEARCH STATUS OF MICRO IRRIGATION IN INDIA

Micro-irrigation is used extensively in many countries and its development in India is very slow compared to the other countries. Experiments and farm trials using micro irrigation research have been conducted in the last 35 to 40 years by various universities and institutions in India. Progressive farmers in Maharashtra, Andhra Pradesh, Tamil Nadu, Karnataka, and Kerala states in India started using micro irrigation in the late seventies and early eighties. Due to the sustained efforts taken by the Central and State Governments and manufacturers of the drip irrigation equipments in India, the use of this system started spreading in the southern and western states of India.

The studies conducted by various institutions have revealed that the water saving in this method compared to surface irrigation is about 40 to 70% and the increased yield is up to 100% for various crops.

3.4 SCOPE OF MICRO IRRIGATION

The experience of numerous farmers in this new method has revealed many interesting results. The old coconut farms are not possible to irrigate as the water availability in the wells has reduced and water table is depleting every year. Numerous farmers in Coimbatore district in Tamil Nadu – India have taken up this irrigation for the coconut trees and it has proved successful. The development of micro irrigation has been very spectacular in Maharashtra state since 1987. This is due to the encouragement provided by the Government and manufacturers. The farmers are also forced to adopt since water has become scarce and expensive commodity in many districts. In Kerala, the coconut and other plantation crops needed water during the dry period of January to May and the farmers are installing micro irrigation to manage the shortage of water. It is picking up very well in Andhra Pradesh, Karnataka, Madhya Pradesh, Gujarat and Rajasthan. The farmers are now convinced that this system helps them to get more yield, with less inputs apart from saving of water.

The constraints experienced in bringing large area under this method are: High initial cost, clogging of drippers and cracking of pipes, lack of adequate technical inputs, damages due to rats and rodents, high cost of spare parts and components, and lack of advice and technical help to the farmers by the extension officers. To exploit the full potential of this system, the constraints must be overcome by appropriate policy instruments, financial supports and technical guidance. This calls for an integrated approach and endeavor on the part of the central and state governments, implementing agencies, manufacturing companies and the farmers. The technology is to be perfected and hence more field oriented research must be taken up by the universities to reduce the cost and constraints. Training should be imparted to the officials and farmers to learn about the system and its maintenance. Seminars and workshops can be organized at the block and district levels to popularize the system to understand the problems and socioeconomic factors. The main policy should be to encourage and to motivate all categories of farmers, since the critical issue is water saving and augment productivity. The state governments can prepare time bound action plan for the coming years to bring more area under drip irrigation.

3.5 ECONOMICS OF MICRO IRRIGATION

The installation cost of drip irrigation varies from Rs. 20,000 to 25,000 per hectare for wide spaced crops like coconut, mango, etc. and from Rs. 70,000 to 80,000 per hectare for closely spaced crops like sugarcane, cotton, vegetables, etc. The cost depends upon the crop, row spacing, crop water needs, distance from water source, etc. The economics of micro irrigation has been calculated, and payback period has been worked out after interviewing more than 50 farmers for different crops. It was observed that the payback period is about one year for most of the crops and the benefit cost ratio varies from 2 to 5.

3.6 NEED FOR AFFORDABLE DRIP IRRIGATION SYSTEM

The drip system is capital intensive and has sophisticated technology. Therefore, it is beyond the reach of the majority of farmers in India. Therefore, if the drip system is made affordable and within the reach of small and marginal farmers (about 80%) in India, it will go a long way in increasing productivity and income of the farmers and conserve the water in the country. Further, this will also improve the capability of the farmers to manage and manipulate the soil, water and crop to obtain maximum yields, since it is suitable for all topographical and agroclimatic conditions, and different crops and soils.

To make this advanced technology accessible to small and marginal farmers, International Development Enterprises (IDE) – USA, has developed a low cost system and is being extensively field tested in the farmers' field. Cost of this system is being reduced by eliminating the use of sophisticated parts, replacing with low cost substitutes without sacrificing the quality and performance. The IDE has reduced the cost by 80% by making the system portable (by shifting the lateral lines) and doing away with emitters/drippers but using holes and sockets or by providing microtubes in the lateral line to deliver water and also by using low cost filters. In case the system cannot be portable, due to the height or coverage of the crop, the reduction is about 50–60% by irrigating 4 or 6 rows of crop from each lateral line, which is affordable by the farmers even without subsidies. It is very difficult and cumbersome to the small and marginal farmers to get the Government subsidy and that too it is not available throughout the year. This technology was used in the early 70's by the author in Coimbatore District of Tamil Nadu, when there were no drip irrigation manufacturers in the Country and most of the research work was done using the material available in the market. The system will catch up very well if the required drip irrigation quality material and accessories are available in the local market. Furthermore research is going on in the country to reduce the thickness of the lateral pipes to bring down the cost and to optimize the lateral lengths to have uniformity of water application for low head systems.

3.7 FUTURE PROSPECTS OF MICRO IRRIGATION

The studies conducted and information gathered from various sources has revealed that drip irrigation is technically feasible, economically viable and socially acceptable. Drip irrigation can be implemented in most of the areas irrigated by open/tube wells, which make about 35% of the total irrigated area in the country. The drip irrigation can be extended to the waste lands after planting tree crops including fruit trees; hilly areas; semiarid zones; coastal sandy belts; water scarcity areas; and command of the community wells

At present, on an average Rs. 100,000 to 150,000 per hectare is being invested for the new irrigation projects. As water is becoming increasingly scarcer, adoption of micro irrigation system offers potential for bringing nearly double the area under irrigation with the same quantity of water without any expenditure. It has been considered as a boon for wide spaced perennial crop namely Mango, Coconut, Oilpalm, Banana, Grapes, Pomegranate, Ber, Citrus, Tea, Coffee, and Cardamom. It is also suited for vegetables, flowers and other commercial crops cotton, banana tobacco and sugarcane.

The area under micro irrigation at present is about two M-ha. The potential area is estimated as 27 M-ha by the Indian Task Force on Drip Irrigation. Hence, there is a great future for the rapid expansion of micro irrigation in India in the coming years. It is expected that the projected area of 20 M-ha (20% of the irrigated area) will be brought under micro irrigation in the next 15 to 20 years.

3.8 PERSPECTIVE PLAN FOR MICRO IRRIGATION RESEARCH

Drip irrigation in the world is under varying degrees of development. In Israel, the entire area is irrigated through drip. In USA, large areas under citrus, grapes, sugarcane, cotton, etc., are irrigated through drip. Similar pattern is noticed in Australia, Southern

Europe and other countries at a faster rate due to the water scarcity and the need to enhance the yield and quality of the farm produce.

In the Indian context, water scarcity has compelled the farmers to go in for this advanced method of irrigation to use the water more efficiently for high value crops. It is reported that farmers using drip irrigation in Maharashtra state are able to get a net profit of Rs. 125,000–250,000 per ha by growing grapes, orange, pomegranate, tomato and other fruit and vegetables crops. In spite of this, the area under drip irrigation is only 2.0 M-ha out of about 100 M-ha under irrigation potential created in India, which is considered a meager achievement. Therefore, it must be emphasized that planning and implementation of drip irrigation programs in future years should be such as to achieve a target of 15–20 M-ha by the year 2025.

To achieve the target, more research is needed on the thrust areas, such as:

- To reduce the cost of the system and problem free systems;
- Package of practices for various crops with drip irrigation;
- Improve the performance of drip components especially clogging;
- The minimum thickness of lateral pipe to withstand pressure and to reduce the cost;
- Design and evaluation of standard micro irrigation system for horticultural, plantation and row crops in different agro ecological regions;
- Evaluating cost effective adaption of drip irrigation systems under various farming situations;
- Development and evaluation of fertigation technology for field and horticultural crops to reduce the fertilizer use;
- Design and evaluation of pressurized irrigation systems as an adjunct with canal irrigation systems; and
- Development of technology for using poor quality water through micro irrigation systems.

Above all, all the state governments should give subsidy and liberalized credit facilities from commercial banks, since water is going to be the constraint in agricultural production in the future

3.9 SUMMARY

Micro-irrigation is having tremendous potential and prospects in India to solve water scarcity conditions in many locations and to increase the production of agriculture and tree crops. The area under this system is only 2 M-ha in India compared to the total irrigated area of more than 100 M-ha in the country. Farmers are convinced about the advantages of the system.

The Central and State Governments are keen in bringing more area under drip irrigation. The research institutions are undertaking more research programs to provide required information about the application of water in different stages of crop growth, reducing the cost of the system, fertigation studies, etc. We have along way to go to find out the solutions on regional basis to implement micro irrigation for various crops on large scale in the country. However, this requires detailed action plan in a phased manner. The country should aim to bring about 20 M-ha under this system in another 15–20 years. Therefore, more and intensive research is very essential to achieve the objectives.

KEYWORDS

- **Affordable systems**
- **Constraint**
- **Economics**
- **Evaluation**
- **Fertigation**
- **Incentives**
- **Inputs**
- **Land and water**
- **National committee on the use of plastics in agriculture – India**
- **Optimum use**
- **Perspective plan**
- **Production**
- **Progressive farmers**
- **Resources**
- **Scope of micro irrigation**
- **Soil problems**
- **Status**
- **Subsidy**
- **Sustainability**
- **Target**
- **Training**
- **Water demand**
- **Water harvesting**
- **Water management**
- **Water requirements**
- **Water saving**
- **Water scarcity**
- **Watershed**

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CHAPTER 4

RESEARCH ADVANCES IN IRRIGATION METHODS FOR EFFICIENT WATER APPLICATION: SOUTH AFRICA

FELIX B. REINDERS

CONTENTS

This chapter has been modified and printed with permission from WRC. The original report was presented at the Water Research Commission (WRC) 40-Year Celebration Conference, Kempton Park – South Africa, 31 August–1 September 2011. Email: reindersf@arc.agric.za. Printed with permission from: http://www.wrc.org.za, Water SA, 37(5) WRC 40-Year Celebration Special Edition 2011. The original article is open source and is available at: http://www.ajol.info/index.php/wsa/article/view/72844.

4.1 INTRODUCTION

Irrigated agriculture plays a major role in the livelihoods of nations all over the world and South Africa is no exception. With irrigated agriculture being the largest user of runoff water in South Africa, there have been increased expectations from government that the sector should increase efficiency and reduce consumption in order to increase the amount of water available for other uses, in particular for human domestic consumption. Irrigation in South Africa is currently practiced on 1.6×10^6 ha. In 2000, it used 62% of the runoff water that was used by all sectors, or 39.5% of the exploitable runoff water [6]. Studies and research over 40 years, on flood-, mobile- and micro irrigation techniques contributed to the knowledge base of applying irrigation methods correctly to improve the efficient application of water. The different irrigation systems vary in terms of individual components, cost and performance and generally they can be classified into three groups:

- Flood-irrigation systems by which water that flows under gravity over soil while infiltrating is applied to the farm lands. This includes basin, border, furrow and short furrow.
- Mobile irrigation systems, which move over the farm land under their own power while irrigating. These include center-pivot, linear and traveling-gun systems.
- Static systems include all systems that remain stationary while water is applied. We distinguish between two types: 1) Sprinkler by which water is supplied above ground by means of sprinklers or sprayers. This includes permanent or portable like quick-coupling, drag-line, hop- along, big-gun, side-roll and boom irrigation systems; 2) Micro-systems, which include microsprayers, mini- sprinklers and drip-irrigation systems.

Aspects that have been addressed in the research were layout, design, selection, management and a number of other factors that can improve the efficiency of the irrigation system. However, great emphasis has been placed lately on how an increase in efficiency will lead to reduced water consumption by agricultural users and thereby 'release' some of the annual water yield for use by the domestic sector. Recommended actions to improve efficiency include measurement of the quantity of water distributed and applied at specific times; preparation of water-use efficiency and risk-management plans; and a reduction of the quantity of water used for irrigation by existing farmers through investment in appropriate technology.

Various research projects funded to date by the Water Research Commission (WRC) demonstrate how improvements can be made to efficiently manage water in South Africa.

4.2 IMPROVED FLOOD-IRRIGATION APPROACH

Increasing the efficiency of flood irrigation has been intensively researched in South Africa since 1972 by engineers of the Department of Agriculture – Division of Agricultural Engineering and implemented as such. It was only in the late 80s and early 90s that, through a WRC-supported project, aspects such as the upgrading of the layout, the management and design of the systems were addressed and a model was developed to simulate the hydraulics of flood irrigation more accurately [5]. In a WRC-sponsored project, Russell [12] studied infiltration under flood-irrigation conditions on a typical crusting soil of the Eastern Cape. He found that infiltration under dynamic (flood) conditions on this soil was very high and remained so over the medium term, in sharp contrast to the quick surface sealing and very low infiltration under static conditions.

4.3 COMPUTERIZED IRRIGATION DESIGN

An Israeli computerized irrigation design package was introduced in South Africa in 1983. The International Commission on Irrigation and Drainage (ICID) predicted in 1985 that an integrated computer process will be the norm for the future and indeed since then a number of computer-aided design routines have been developed and reported on. In 1987, MBB Inc. completed a WRC-supported project titled, 'The development of procedures for design and evaluation of irrigation systems' [8]. Irrigation design principles and procedures were studied in depth and evaluated critically. Different design algorithms were developed that were based on the well-known principles of the PolyPlot software. The research eventually resulted in the development of the IDES irrigation design and evaluation program, which was the front-runner for the popular design program ModelMaker that was only introduced towards the end of the century. Today a range of excellent computer programs are available for modern-day design of efficient irrigation systems.

4.4 CONTAINING LOSSES DURING CENTER-PIVOT IRRIGATION

During the period 1970–1982, the efficiency of center pivot systems were estimated at 80%. A research project was supported by the WRC to investigate, identify and quantify the spray losses between the emitters on a center pivot and the plant canopy [14]. Apart from technical measurements, meteorological and other factors influencing irrigation losses were identified. It was found that the average losses rarely exceed 10% of the pumped water if the emitter package is properly designed and the wind speed is less than 6 m/s. From the results obtained with single nozzles it was clear that droplet size has an important effect on spray losses. This research provided valuable guidelines in terms of emitter selection, application depth and management of center pivots. The WRC also sponsored a project aimed at deriving criteria for the adaptation of overhead irrigation systems, including center pivots, to the infiltrability of different soils, so as to minimize water losses through runoff and/or evaporation due to ponding (1 to 4). The energy flux (or kinetic energy), given by a combined effect of drop size, falling height and application rate was found to be a key factor. Equations were derived for predicting the maximum allowable kinetic energy (MAKE) for different scenarios [2].

4.5 PERFORMANCE OF TWO TYPES OF SPRINKLER IRRIGATION EMITTERS

In a WRC-supported project, two types of sprinklers operating on a dragline and a floppy sprinkler (*Floppy Sprinkler* Pvt. Ltd.) on a permanent layout were evaluated [13]. The individual sprinklers were evaluated on the sprinkler test bench of the ARC

Institute for Agricultural Engineering, and the installed systems were evaluated in-field. The performance of the coefficient of uniformity (CU), distribution uniformity (DU) and the scheduling coefficient (SC) were determined. The importance of this is that high CU values and DU values in-field have a direct influence on the potential yield of the crop. In this research it was illustrated that layout, pressure variation, droplet size and maintenance of sprinkler systems have a significant impact on the irrigation system's performance.

4.6 MANAGEMENT OF SURFACE- AND SUBSURFACE-DRIP IRRIGATION SYSTEMS

Drip irrigation is considered to be one of the most efficient irrigation systems available, but through a WRC-supported research project evidence was obtained from the literature as well as from on-farm and in-field testing that even this system can be inefficient, as a result of poor water quality, mismanagement and maintenance problems [10]. Apart from the research on the performance of various types and ages of drippers [7] and filters under different water quality and typical farming conditions [15], guidelines were developed to make the correct dripper and filter choice. Through this research excellent guidelines were provided for proper choice, maintenance schedules and management of filters and drip-irrigation systems.

4.7 THE WATER-BALANCE APPROACH

In a recently completed WRC research project on irrigation efficiency [11], the selected approach is that irrigation efficiency should be assessed by applying a water balance to a specific situation, rather than by the calculation of various performance indicators, based on once- off measurements of samples. The purpose of an irrigation system is to apply the desired amount of water, at the correct application rate and uniformly to the entire field, at the right time, with the least amount of nonbeneficial water consumption (losses), and as economically as possible. When applying water to crops, it should be considered both as a scarce and valuable resource and an agricultural input to be used optimally. Not all the water that is abstracted from a source for the purpose of irrigation reaches the intended destination (the root zone) where the plant can make best use of it. The fraction of the water abstracted from the source that is used by a planted crop is called the beneficial water-use component. Optimized irrigation water supply is therefore aimed at maximizing this component and implies that water must be delivered from the source to the field both efficiently (with the least volume for production along the supply system) and effectively (at the right time, in the right quantity and at the right quality). Optimizing water use at farm level requires careful consideration of the implications of decisions made during both development (planning and design), and management (operation and maintenance), taking into account technical, economic and environmental issues.

Perry [9] presented a newly developed framework for irrigation efficiency as approved by the ICID (Fig. 1). He describes in detail the history and subsequent confusion surrounding the calculation and interpretation of so-called irrigation or water use 'efficiency' indicators. The framework and proposed terminology are scientifically sound, being based on the principle of continuity of mass, and promote the analysis of irrigation water-use situations or scenarios in order to expose underlying issues that can be addressed to improve water management, rather than simply using the calculation of input-output ratios as done in the past.

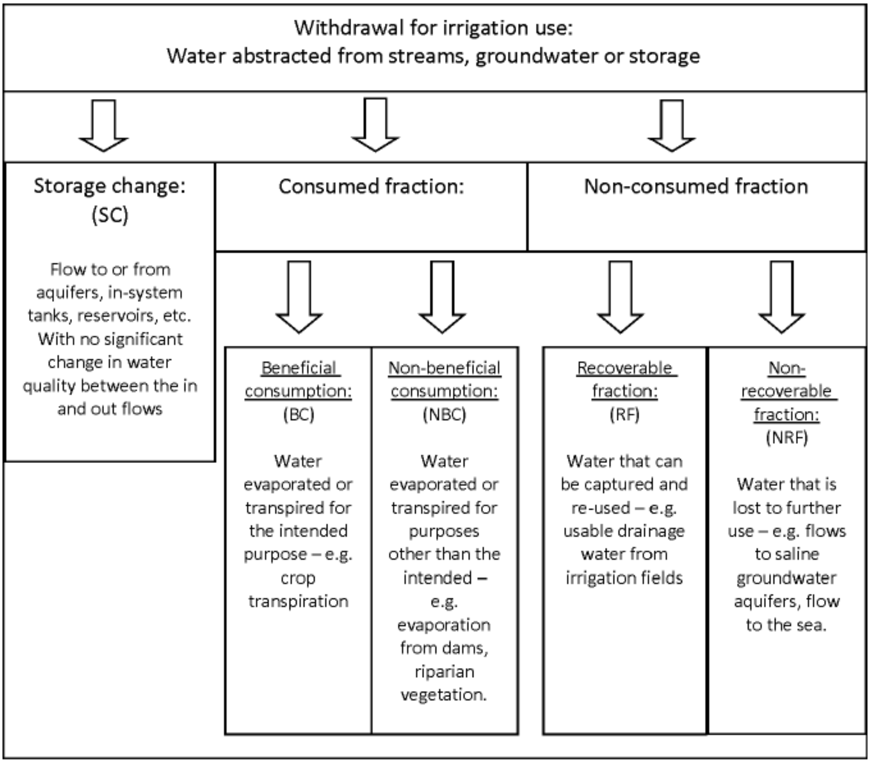

FIGURE 1 ICID water-balance framework for irrigation water management [9].

The basis of the framework is that any water withdrawn from a catchment for irrigation use contributes either to storage change, to the consumed fraction, or to the nonconsumed fraction at a point downstream of the point of abstraction. The water that is consumed will either be to the benefit of the intended purpose (beneficial consumption) or not (nonbeneficial consumption). Water that is not consumed but remains in the system will either be recoverable (for reuse) or nonrecoverable (lost to further use).

In order to improve water availability in a catchment, the relevant authority needs to focus its attention on reducing nonbeneficial consumption and nonrecoverable fractions; the activities undertaken to achieve this result can be called best management practices. The ICID water-balance framework, based on Perry's model [9], is shown schematically in Fig. 1.

FIGURE 2 Root zone application.

FIGURE 3 Dam wall for release of water.

FIGURE 4 "Mobile unit", Mobile irrigation laboratory of ARC-Institute for Agricultural Engineering, South Africa.

In order to apply this framework to irrigation areas, typical components of the water-infrastructure system are defined wherein different scenarios may occur. In South Africa, most irrigation areas make use of a dam or weir in a river from which water is released for the users to abstract, either directly from the river or in some cases via a canal (Figs. 2–4). Water users can also abstract water directly from a shared source, such as a river or dam/reservoir, or the scheme-level water source could be a groundwater aquifer. Once the water enters the farm, it can either contribute to storage change (in farm dams), enter an on-farm water distribution system or be directly applied to the crop with a specific type of irrigation system. The South African framework covers four levels of water-management infrastructure as shown below (Table 1):

1. The water source;
2. The bulk conveyance system;
3. The irrigation scheme and the irrigation far; and
4. The relevant water-management infrastructure.

TABLE 1 Four levels of water management infrastructure [11].

Water management level	Infrastructure system component		
Water Source	Dam/Reservoir		Aquifer
Bulk conveyance system	River	Canal	
Irrigation scheme	On-scheme dam		
	On-scheme canal		
	On-scheme pipe		
Irrigation farm	On-farm dam		
	On-farm pipe/ canal		
	In-field irrigation system		

The different components of the water-balance framework system and their classification according to the ICID framework, for whichever agricultural water-management system, have been developed as a guide to identify the different areas were water losses can occur. In order to improve water-use efficiency in the irrigation sector, actions should be taken to reduce the nonbeneficial consumption (NBC) and nonrecoverable fraction (NRF). Desired ranges for the NBC and NRF components have been developed to assist the practitioner in evaluating the results obtained when first constructing a water balance.

Finally, it is recommended that the water user's lawful allocation is assessed at the farm edge, in order to encourage on-farm efficiency. At scheme level, conveyance, distribution and surface storage losses need to be monitored by the water user association (WUA) or other responsible organization.

TABLE 2 Irrigation schemes where fieldwork took place and system components were assessed [11].

Irrigation scheme	Bulk conveyance	On-scheme distribution	On-scheme return flow	Irrigation system (application)	Irrigation management (Soil storage)
Breede River	X	X	X	X	
Dzindi	X			X	
Gamtoos	X			X	X
Hartbeespoort	X			X	
Hex River				X	
KZN scheme	X	X		X	X
Loskop	X			X	
Nkwalini	X			X	
ORWUA	X	X	X	X	X
Steenkoppies					X
Vaalharts	X		X	X	
Worcester East				X	

Acceptable ranges need to be set, and agreement obtained with the Department of Water Affairs (DWA) as to where in the system provision should be made to cover losses. The fieldwork undertaken in the course of the WRC project, 'Water Use Efficiency from Dam Wall Release to Root Zone Application' [11], comprised various approaches and strategies applied at each of the irrigation schemes that were investigated (Table 2) aimed at quantifying some of the water-use components mentioned. As the application of water-balance approach was an outcome of the research rather than anticipated solution at the outset, the fieldwork was not initially designed to produce results to which the water- balance approach could be readily applied. However, at many of the schemes where fieldwork was undertaken, at least some of the system components could be assessed using the water- balance approach. The research activities undertaken and the outcomes implemented were done in four phases:

1. **Baseline study phase:** The various performance indicators previously available were reviewed, and irrigation systems evaluated to obtain information on the current status of irrigation schemes and systems. The outcome of this phase was a decision to introduce the water-balance approach in which the frame- work components have to be defined and quantified for the boundary conditions selected, using standardized measurements rather than the performance-indicator approach.
2. **Assessment phase:** During this phase, existing best management practices were used to assess the current status of irrigation schemes and systems and to identify which components of the water- balance framework improvements

can be made. This may be at water management area (WMA) scheme or farm level where different sources of information are available for assessment.

3. **Scenario development phase:** During this phase, alternative scenarios were developed for the components requiring change, and the feasibility of implementing the changes was assessed from technical, environmental and economic perspectives. Models were used for feasibility assessment, making use of available computer programs and datasets.
4. **Implementation phase:** In this phase recommendations were made for implementing feasible changes, and guidelines were developed.

These guidelines should be promoted among all levels of stakeholders (WMA, scheme and farm), as a means of influencing the way in which water-use efficiency is reported at the different management levels, for example, in water-use efficiency accounting reports, water-management plans and water-conservation plans.

Within this phase, the main outcome was developed, viz. 'Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application' [11]. The structure and con- tent of the Guidelines are based on the lessons learnt locally and internationally during the course of the project. Hence, the conventional set of performance indicators with benchmarks was moved away from and a water-balance approach is instead being promoted as a more meaningful and sustain- able approach to improving water-use efficiency in irrigation.

These Guidelines are aimed at assisting both water users and authorities to achieve a better understanding of how irrigation water management can be improved, thereby building human capacity and allowing targeted investments to be made with fewer social and environmental costs. The guidelines comprise of four modules:

- Module 1: Fundamental concepts.
- Module 2: In-field irrigation systems.
- Module 3: On-farm conveyance systems.
- Module 4: Irrigation schemes.

The guidelines developed as part of this project contain information on aspects of irrigation water-use efficiency that is either new or supplements previously available information:

- The ICID framework was applied to reassess the system efficiency indicators typically used by irrigation designers when making provision for losses in a system and converting net to gross irrigation requirement. A new set of system efficiency (SE) values for design purposes has been developed. These values are illustrated in Table 3 and are considerably more stringent than previous system-design norms.
- System efficiency defines the ratio between net and gross irrigation requirements (NIR and GIR). NIR is therefore the amount of water that should be available to the crop as a result of the planned irrigation system and GIR is the amount of water supplied to the irrigation system that will be subject to the envisaged in-field losses.
- The new application efficiency values are shown in the 'Norms' column of Table 3, while the different water-use components and their losses at the point of application within a specific irrigation system have each been incorporated

in the default system efficiency value. The approach makes provision for the occurrence of nonbeneficial spray evaporation and wind-drift, in-field conveyance, filter and other minor losses.

- When an irrigation system is evaluated, the system efficiency value can be compared with these default values, and possible significant water loss components identified as areas for improvement. The approach is therefore more flexible and easier to apply than the original efficiency framework where definitions limited the applications.

It should always be kept in mind that a system's water-application efficiency will vary from irrigation event to irrigation event, as the climatic, soil and other influencing conditions are never exactly the same. Care should therefore be taken when applying the SE indicator as a benchmark, as it does not make provision for irrigation management practices.

TABLE 3 New default system efficiency values [11].

Irrigation system	**Losses**				**New default system efficiency (net to gross ratio) (%)**
	Non-beneficial spray evaporation and wind drift (%)	**In-field conveyance losses (%)**	**Filter and minor losses (%)**	**Total Losses (%)**	
Drip (surface and subsurface)	0	0	5	5	95
Microspray	10	0	5	15	85
Centre Pivot, Linear move	8	0	2	10	90
Centre Pivot LEPA	3	0	2	5	95
Flood: Piped supply	0	3	2	5	95
Flood: Lined canal supplied	0	5	2	7	93
Flood: Earth canal supplied	0	12	2	14	86
Sprinkler permanent	8	0	2	10	90
Sprinkler movable	10	5	2	17	83
Traveling gun	15	5	2	22	78

It is recommended that system efficiency be assessed in terms of the losses that occur in the field. This can be determined as the ratio between the volume of water lost to nonbeneficial spray evaporation and wind-drift, in-field conveyance, filter and other minor losses, and the volume of water entering the irrigation system, for a specific period of time. The losses can also be expressed as a depth of water per unit area, rather than a volume.

Irrigation uniformity is a characteristic of the type of irrigation system used, together with the standard to which a given system has been designed, is operated and is maintained. It can also be affected by soil infiltration characteristics and by land preparation. The traditional approach to accounting for the distribution uniformity of the lower quarter (DU_{lq}) has most likely resulted in the default irrigation efficiencies customarily referred to, for example, that furrow irrigation is assumed to be 65% efficient and center-pivot irrigation is assumed to be 85% efficient. Unfortunately, the rationale for these assumed efficiencies, that is, the typical or assumed nonuniformity, is seldom well considered, and water is often thought to just 'disappear' with the assumed low efficiencies. However, once the water-balance approach is applied, it is realized that the water does not 'disappear' but could contribute to increased deep percolation, which may eventually appear as return flow further along the drain- age system.

The bottom line is that assuring high irrigation uniformity is of primary importance, and should be the goal of good design and maintenance procedures. It is very unlikely that low crop yields caused by nonuniform irrigation water applications will be improved by assuming low irrigation efficiencies and therefore increasing the water applications accordingly.

If poor uniformity results in low crop yields, the uniformity needs to be corrected in order to improve system performance. Simply applying more water to compensate for the part of the field that is being under-irrigated is unlikely to result in improved crop yields, as large parts of the field will now suffer from overirrigation, and the risk of long-term problems developing due to a raised water table will increase. The preferred recommendation in this case would be to deal specifically with the problem of poor uniformity. For planning purposes, the GIR at the field edge should therefore be calculated as the product of the NIR and system efficiency.

4.8 CONCLUSIONS AND RECOMMENDATIONS

Studies and research over 40 years on mainly the engineering aspects of the techniques of flood-, mobile- and micro irrigation contributed to the knowledge base of applying irrigation methods correctly to improve the efficient application of water. In particular, the research that was carried out to improve irrigation-water management from dam-wall release to root-zone application has to a large extent consolidated and contributed to local knowledge on issues regarding irrigation water-use efficiency. The resulting approach of 'measure; assess; improve; evaluate,' promotes an investigative approach to improving efficiency, rather than relying merely on water accounting.

The main output of this research was the compilation of guidelines for improved irrigation-water management from dam-wall release to root-zone application. The guidelines are aimed at assisting both water users and authorities to achieve a better understanding of how irrigation-water management can be improved, thereby building human capacity, allowing targeted investments to be made with fewer social and environ- mental costs. Using the lessons learnt during the WRC project, best practices and technologies were identified and then illustrated.

It is recommended that the research output, that is, the guidelines for management advice on improved efficiency of irrigation-water use, should be further developed into a user-friendly package with supporting training material, targeting farmers, service providers and policy advisors. This will contribute to better understanding of the realities and potential for efficient irrigation water use across all levels of water management, and encourage the adoption of the water-balance approach.

4.9 SUMMARY

The purpose of an irrigation system is to apply the desired amount of water, at the correct application rate and uniformly to the whole field, at the right time, with the least amount of nonbeneficial water consumption (losses), and as economically as possible. We know that irrigated agriculture plays a major role in the livelihoods of nations all over the world and South Africa is no exception. With the agricultural water-use sector being the largest of all water-use sectors in South Africa, there have been increased expectations that the sector should increase efficiency and reduce consumption in order to increase the amount of water available for other uses.

Studies and research over 40 years, on the techniques of flood-, mobile- and micro irrigation have contributed to the knowledge base of applying irrigation methods correctly. In a recent study on irrigation efficiency, the approach is that irrigation efficiency should be assessed by applying a water balance to a specific situation rather than by calculating various performance indicators. The fraction of the water abstracted from the source that is used by the plant is called the beneficial water-use component, and optimized irrigation water supply is therefore aimed at maximizing this component. It implies that water must be delivered from the source to the field both efficiently and effectively. Optimizing water use at farm level requires careful consideration of the implications of decisions made during both development (planning and design), and management (operation and maintenance), taking into account technical, economic and environmental issues. An exciting, newly developed South African Framework for Improved Efficiency of Irrigation Water Use covers four levels of water-management infrastructure: the water source, bulk conveyance system, the irrigation scheme and the irrigation farm. The water-balance approach can be applied at any level, within defined boundaries, or across all levels to assess performance within the entire water management area.

KEYWORDS

- **Beneficial water use**
- **Conveyance system**
- **Department of Water Affairs and Forestry, SA**
- **Flood irrigation**
- **ICID**
- **Irrigation efficiency**
- **Irrigation methods**
- **Irrigation uniformity**
- **Micro-irrigation**
- **Mobile irrigation**
- **Murray Biesenbach and Badenhorst (MBB) Inc., SA**
- **PolyPlot software**
- **South African framework**
- **Sprinkler irrigation**
- **Subsurface drip irrigation**
- **Subsurface irrigation**
- **Water consumption**
- **Water Research Commission, SA**
- **Water-balance approach**
- **Water-use efficiency**

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CHAPTER 5

PERFORMANCE OF IRRIGATION SYSTEMS IN SOUTH AFRICA

FELIX B. REINDERS

CONTENTS

This project was made possible with the initiative and guidance of Erik Schmidt of the South African Sugar Association Experimental (SASAE); and with financing by SASAE. The author also acknowledges the invitation of Dr. Singels of the South African Sugar Industry – Agronomists Association, to deliver this presentation at its Annual General Meeting held on 25 October 2001.

5.1 INTRODUCTION

The process of efficient irrigation water management includes determination and the control of rate, amount, timing and distribution of irrigation water so that the crop water requirements are met in a planned and effective manner. This not only depends on the correct technical and agricultural design but ultimately also on the standard of management and maintenance of the irrigation system.

This chapter presents the status of the performance of irrigation systems that was determined by evaluation of irrigation systems in five sugar growing areas of South Africa by the Agricultural Research Council of Institute for Agricultural Engineering (ARC-IAE, 1), on behalf of the South African Sugar Association.

Thirty-eight systems were evaluated, such as: Overhead (sprinkler and floppy), center pivot, micro and drip-(surface and subsurface)-irrigation systems. The target areas in South Africa were Malelane, Komatipoort, Umfolozi, Heatonville and Pongola. Although the performance of most of the irrigation systems was lower that the accepted norms, yet it was within the normal range for in-field evaluations.

5.2 IRRIGATION EFFICIENCY

The irrigation efficiency is difficult to define since it is a concept that represents the maximizing of inputs. This concept requires the evaluation of many factors that influence the overall performance of an irrigation system. These factors are definable, but are specific for each situation. Figure 1 shows these efficiencies schematically and it is important to understand these, the factors that influence it, and how to apply these. Figure 1 reveals that water movement through an irrigation system, from its source to the root zone, is regarded as three separate operations: Conveyance, system distribution and field application. Conveyance is the movement of water from its source through the mains and sub mains or canals to the farm block off-takes. System distribution is the movement of water through the distribution system or canals to the emitter outlets and on to the soil surface. Field application is the movement of the water from the emitter outlets into the root zone of the crop. With the evaluations, only the system efficiency was addressed.

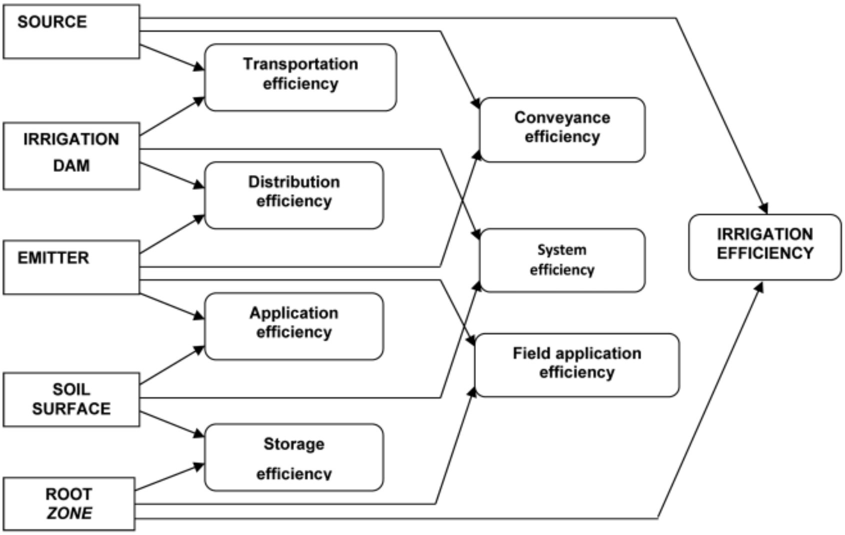


FIGURE 1 Irrigation efficiencies.

5.3 UNIFORMITY COEFFICIENTS OF IRRIGATION SYSTEMS

5.3.1 COEFFICIENT OF UNIFORMITY

The coefficient of uniformity (CU) is used to express how evenly the water is spread over the irrigated area. Uniformity coefficient values are determined by catching discharge from sprinklers on emitters in equally spaced cans and evaluating the catchments mathematically. The values are considered satisfactory, when the CU is greater than 84%.

$$CU = 100x\{1 - [\textstyle\sum_{i=1}^{n}(Ri - m)] \div (m\ x\ n)\} \tag{1}$$

The CU is an indicator of how the individual rain gauge readings deviate from the mean and it is calculated using Eq. (1), where: R_i = Individual rain gauge reading in mm; m = Rain gauge mean reading (mm); and n = Number of rain gauges. For a center pivot, we must use the modified form of CU formula, which involves area weighing (multiplying by the area) of each individual rain gauge reading to its representative section of the pivot area.

5.3.2 DISTRIBUTION UNIFORMITY

Distribution uniformity (DU) is defined as a ratio of the smallest 25% accumulated depths in the distribution to the average depth of the whole distribution. Values of DU less than 60% are generally considered low and a value of DU greater than 75% is considered satisfactory. DU can be calculated using Eq. (2), where DU = distribution uniformity (%); m_{25} = mean of the lowest 25% of rain gage readings (mm); and m = mean for all the rain gages (mm).

$$DU = 100 \times \{(m_{25}) \div (m)\} \tag{2}$$

5.3.3 APPLICATION EFFICIENCY

The application efficiency (AE) is an indicator of water that is lost during the process of supplying water to the field due to evaporation and wind drift losses. It is defined as the volume of water applied to the surface divided by the volume of water exiting the sprinkler emitter. The Eq. (3) is used to determine the AE is in a CU test. In Eq. (3), AE = Application efficiency (%); A = Plot area (m^2); V_s = Volume of the exiting emitter during CU test (m^3); and m = Mean application depth (mm). The volume of AE > 75% is always strived for.

$$AE = 100 \times \{(m \times A) \div (V_s)\} \tag{3}$$

5.3.4 STATISTICAL UNIFORMITY

The statistical uniformity (SU) for micro and drip systems is determined by using the coefficient of variation (CV), as defined in Eq. (4) where: SU = Statistical uniformity (%); and CV = Coefficient of variation defined in Eq. (5). The SU which is >95% is considered excellent. The SU of >85% is considered as good.

$$SU = 100\,(1 - CV) \tag{4}$$

$$CV \;=\; (1/X)\left[\sqrt{\{1/(1-n)\}}x\ \{\sum_{i=1}^{n}(Xi - X)^2\}\right] \tag{5}$$

5.3.5 EMISSION UNIFORMITY

The emission uniformity (EU) characterizes the uniformity of micro systems and is defined in Eq. (6),

$$EU \;= 100 \times \left[1 - 1.27\left(CV \div \sqrt{n}\right)\right] x\ [{}^{Qlq}/_{Qavg}] \tag{6}$$

where: EU = Emission uniformity; CV = Manufacturers' coefficient of variation; n = Number of emitters; Q_q = Average low-quarter emitter discharge (l/h); and Q_{avg} = Overall average of emitter discharge (l/h).

5.4 METHODOLOGY

The environment in which irrigation farmers must function has changed significantly in recent years because of changes in legislation that regulates the use of water in South Africa. The National Water Act (Act 36 of 1998) provides for: Water resources to be developed; and for water to be protected, used, conserved and controlled in a sustainable and equitable manner.

The objective of the research for field evaluation was therefore to quantify the performance of the irrigation systems and to assist in improving the efficiency of water application by the irrigators. Evaluations were based on the standards by American Society of Agricultural and Biological Engineers (ASABE) and these evaluations were expressed in terms of the uniformity coefficients.

5.4.1 FACTORS

The uniformity of each type of irrigation system is influenced by the following factors [2 to 5]:

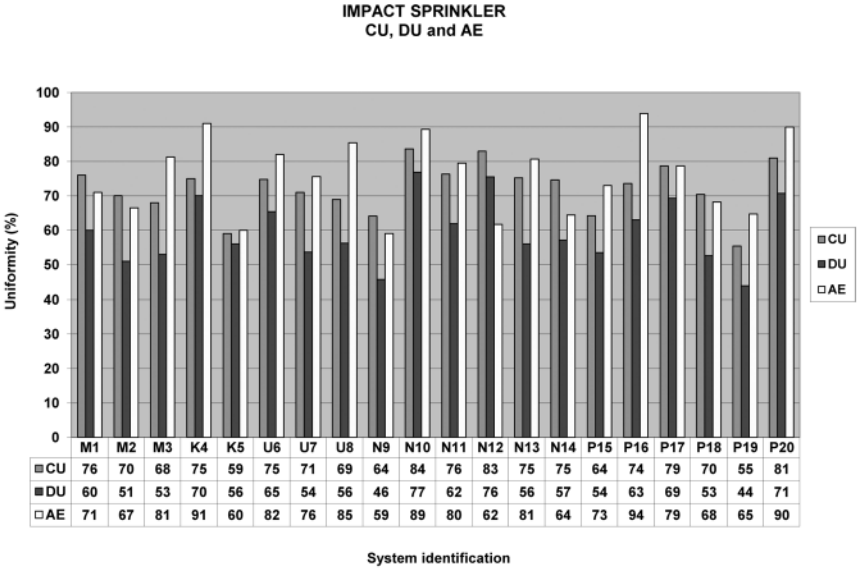
1. Sprinkler:
   - pressure
   - variation in pressure
   - sprinkler spacing
   - nozzle wear
   - the water distribution pattern
   - wind speed
   - climatic conditions.
2. Center pivot
   - pressure
   - variation in pressure
   - nozzle wear
   - wind speed
   - climatic conditions
3. Micro
   - pressure
   - variation in pressure
   - emitter characteristics
   - manufacturing coefficient of variation
   - type of filtering system
   - percentage blockages or clogging

5.5 RESULTS AND DISCUSSION

The Table 1 and Figs. 2 to 5 summarizes the results for the coefficient of uniformity (CU), emission uniformity (EU), low quarter distribution (DU), application efficiency (AE) and statistical uniformity (SU). The systems in the different areas are identified with a letter: "M" for Malelane, "K" for Komatipoort, "U" for Umfolozi, "N" for Nkwaleni and "P" for Pongola. In majority of the irrigation systems, the CU or EU, DU and SU were lower than the accepted norms.

TABLE 1 Summary of all the uniformity parameters for types of irrigation systems.

Parameter	Type of Irrigation system			
	Dragline	**Floppy**	**Center Pivot**	**Micro and Drip**
No of systems tested	20	3	4	11
CU% or EU% (micro)	72	74	89	72
DU%	60	67	83	68
AE% or SU% (micro)	76	77	82	74
Design capacity (mm/day)	4.1	5.1	5.9	4.3



	M1	M2	M3	K4	K5	U6	U7	U8	N9	N10	N11	N12	N13	N14	P15	P16	P17	P18	P19	P20
▨CU	76	70	68	75	59	75	71	69	64	84	76	83	75	75	64	74	79	70	55	81
■DU	60	51	53	70	56	65	54	56	46	77	62	76	56	57	54	63	69	53	44	71
□AE	71	67	81	91	60	82	76	85	59	89	80	62	81	64	73	94	79	68	65	90

FIGURE 2 Performance of impact sprinkler systems.

Results in this study indicated that the coefficient of uniformity (CU) was 72% for the dragline, 74% for the floppy and 89% for the center pivot systems, with the accepted norm of 84% or higher. The emission uniformity (EU) for the micro and drip systems was 72% with the norm of 92% and higher. The average low quarter distribution uniformity (DU) was 60% for the dragline, 67% for the floppy, 83% for the center pivot and 68% for the micro and drip, respectively, with the accepted norm of 75% and higher. The average application efficiency (AE) was 76% for the dragline, 77% for the floppy and 82% for the center pivot. The statistical uniformity (SU) for the micro and drip systems was 74% with the accepted norm of 90% or higher.

The Tables 2 and 3 show the percentage of irrigation systems that comply with the norms. It can be observed that only a small amount of center pivot, floppy and micro systems had been tested and it might not be a true statistical reflection of the performance of these systems in the different areas. All the center pivots had an excellent CU and DU and none of the floppy irrigation systems exceeded the CU or DU norm.

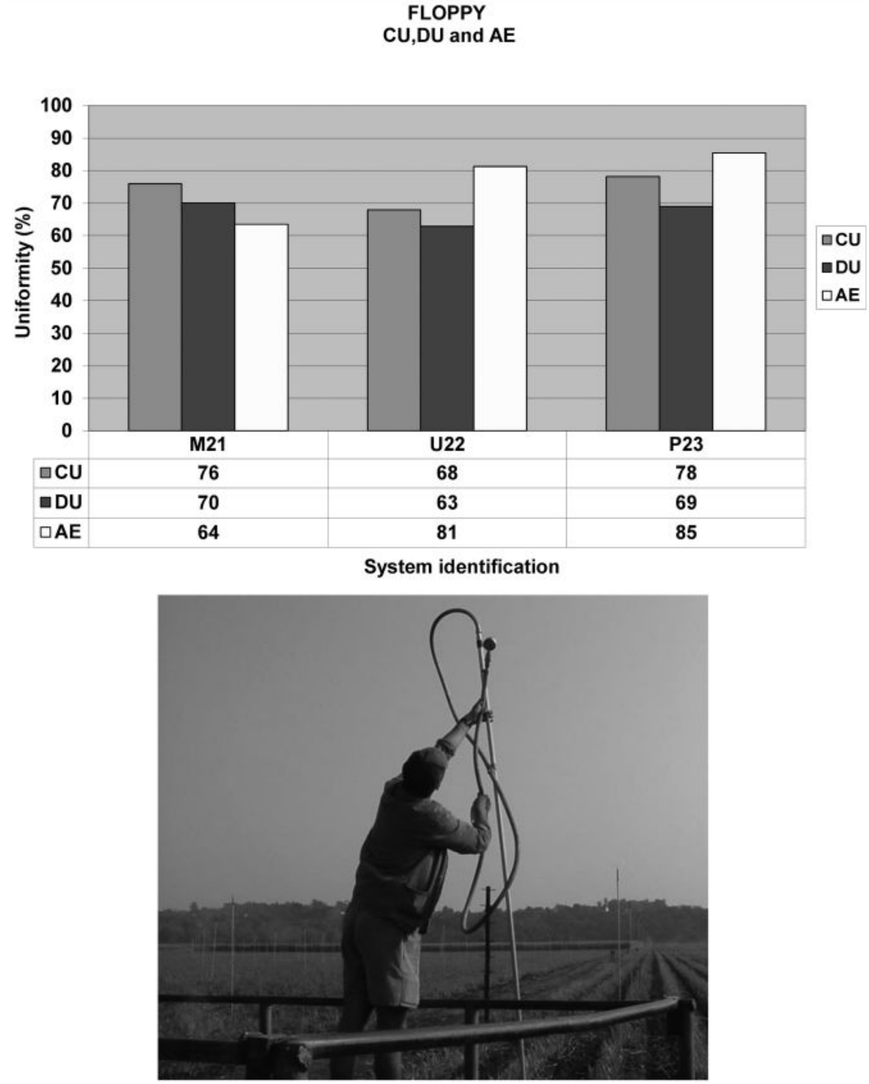
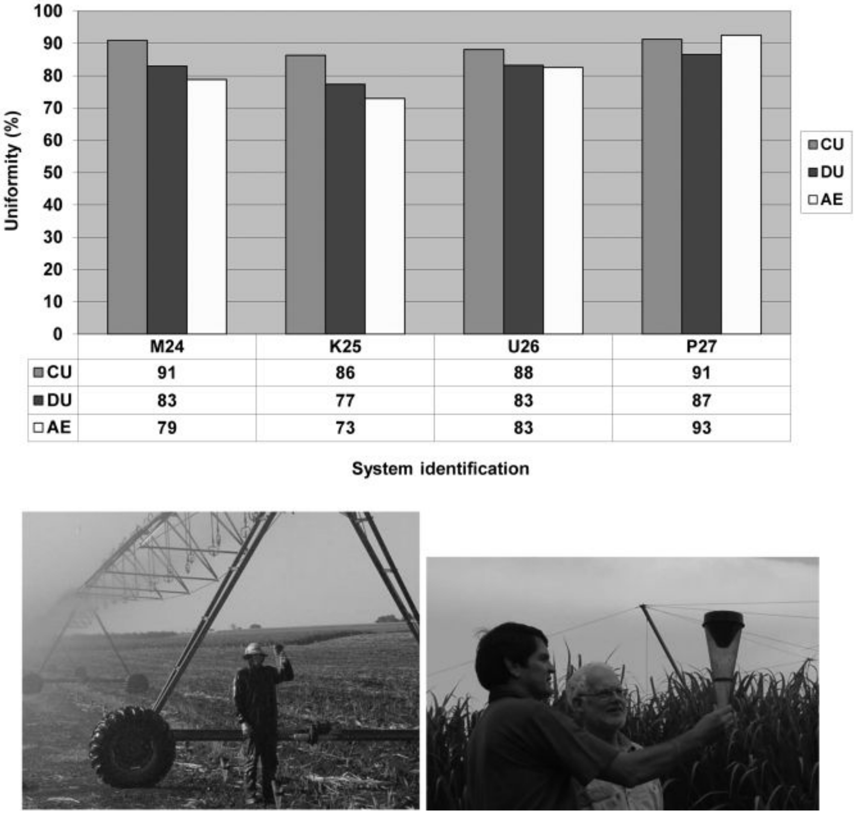


FIGURE 3 Performance of floppy systems.



	M24	K25	U26	P27
▨CU	91	86	88	91
■DU	83	77	83	87
☐AE	79	73	83	93

FIGURE 4 Performance of center pivot systems.

TABLE 2 Percentage of dragline, floppy and center pivot irrigation systems that comply with the norms.

Uniformity		Type of irrigation system		
Parameter	**Norm (%)**	**Dragline**	**Floppy**	**Center Pivot**
No. of systems	-	20	3	4
CU	84	5%	0%	100%
DU	75	5%	0%	100%
AE	75	60%	67%	75%

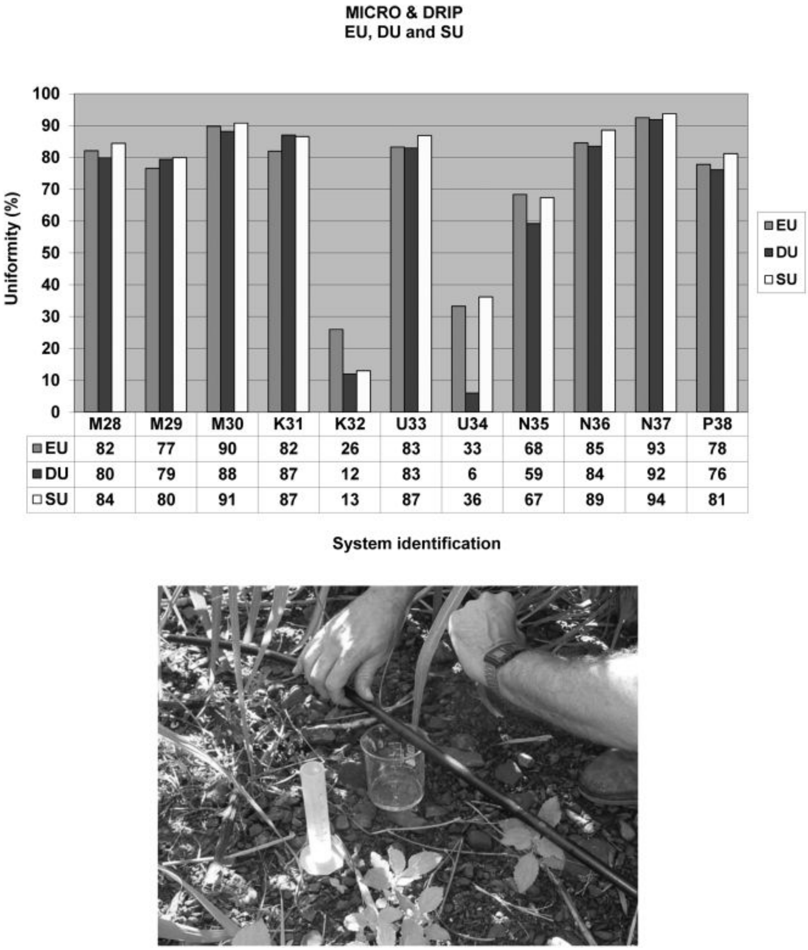


FIGURE 5 Performance of micro and drip irrigation systems.

TABLE 3 Percentage of micro drip systems that comply with the norms.

Uniformity		Irrigation type	
Parameter	**Norm (%)**	**Micro**	**Drip**
No. of systems	-	2	9
EU	92	0%	11%
DU	85	0%	33%
SU	90	0%	22%

The possible reason for the low percentage of dragline systems that comply with the norms, can be attributed to the incorrect system pressure (of the 20 dragline systems which were tested only six of them operated within the acceptable pressure range), worn nozzles, incorrect spacings and the climatic conditions, where relatively high wind speeds prevailed during testing. The wind speeds varied from 1 to 11 m/s. The wind also affected the performance of the floppy system but not as much as with the dragline systems. The CU and DU values were in the same order as was found with this project (Table 4), in a research project by the ARC-IAE [1] where impact sprinklers and floppy systems were evaluated.

TABLE 4 Results of research on impact sprinklers and floppy systems (WRC report, 5).

Parameter	Impact Sprinkler A	Impact Sprinkler B	Floppy
CU%	78	76	78
DU%	68	63	71

Figure 5 shows the performance of the micro systems (M_{28} and M_{29}) and the drip systems (from M_{30} to P_{38}). None of the micro irrigation systems exceeded the EU, DU and SU norms and only 11% of the drip systems exceeded the EU, 33% the DU and 22% the SU. Pressure variation and clogging is the mayor problem. Especially system K32 and U34 were severely clogged. The results of the uniformity of the micro and drip irrigation systems were similar to that of the other irrigation systems. This is contrary to the common belief that micro and drip systems have much higher uniformities than other irrigation systems.

5.6 CONCLUSIONS

Although most of the systems performed lower than the accepted norms, yet it is within the range of what is normally found under in-field evaluations. It is however of the utmost importance that the irrigation systems should be properly maintained and operated within their specified design parameters to ensure optimal efficiency and operation of the system. The results showed that well maintained and correctly operated systems can achieve or exceed the uniformities, which are considered reasonable and acceptable.

In order to conserve water resources, close attention must be paid to the performance of irrigation systems. The frequent evaluation and maintenance of irrigation systems are imperative to keep the performance on a high level and to optimize water use efficiency.

5.7 SUMMARY

Irrigated agriculture is the largest user of water in South Africa and due to the pressure on the limited amount of water, the efficient use is of paramount importance. The environment in which irrigation farmers must function has also changed significantly in recent years. In particular, changes in legislation that regulates the use of water, impacts directly on irrigation practice. The National Water Act (Act 36 of 1998) provides for water resources to be developed and for water to be protected, used, conserved and controlled in a sustainable and equitable manner. This can only be achieved through effective design, maintenance and management of irrigation systems.

The status of the performance of irrigation systems in South Africa was studied through evaluations of irrigation systems in five sugar growing areas of South Africa by the Agricultural Research Council – Institute for Agricultural Engineering on behalf of the South African Sugar Association.

Thirty-eight systems were evaluated which included overhead (sprinkler and floppy), center pivot, micro and drip-(surface and subsurface)-irrigation systems. Malelane, Komatipoort, Umfolozi, Heatonville and Pongola were the target areas.

Results indicated that the coefficient of uniformity (CU) was 72% for the dragline, 74% for the floppy and 89% for the center pivot systems, with the accepted norm of 84% or higher. The emission uniformity (EU) for the micro and drip systems was 72% with the norm of 92% and higher. The average low quarter distribution uniformity (DU) was 60% for the dragline, 67% for the floppy, 83% for the center pivot and 68% for the micro and drip, respectively, with the accepted norm of 75% and higher. The average application efficiency (AE) was 76% for the dragline, 77% for the floppy and 82% for the center pivot. The statistical uniformity (SU) for the micro and drip systems was 74% with the accepted norm of 90% or higher.

Although most of the systems performed lower than the accepted norms, it is within the range of what is normally found with in-field evaluations. The impact, however, is that with every 1% drop in CU, the yield might drop by 2%. The water use efficiency is also directly related to the application efficiency and the results showed that between 24% and 18% of the water were lost due to evaporative and wind drift losses. The percent of systems that had an acceptable DU were 100% for center pivot, 33% for drip, 5% for sprinkler, 0% for micro and 0% for floppy. Systems, that were well maintained and correctly operated, generally had a high and acceptable DU.

The possible reasons, for the low percentage of the systems that comply with the norms, can be a combination of incorrect pressures and spacings, worn nozzles, incorrect designs and climatic conditions with high wind speeds and temperatures. Continued evaluation and maintenance of irrigation systems are imperative to keep the performance on a high level and to optimize water use efficiency.

KEYWORDS

- **Agricultural Research Council, SA**
- **American Society of Agricultural and Biological Engineers**
- **Center pivot irrigation**
- **Dragline irrigation**
- **Drip irrigation**
- **Efficiency, application**
- **Field evaluation**
- **Floppy irrigation**
- **Institute for Agricultural Engineering, SA**
- **Irrigation efficiency**
- **Irrigation methods**
- **Irrigation uniformity**
- **Micro irrigation**
- **Mobile irrigation**
- **Overhead irrigation**
- **Performance**
- **Rain gage**
- **South Africa**
- **South African Sugar Association**
- **Sprinkler irrigation**
- **Subsurface drip irrigation**
- **Subsurface irrigation**
- **Surface drip irrigation**
- **Uniformity coefficient**
- **Uniformity, distribution**
- **Uniformity, emission**
- **Uniformity, statistical**
- **Water Research Commission, SA**
- **Water-use efficiency**
- **Wind speed**

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CHAPTER 6

IMPACT OF FLUSHING AND FILTRATION SYSTEM ON PERFORMANCE OF MICRO IRRIGATION SYSTEMS

VINOD KUMAR TRIPATHI

CONTENTS

6.1 INTRODUCTION

Increased water demand in domestic, industrial and other sectors causes reduction in water availability water for agricultural sector. Micro-irrigation system with wastewater is a viable alternative to overcome the problem of water shortage for agricultural sector without sacrificing the productivity. However, poor quality of wastewater can restrict the use of micro irrigation systems due to emitters, which are highly susceptible to clogging by water impurities [8, 16, 24]. The obstruction of emitters affects the hydraulic performance of the irrigation system, reducing the uniformity of water distribution, increasing the operating costs and the investment risks, and discouraging farmers from employing micro irrigation technology. To minimize the limitations of this system, it is recommended to provide suitable water filtration systems to remove the impurities (e.g., physical, chemical, or both simultaneously).

In drip irrigation system, quality of irrigation water, filtration system and emitter play a vital role. Wastewater treatment through filtration is a key to reduce emitter clogging. Although an adequate filtration system can control emitter clogging with wastewater [20, 23], yet clogging cannot be avoided completely [29]. The type of particles in wastewater depends on the source and pretreatment process [2, 3, 31]. The factors, that influence whether a particle is retained by a filter, include size, shape, surface load, settling velocity. Since these factors vary from one type of particle to another, the particle size distribution, the variety of shapes and the density intervals must also be considered [18]. Extent of dripper clogging was studied by many researchers in details [10, 25, 30].

The emitter clogging can be classified into three types: physical clogging, chemical clogging and biological clogging [7]. Physical clogging is caused by suspended inorganic particles (such as sand, silt and clay), organic materials (animal residues, snails, etc.), and microbiological debris (algae, protozoa, etc.); physical materials are often combined with bacterial slimes. Chemical clogging problems are due to dissolved solids interacting with each other to form precipitates, such as the precipitation of calcium carbonate in waters having calcium and bicarbonates [32]. Biological clogging is due to algae, iron and sulfur slimes. De Kreij et al. [11] found that drip-line with laminar flow suffers more severe clogging than the labyrinth type emitter having turbulent flow, because laminar flow is predisposed to clogging. Capra and Scicolone [9] found that vortex emitters are more sensitive to clogging than labyrinth emitters.

Filtering can prevent inorganic particles and organic materials from entering the drip irrigation system. In India, mostly gravel media filter, screen and disk filters are used in drip irrigation system. Gravel media filter prevents passage of solid particles, only if these particles are smaller than the filter pores as the capture of particles is controlled by both physical and chemical mechanism [1]. Disk filter is simple, economical, and easy to manage and filtration is done at two stages. The larger outer surface operates as a screen filter and collects the larger particles. The grooves inside the disk allow the adhesion of fine particles, mainly organic matter. It retains the particles in the grooves of the disks. Capra and Scicolone [9] observed that screen filters, either locally or internationally available, were not suitable for use with wastewater, with the exception of diluted and settled wastewater. They also observed almost similar performance by disk and gravel media filter with treated municipal wastewater. Performance of media and disk filter in combination may be the good strategy to improve filtration efficiency was not studied for wastewater.

Subsurface drip irrigation (SDI) systems diminish human exposure to effluents and vandalism, but have a higher initial investment cost, and need careful and consistent operation, maintenance and management. It must have good and consistent filtration, water treatment, flushing and maintenance plans to ensure long economic life [17]. Filtration systems do not normally remove clay and silt particles, algae and bacteria because they are too small for typical economical filtration. These particles may travel through the filters as individual particles, but then flocculate or become attached to organic residues and eventually become large enough to clog emitters [22].

To minimize the buildup of sediment and organic residues, regular flushing of micro irrigation systems is recommended. The system should be designed such that the mainline, laterals and valves are sized to permit a sufficient flushing velocity (0.3 m sec^{-1}) recommended by ASABE [5]. Flushing valves should be installed at the end of mains, submains, and flush-lines (if present). The flush-lines provisions should be made for flushing individual laterals that connect the downstream ends of the laterals. A regular maintenance program of inspection and flushing will help significantly in preventing emitter clogging. Therefore, drip-line flushing is periodically needed to remove these particles and organisms that are accumulated within the laterals [26]. The irrigation system should be designed so that it can be flushed properly. To be effective, flushing must be done at frequent intervals at appropriate velocity to dislodge and transport the accumulated sediments [22].

Several researchers have different opinion about flushing frequencies: daily [27], twice per week [29] and once per week [14, 29] with a secondary clarified effluent, every two weeks with stored effluents [27] and with a secondary effluent [13] or fortnightly and monthly with stored groundwater [14]. However, in many areas, only one flushing is carried out at the beginning and/or at the ending of irrigation season.

In India, untreated or partially treated municipal wastewater is frequently used by the farmers for growing vegetables. There is need to develop the methodology for using wastewater through drip irrigation system in combination with filtration and flushing. Investigation is needed to conduct field trials on drip irrigation system by placing emitter laterals on surface and subsurface conditions under different filtration and flushing strategies. This chapter discusses the effects of filtration and flushing on clogging of surface and sub surface placed emitters in micro irrigation system using municipal wastewater.

6.2 MATERIALS AND METHODS

6.2.1 WATER RESOURCES

Wastewater (WW) samples were collected across the drain passing through Indian Agricultural Research Institute (IARI), Pusa – New Delhi – India at 15 cm depth below the water level surface. The preservation and transportation was performed according to the standard methods [4]. Collected wastewater samples were analyzed for pH, electrical conductivity (EC), total solids (dissolved and undissolved), turbidity, calcium, magnesium, carbonate, and bicarbonate, according to the standard methods [4].

6.2.2 EXPERIMENTAL SET-UP

Drip irrigation system was installed with in-line lateral (J-TurboLine) with emitter spacing at 40 cm. It was laid on the ground for surface drip and was buried at a 15 cm depth from ground surface for subsurface drip (SDI). System included: 1. Sand media filter (F1) with flow rate of 30 m^3 h^{-1}, 50 mm size, silica sand 1.0 to 2.0 mm, thickness 80 cm, and with backflush mechanism; 2. Disk filter (F2) with flow rate of 30 m^3 $h^{-1,}$ 20 mm size, 130 microns, disc surface of 1.198 cm^2, screen surface of 815 cm^2 (AZUD helix system, model 2NR). WW was allowed to pass through filters F1 and F2 alone as well as in combination of both the filters (F3). Main line (50 mm diameter, PVC pipe) was connected to submains (35 mm diameter, PVC pipe) for each of the plots through a gate valve.

6.2.3 OPERATIONAL PROCEDURE

WW collected from the drain was stored in a sedimentation tank for a period of 24 h so that all the suspended foreign particles got settled. Then, the settled WW was fed to the filtration system and then allowed to pass through emitters. The pump was turned on, and emitters were allowed to drip for approximately 2 min so that lateral and pipeline were free from air. The water collection period was set at 5 min. Quantity of flow of water from drip emitter was collected in containers at 98.06 kPa pressure and was repeated for three times. The flow rate was estimated by dividing total volume collected by the time of collection. The measurement was taken from randomly located sampling emitters for performance evaluation. Discharge from SDI laterals were measured by excavating the soil around the buried drip laterals so that an emitter is visible with sufficient space below it for placement of the container to collect discharged water from it, as suggested by Magwenzi [19]. Performance of system was evaluated at normal operating pressure to discharge sufficient water for infiltration and to avoid ponding near the emitter. As per manufactures' recommendation, operating pressure of 98.06 kPa was considered adequate. To achieve accurate pressure, emitter level measurement was done at the lateral with digital pressure gage having the least count of 0.01 kPa.

Flushing was carried out with the system main, sub main and then proceeds to the lateral pipes. It was continued at 2.0 kg cm^{-2} pressure until clean water runs from the flushed line for at least two minutes. Flushing operation was done at the end of the crop season. Discharge from emitters under different treatments was measured before and after flushing operation (Fig. 1), and emitter performance evaluation parameters were estimated.

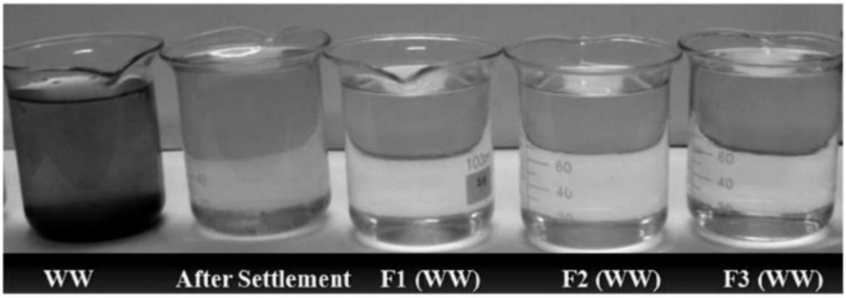

FIGURE 1 Collection of wastewater (WW) before and after filtration.

6.2.4 EVALUATION OF FILTRATION SYSTEM

Performance of filters was evaluated by estimating the Filtration efficiency (E) of the filters, using Eq. (1).

$$E(\%) = \frac{N_0 - N}{N_0} \times 100 \tag{1}$$

where: N_0 is a value of specific quality parameter of unfiltered wastewater and N is the value of the same parameter after filtration.

6.2.5 EVALUATION OF PARAMETERS FOR EMITTER PERFORMANCE

6.2.5.1 UNIFORMITY COEFFICIENT (UC)

$$UC = 100\left[1 - \frac{\frac{1}{n}\sum_{i=1}^{n}|q_i - q|}{q}\right] \tag{2}$$

where, q_i = the measured discharge of emitter i (lh^{-1}); q = the mean discharge at drip lateral (lh^{-1}); and n = the total number of emitters evaluated.

6.2.5.2 EMITTER FLOW RATE (% OF INITIAL, R)

$$R = \frac{q}{q_{ini}} 100 \tag{3}$$

where: q = the mean emitter discharges of each lateral (lh^{-1}); and q_{ini} = corresponding mean discharge of new emitters at the same operating pressure of 98.06 kPa (lh^{-1}).

6.2.6 STATISTICAL ANALYSIS

Statistical analysis was carried out using the GLM procedure of the SAS statistical package (SAS Institute, Cary, NC, USA). The model used for analysis of variance (ANOVA) included water from different filters and placement of lateral as fixed effect and interaction between filtered water and emitter placement depth. The ANOVA was performed at probabilities of 0.05 or less level of significance to determine whether significant differences existed among treatment means.

6.3 RESULTS AND DISCUSSIONS

6.3.1 PERFORMANCE OF FILTRATION SYSTEM

Filtration efficiency for WW filtration by filter F1, F2, and their combinations (F3) during the experiments are presented in Table 1. Filtration efficiency 64.3±29.8% for turbidity and 19.21±19.3% for total solids were achieved with F3. Negative filtration efficiency was observed for TS and Mg (column F1 in Table 1). The value for TS was −3.08±21.5. It shows the variation in filtration efficiency from −24.58% to 18.42%. This was due to variation in amount of TS available in WW and as testing was done for the same filter without cleaning. Sometimes, if filter was not cleaned and WW containing lower TS was passed through F1 then TS available in F1 came out with WW. Thus the amount of TS available in WW, was higher and resulted in negative filtration efficiency using Eq. (1). Similar reasoning can be made for negative filtration efficiency in case of Mg through F1. Negative filtration efficiency was also observed by Duran-Ros et al. [12] with screen and disk filter for turbidity and TS. Duran-Ros et al. [12] observed 12.42±23.53% filtration efficiency for turbidity and 8.47±18.36% for total suspended solids (TSS) with combination of screen and disk filter at 500 kPa inlet pressure. The presence of less organic material after the sand media filters was also observed by Tajrishy et al. [29] and can explain the lower fouling of emitters protected by this type of filter [12]. Combination filter and lower inlet pressure caused more effective filtration. Combination filter gave best results for removal of bicarbonate (HCO_3) and carbonate (CO_3) in comparison to F2. However, filtration efficiency obtained through F1 was close to F3. Therefore, F1 and F3 are not significantly different (P=0.387) as shown in Table 1.

TABLE 1 Filtration efficiency and *P* value for difference in filtration of different water quality parameters.

Quality parameter	Filtration efficiency (%) (mean and SD)			*P* value for LSD at α = 0.05		
	F1	F2	F3	F1-F2	F1-F3	F2-F3
Turbidity	51.1±37.5	63.9±30.6	64.3±29.8	0.058	0.023	0.388
Total Solids, TS	–3.08±21.5	2.66±18.2	19.21±19.3	0.540	0.089	0.191
Ca	8.79±2.34	1.65±12.4	12.1±27.2	0.626	0.816	0.492
Mg	–2.53±6.88	6.38±1.6	7.33±4.16	0.017	0.012	0.696
CO_3	6.47±3.25	15.7±14.2	16.36±13.6	0.163	0.141	0.908
HCO_3	19.3±12.3	12.6±10.7	21.3±6.91	0.034	0.387	0.092

Removal of turbidity was highest with combination filter (F3) but it was close to F2. It can be seen that F1–F3 were significantly different (*P*=0.023) but F2–F3 were not significantly different (*P*=0.388). Effect of filtration systems was not significantly different for removal of CO_3, Ca, and total solids from WW. The small filtration efficiencies by filters were in agreement with other published works [2, 28]. Capra and Scicolone [9] observed similar performance by disk and media filters. In sand filters, the smaller effective size of sand particles has effect on the sand filtration efficiency [15]. The combined filtration system always gave better results than individual filters, for example, F1 and F2.

6.3.2 EVALUATION OF EMITTER FLOW RATE

Emitter flow rate variations were evaluated with Analysis of Variance (ANOVA) by maintaining no variation in pressure so that the flow rate variation will only be affected by the clogging of emitters. ANOVA for variations in average flow rate under different filtration systems for beginning, end of season and after flushing are presented in Table 2.

TABLE 2 Significance level (*P*-value) of the statistical model and of each factor and interaction for emitter flow rate.

Parameter	Time		
	Beginning	**End of season**	**After flushing**
Model	*** (R^2=0.95)	***(R^2=0.91)	** (R^2=0.84)
Filter (F)	n.s.	***	**
Emitter placement (EP)	n.s.	*	n.s.
F × EP	n.s.	***	**

n.s.: not significant, P> 0.05; *: P <0.05; **: P <0.01;
***: P <0.001.

Maximum reduction in flow rate (7%) was observed with filter F1 under subsurface drip (30 cm depth) while the minimum (4.8%) with combination filter. Reduction in flow rate with F2 was 5.34%, which is between the values of F1 and F3 as mentioned above. Effect of filtration system as well as emitter placements are factors responsible for emitter flow rate and subsequently emitter clogging. The results from statistical analysis revealed that, after the end of crop season, there was significant effect of filter, emitter placement and their interaction. At the beginning of the experiment there was no significant effect of emitter placement and their interaction with filter. It is obvious because emitters were new at the beginning and had negligible chance of clogging. After continuous use of the system, clogging takes place and effect of different filtration systems starts affecting the flow rate. After flushing, filtration systems were significantly different but emitter placement was nonsignificant. But interaction of filtration system with emitter placement was significant (*P* <0.01). Good filtration system can control these anomalous results. This indicated clogging to be a dynamic phenomenon and to change with time [26].

6.3.3 EFFECT OF FLUSHING AND FILTRATION SYSTEMS ON EMITTER DISCHARGE

The effect of flushing and different filtration system on emitter discharge is presented in Fig. 2. Flushing of main, submain and lateral removes the accumulation of sediments, dislodge bacterial slime and biofilms. Flushing was effective to improve the discharge rate of emitters supplied through gravel media, disk and combination filters. Maximum effectiveness in improving the discharge was observed under F1 in surface drip (2.7%). Surface placement of lateral with F2 shows least improvement (0.5%). It may be due to better filtration from F2, which is also evident from the filtration efficiency of filters. Overall, higher improvements in flow rate of emitters under subsurface placed lateral were more than surface placed lateral in all the filtration system. It may be due to flushing of soil particles from emitters under higher water velocity in the path of emitters. To control the emitter clogging, acidification can also work but it causes acidification of soil after long time application of acid flushing [21].

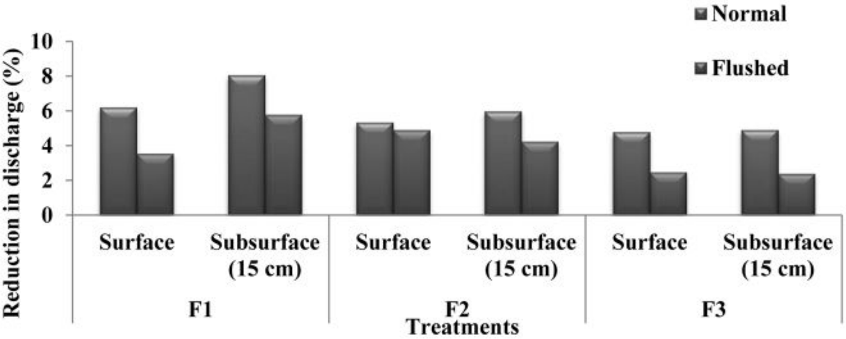

FIGURE 2 Effect of flushing and different filtration systems on reduction in emitter discharge.

6.3.4 EFFECT OF FLUSHING ON UNIFORMITY OF WATER APPLICATION

Variations in uniformity coefficients (UC) are presented in Table 3. Highest UC was observed at beginning of the field experiment. After end of the season, UC decreases considerably. However, performance of surface and subsurface drip system using both filters combination comes under good category because UC was more than 95%. Similar observations were made by Puig-Bargues et al. [25].

TABLE 3 Uniformity coefficient resulting from the performance evaluation of drip irrigation system.

Filter	Depth of placement of lateral	UC (%)		
		Beginning	End of season	After flushing
Gravel media (F1)	Surface	98.59	96.26	97.41
	15 cm	98.56	95.24	96.40

TABLE 3 *(Continued)*

Filter	Depth of placement of lateral	UC (%)		
		Beginning	End of season	After flushing
Disk (F2)	Surface	98.89	96.12	96.64
	15 cm	98.91	95.00	96.27
Combination of F1 and F2	Surface	99.01	96.60	97.49
	15 cm	99.05	95.20	96.34

At the end of season, surface and subsurface drip with combination filters shows highest UC 96.67% and 95.70%, respectively. It indicates that WW with combination filters can give better filtration in comparison with single filters. Significant improvement in UC was observed after flushing of the system. Higher improvement in UC was observed in subsurface drip in comparison to surface drip after flushing (Table 3). Higher improvements in the SDI emitters may be explained by exit of ingested external soil particles, which may stuck in the biofilm at the emitter outlet leading to increased clogging. Installation of air/vacuum relief valves at the high elevation points can help prevent soil ingestion in SDI [17]. Effluent chlorination has been found to be effective in reducing clogging caused by biofilm growth [27, 29]. Chemical treatments such as acidification can be also used for increasing chlorination effectiveness [22].

6.4 CONCLUSIONS

Drip emitters experienced continuous use of wastewater from different filtration system and revealed that filtration with a combination of gravel and disk filter was most appropriate strategy against emitter clogging. It resulted in a better emission uniformity and reasonable lower reduction in discharge. Filters can be used for significant removal of for turbidity, total solids, carbonate and bicarbonate available in wastewater. Filter, emitter placement and their interaction have significant effect on emitter clogging. Flushing is helpful in partial removal of emitter clogging. It gives significant improvement in discharge and uniformity coefficient. This revealed that the flushing at 2 $kg.cm^{-2}$ pressure is adequate when it was performed at the end of the irrigation season. Pressure compensating emitters may be good choice over the nonpressure one when applying wastewater. It is also recommend that an air/vacuum relief valve may be used for subsurface drip irrigation to avoid ingestion of soil particles due to formation of soil solution.

6.5 SUMMARY

Filtration plays a vital role to improve the efficacy and reduce the maintenance of micro irrigation systems. The experiment was conducted to evaluate the conventional micro irrigation filters (gravel media filter, disk filter and their combination) for wastewater filtration. Physical, chemical and biological parameters of wastewater responsible for emitter plugging, such as total solids, turbidity, Ca, Mg, CO_3 and HCO_3 were analyzed in the effluents at the entry and exit points of the filters. The filtration efficiency for water quality parameters was estimated with individual filters and in combination. Significant improvement in water quality was observed for turbidity, total solids, carbonate and bicarbonate. The filtration efficiency with combination filter was 64.3±29.8% for turbidity and 19.21±19.3% for total solids. Negative filtration efficiency was also observed for total solids and Mg.

Gravel media filter gave better results for filtration of bicarbonate (HCO_3) from wastewater in comparison to the disk filter. Emitters protected by the gravel media filter experienced the largest flow rate reductions but emitters protected by combination filters experienced least flow rate reduction. Backwashing of filters reduces the filtration efficiency and head loss through it. To reduce emitter plugging by removal of accumulated sediment, flushing of mains, submains and laterals was done. Higher improvement in uniformity coefficient was observed in subsurface drip in comparison to surface drip after flushing. It gave maximum improvement in the emitter discharge rate with emitters experienced gravel media filter and least with disk filter.

KEYWORDS

- **Clogging**
- **Coefficient of variation**
- **Disk filter**
- **Dripper**
- **Emitter**
- **Emitter discharge**
- **Emitter flow rate**
- **Emitter placement**
- **Filter**
- **Filtration**
- **Filtration efficiency**
- **Flushing**
- **Gravel media filter**
- **Micro-irrigation**
- **Plugging**
- **Subsurface drip**
- **total solids**
- **total soluble solids**
- **Uniformity coefficient**
- **Wastewater**
- **Wastewater quality**

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CHAPTER 7

CLOGGING AND MAINTENANCE OF MICRO IRRIGATION SYSTEMS

JUAN ENCISO

CONTENTS

7.1 INTRODUCTION

Subsurface drip irrigation (SDI) systems are preferably used over alternative systems for crop production in several parts of the world because the large initial SDI system costs can be offset by crop profits. If the longevity of the SDI systems can be increased through properly designed and maintained systems, these systems could be economically justified for a great diversity of row crops. In some regions, SDI systems have been used for lower-value commodity crop production such as in Kansas for irrigating corn and West Texas to irrigate cotton [8, 13, 14]. Cotton producers have replaced furrow irrigation systems with SDI systems to spread limited water resources for the declining aquifers of West Texas and also to remain profitable.

The use of SDI systems in row crops may also be influenced by the initial cost of the system. The cost of an SDI system will depend on the drip-line spacing or the row configuration [8]. The cost percentages by irrigation components for a 1.02 m drip-line spacing are approximately: pump and filters 14%, drip-line 38%, PVC pipe 25%, installation 15%, and fertilizer injectors and accessories 8% [11]. The drip-line represents the greatest cost of the system and its longevity can greatly impact the system's annual amortized cost. Economic comparisons of SDI systems and center pivot sprinkler irrigation systems (CP) for corn production in Kansas have indicated that SDI systems must last at least 10 to 15 years to approach economic competitiveness with CP systems [15]. Successful maintenance programs can help prevent emitter clogging and increase the longevity of the system. The longevity of subsurface drip irrigation (SDI) systems is a key factor in the profitability of these systems when used for lower-value commodity crops (typically the fiber and grain crops). The system management and maintenance protocols, as well as the source water quality, can greatly impact the longevity of these systems. Enciso et al. [10] evaluated 10 subsurface drip irrigation systems in 2008 and 8 additional systems in 2009 that had been in operation between 6 and 20 years. System uniformity was evaluated by the uniformity parameters, emitter discharge variation, qvar, and the lower quartile distribution uniformity of emitter discharge, DUlq. Pressure measurements along the drip-line also were used to determine if qvar was primarily explained by friction losses. Two-thirds of the evaluated SDI systems had qvar less than 20% and DUlq greater than 80, which would be acceptable, and one-third of the systems had qvar less than 10% and DUlq greater than 90, which would be good to excellent uniformity. There was very little correlation in system uniformity and system life with the oldest system (20 years) having the greatest uniformity. Uniformity problems on nearly two-thirds of the systems appeared to have been exacerbated by incorrect operating pressure (both too low and too high) with the six best performing systems operating between 65% and 100% of the manufacturer's specified nominal operating pressure. Water hardness and total dissolved salts were the major water quality concerns. Poor maintenance (e.g., no or infrequent chlorination; inadequate filtration system back flushing) appeared to reduce uniformity in between one-third and one-half of the systems. The producer's lack of installation records and operator's guides likely negatively impacted system uniformity through these poor management and maintenance procedures. The use of both qvar and DUlq to evaluate performance of SDI systems appeared to enhance the determination of the primary causes of SDI system nonuniformity. The evaluation proposed by Enciso et al. [9] is a novel technique that may be used as a standard to evaluate subsurface drip irrigation systems.

Emitter clogging can be produced by physical, chemical, and biological causes [2]. Physical clogging is caused by suspended inorganic particles (such as sand, silt, clay, plastic fragments from the installation process), organic materials (spiders, ants, snails, etc.), and microbiological debris (algae and protozoa).

Boman [1] determined that 46% of the clogging of microsprinklers was due to algae, 34% from ants and spiders, 16% from snails, and 4% from physical particles such as sand and fragments of PVC. Boman also found that the clogging rate was inversely related to the orifice area of the emitters. Filtering of the water and flushing of manifolds and drip-lines are simple and necessary procedures that can help to prevent or reduce physical clogging [19].

Filtration can help prevent inorganic particles and organic materials suspended in water, and precipitates formed during chemical injection from entering the SDI system. Flushing of drip-lines and manifolds removes the inorganic and organic materials deposited on the inside wall of drip-lines from the system, thus helping to reduce clogging [21, 22]. Chlorine injections, greater emitter orifice area, and a built-in filtration area for the emitters can reduce biological emitter clogging produced by algae and protozoa [6]. Another biological clogging problem can be produced by root intrusion into the emitters especially in Bermuda grass irrigation, or in vines and trees, which is commonly controlled by injections of trifluralin [3, 5].

The chemical composition and pH of the water source and the water's interaction with chemicals added during chemigation can have a very significant influence on the level of emitter clogging. Emitter clogging criteria were proposed by Bucks et al. [2] for emission devices with discharges ranging from 2 to 8 L/h. The primary water characteristics that can affect chemical clogging are: pH, salts, bicarbonates, manganese, total iron, and hydrogen sulfide [8, 9, 23]. Even phosphoric acid, which is often injected in micro irrigation system water to prevent chemical clogging, can result in phosphate precipitants with the calcium and magnesium when the injection rate is too low allowing too much dilution of the acid (i.e., pH rises with dilution). For high pH waters, it is advisable to consider mixing the phosphoric acid with urea-sulfuric-acid (e.g., N-phuric 15/49) prior to injection to help ensure the water pH will remain at 3.0 or lower [3, 4]. Chlorine (e.g., sodium hypochlorite) and acid (e.g., sulfuric acid) chemical injections are often needed to avoid emitter clogging caused by bacterial growth, algae, iron and manganese oxides and sulfides, calcium and magnesium precipitation, and root intrusion [3].

Micro-irrigation has been used with a variety of water sources such as ground water, surface water, or treated effluent. Secondary municipal effluent has been successfully used with surface drip irrigation by using sand media filtration and injecting continuous chlorination to a free chlorine residue concentration of 0.4 mg/L without reducing emitter discharge [12]. Beef lagoon effluent has also been used successfully with manageable clogging problems [24] with smaller emitters typically used for freshwater applications perhaps too risky for use with effluent even with disk filtration to 75 microns (200 mesh). In a later report of the same study, Lamm et al. [14, 16] found the discharge rates of the two smallest emitter sizes (0.6 and 0.9 L/h-emitter) decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging. The three drip-lines with the greatest discharge rate emitters (0.1.5, 2.3, and 3.5 L/h) only had approximately 7%, 8%, and 13% emitter discharge reductions, respectively. Sewage water clogged 26% more emitters than groundwater [17] in a study in China. They also found that with pressure compensating emitters that the clogging distribution occurred randomly along the drip-line, but the clogging of non-pressure compensating emitters tended to occur at the distal end of the drip-lines. Clogging of drip emitters can be also affected by the type of emitter [7, 18].

It has been observed that on-line pressure compensating emitters have better anti-clogging properties than in-line emitters. The on-line emitters are when the drip-line is punched and the emitters are inserted into the line and the in-line emitters are when the emitters are extruded into the drip-line. It has also been observed that turbulent-flow emitters have better anti-clogging properties than laminar-flow emitters [7, 17, 18]. Most of the reported clogging studies have been conducted in controlled field experiments with duration of less than 4 years. More studies, which document the performance of older SDI systems that are still currently operational, are needed. It is also important to document how these systems have been affected by the source water quality, what management and maintenance practices have been adopted, and whether the longevity of operation has affected system performance and irrigation uniformity. Considering the large investment needed for SDI, it is vital to extend their lifetime with proper design, management, and maintenance practices.

This chapter describes and provides ideas on how to conduct preventive maintenance, evaluate a drip irrigation system, inject chlorine and sulfuric acid, and provides some other considerations for maintaining these irrigation systems.

7.2 PREVENTIVE MAINTENANCE

A permanent system, properly designed and maintained, should last more than 20 years. A maintenance program includes cleaning the filters, flushing the lines, adding chlorine, and injecting acids. These preventive measures will reduce the need for major repairs and extend the life of the system.

The purpose of preventive maintenance is to keep the emitters from plugging. Emitters can be plugged by suspended solids, magnesium and calcium precipitation, manganese-iron oxides and sulfides, algae, bacteria and plant roots. Each SDI system should contain a flow meter and at least two pressure gauges-one gauge before the filters and another after the filters. Flow meters and pressure gauges, which should be inspected daily, indicate whether the system is working properly. A low pressure reading on a pressure gauge indicates a leak in the system (such as a leaking component or broken pipe). A difference in pressure between the filters may imply that the system is not being back flushed properly and that the filters need to be cleaned. In larger systems, pressure gauges should be installed in each field block or zone.

Water quality determines the relative risk of emitter plugging and other problems; therefore, the properties of the water should be taken into account in the system maintenance program. Examples of water quality parameters and their effect on emitter plugging potential are summarized in Table 1.

TABLE 1 Effects of water quality parameters on emitter plugging potential.

Chemical property	Low	Moderate	Severe
PH	<7.0	7.0–8.0	>8.0
Bicarbonate (ppm)		<100.0	
Iron (ppm)	<0.2	0.2–1.5	>1.5
Sulfides (ppm)	<0.2	0.2–2.0	>2.0
Manganese (ppm)	<0.1	0.1–1.5	>1.5

7.2.1 MAINTENANCE OF FILTERS

Filters are essential components of an SDI system and they remove suspended solids from the water. There are three main types of filters: cyclonic filters (centrifugal separators); screen and disk filters; and media filters. It is common practice to install a combination of filters to effectively remove particles of various sizes and densities.

7.2.1.1 CENTRIFUGAL SEPARATORS

These filters need little maintenance, but they require regular flushing. The amount of sediment in the incoming water, the volume rate of water used, and the capacity of the collection chamber at the bottom of the filter will determine how often and how long the flushing valve needs to operate. The sediment can be released manually or automatically. If it is done manually, the bottom valve of the filter should be opened and closed at regular intervals. An electronic valve controlled by a timer can automatically open the bottom valve. Automated operation of the valve should be checked at least every other day during the season.

7.2.1.2 SCREEN AND DISK FILTERS

Small screen filters use a nylon strainer or bag, which should be removed and checked periodically for small holes. The flush valve controls the flushing of the screen filter. This can be operated manually or automatically. The screen filter should be flushed when the pressure between the two pressure gauges drops 5 psi (one is located before the filters and the other after them). Automatic filters use a device called a "pressure differential switch" to detect a pressure drop across the filters. Other systems use a timer, which is usually set by the operator. The flushing can be timed according to the irrigation time and the quality of the water. The interval between flushing can be adjusted to account for differences in pressures across the filters. Automated flushing devices should be checked at least every other day on large systems.

7.2.1.3 SAND MEDIA FILTERS

With these filters the most important task is to adjust the restrictor backflush valve. If the backflow rate is too high sand filter media will be washed out of the filter container. If the backflow rate is too low contaminating particles will not be washed out of the filter. Bacterial growth and the chemistry of the water can cause the sand media to cement. Cementing of the media causes channels to form in the sand, which can allow contaminated water to pass unfiltered into the irrigation system. Chlorination can correct or prevent sand media cementing.

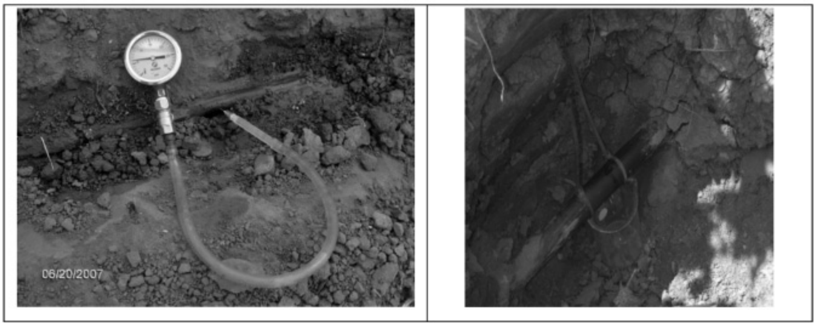

FIGURE 1 Measuring pressure and emitter discharge in a subsurface drip irrigation system.

7.2.2 EVALUATION OF MICRO IRRIGATION SYSTEM

One method to evaluate clogging problems is to perform an evaluation of the irrigation system. It is recommended to measure emitter discharge and pressure at 18 selected locations within a single zone to detect problems (Fig. 1).

Enciso et al. [9] recommends to pick six drip-lines, evenly spaced across the width of the zone for sampling. Along each of the six drip-lines, three measurements should be made, near the inlet and distal ends (approximately 8–9 m from ends) and near the center of the drip-line length. The measurements can be made by placing a container under selected emitters as shown in Fig. 1. In case of subsurface drip irrigation the measurements can be made by carefully excavating the soil by hand, trying to avoid damaging the drip-line, to a depth below the emitter to allow small water collection containers. Water dripping from each sampled emitter can be collected for a period of time as measured by a stop watch. Collection errors can be further reduced by collecting and averaging two or three water collection samples for each of the 18 selected emitters. Emitter discharge is calculated as the average sample catch volume divided by sample time. The emitter discharge collected at different locations should be compared against the design flow rate. The drip-line pressure at each sampling location can be determined using a glycerin-filled pressure gage (±1.5% of full scale, 0 to 207 kPa). A syringe, connected to the pressure gage with plastic tubing, can be used to pierce the drip-line, providing a nonleaking interference fit. After using the syringe to measure the drip-line pressure, a small plastic plug (also known as goof plug: to provide an interference fit) can be inserted into the hole of the drip-line as a permanent repair of the leak. Sadler et al. [20] reported the excavation process itself can affect the emitter discharge with increases of as much as 4% due to removal of overburden on some soil types. However, these differences in emitter discharge are still small and the emitter discharges are being compared against each other (i.e., all sampled emitters are being excavated) so the effect is less important.

The Lower Quartile Distribution Uniformity is calculated using Eq. (1).

$$DU_{lq} = 100\left[\frac{q_{lq}}{\overline{q}}\right] \tag{1}$$

where: q_{lq} is the average emitter discharge from the lower quartile of sampled emitters; and is the mean emitter discharge for all of the emitters.

The Fig. 2(top) shows a field with plant stress produced by emitter clogging caused by manganese oxides at the Texas Agricultural Experiment Station Helms Research Farm, south of Halfway, Texas. The general condition of a drip system can be easily evaluated by frequent observation of system pressures and flow rates. If emitter plugging occurs, system pressures will increase and flows will decrease. Acid injection can reduce clogging problems so fields are irrigated uniformly, as shown in Fig. 2(bottom). The Fig. 3 indicates the roots that are penetrating the drip-lines.

7.2.3 FLUSHING LINES AND MANIFOLDS

Very fine particles pass through the filters and can clog the emitters. As long as the water velocity is high and the water flow is turbulent, these particles remain suspended. If the water velocity slows or the water becomes less turbulent, these particles may settle out. This commonly occurs at the distant ends of the lateral lines. If they are not flushed, the emitters will plug and the line eventually will be filled with sediment from the downstream end to the upstream end. Systems must be designed so that mainlines, submains, manifolds and laterals can all be flushed. Mainlines, submains and manifolds are flushed with a valve installed at the very end of each line. Lines can be flushed manually or automatically. It is important to flush the lines at least every 2 weeks during the growing season.

FIGURE 2 Plants in this field are drought-stressed because emitters are clogged (Top). Acid injection can reduce clogging problems so fields are irrigated uniformly (Bottom).

FIGURE 3 Roots penetrating an emitter in the drip-line.

7.2.4 INJECTING CHLORINE

At a low concentration (1 to 5 ppm), chlorine kills bacteria and oxidizes iron. At a high concentration (100 to 1000 ppm), it oxidizes (destroys) organic matter.

7.2.4.1 BACTERIA PROMOTED BY DISSOLVED IRON AND MANGANESE

The most serious problems with bacteria occur in waters that contain ferrous or soluble iron. Iron and/or manganese concentrations higher than 0.1 ppm can promote bacterial growth and chemical precipitation that clogs emitters. Iron bacterial growth looks reddish, whereas manganese bacterial growth looks black. These bacteria oxidize iron and/or manganese from the irrigation water. In the western part of Texas, these bacteria often are associated with well water.

Extreme caution should be maintained when injecting chlorine into irrigation water containing dissolved manganese since chlorine can oxidize this element and cause precipitation beyond the filter system.

It is hard to eliminate iron bacteria, but it may be controlled by injecting chlorine into the well once or twice during the season. It might also be necessary to inject chlorine and acid before (upstream of) the filters. When the water contains a lot of iron, some of the iron will feed the bacteria and some will be oxidized by chlorine to form rust (or insoluble iron, ferric oxide). The precipitated ferric oxide is filtered out and flushed from the system. If iron concentration is high and problems persist, aeration of the irrigation water will help to oxidize the iron and facilitate settling of sediment. Aeration can be accomplished by pumping water into a reservoir and then repumping it with a booster pump to the irrigation system.

A swimming pool test kit can be used to test for free or residual chlorine in the water at the end of the lateral line. It is worth noting that some of the injected chlorine may be removed from solution through chemical reactions with other constituents or absorbed by organic matter in the water. For continuous injection, 1 ppm of free residual chlorine at the ends of the laterals will be enough to kill most bacteria. For intermittent injection (once every several days) the chlorine concentration should be maintained at 10 to 20 ppm for 30 to 60 min.

If emitters are already partially plugged by organic matter, “super-chlorination” treatment is warranted; it involves maintaining a concentration of 200 to 500 ppm chlorine in the system for 24 h.

Some extra chlorine should be injected to account for the tied up chlorine.

7.2.4.2 INJECTION RATE FOR CHLORINE

The equations to calculate the injection rate (English and metric units) are shown in Table 2. The percentage of chlorine for different compounds and a numerical example are also presented in Table 2. The necessary injection rate in gallons per hour of chlorine is shown in Table 3.

TABLE 2 Formulas to calculate the injection rate for chlorination.

English Units Calculation	**Metric Units Calculation**
$IR = \frac{0.006xFxC}{P}$ (2)	$IR = \frac{0.06xFxC}{P}$ (3)
where:	where:
IR = Injection rate, GPH	IR = Injection rate, liters/hr.
F = Flow rate of the system (GPM)	F = Flow rate of the system (LPS)
C =Concentration of chlorine wanted, ppm	C = Concentration of chlorine wanted, ppm
P = Percentage of chlorine in the solution*	P = Percentage of chlorine in the solution*

*The percentage of chlorine for different compounds is as follows:

calcium hypochlorite—65%

sodium hypochlorite (household bleach)—5.25%

lithium hypochlorite—36%

Numerical example:

A farmer wants to inject chlorine into his system at a concentration of 5 ppm in a system with a flow rate of 100 GPM. He is injecting household bleach that has a chlorine concentration of 5.25%.

$$IR = \frac{0.006xFxC}{P} = \frac{0.006x100x5}{5.25} = 0.571\,GPH$$

Of *sodium hypochlorite (household bleach)*

TABLE 3 Injection rate of chlorine in gallons per hour.

Gallons of chlorine (5.25% solution) per hour									
Desired chlorine level in ppm	**Irrigation Water Flow Rate, gallons per minute (GPM)**								
	100	150	200	250	300	350	400	450	500
1	0.114	0.171	0.229	0.286	0.343	0.400	0.457	0.514	0.571
2	0.229	0.343	0.457	0.571	0.686	0.800	0.914	1.029	1.143
5	0.571	0.857	1.143	1.429	1.714	2.000	2.286	2.571	2.857
10	1.143	1.714	2.286	2.857	3.429	4.000	4.571	5.143	5.714
15	1.714	2.571	3.429	4.286	5.143	6.000	6.857	7.714	8.571
20	2.286	3.429	4.571	5.714	6.857	8.000	9.143	10.29	11.43
25	2.857	4.286	5.714	7.143	8.571	10.00	11.43	12.89	14.29
30	3.429	5.143	6.857	8.571	10.29	12.00	13.71	15.43	17.14
50	5.714	8.571	11.43	14.29	17.14	20.00	22.86	25.71	28.57
Gallons of chlorine (10% solution) per hour									
Desired chlorine level in ppm	**Irrigation Water Flow Rate, gallons per minute (GPM)**								
	100	150	200	250	300	350	400	450	500
1	0.060	0.090	0.120	0.150	0.180	0.210	0.240	0.270	0.300
2	0.120	0.180	0.240	0.300	0.360	0.420	0.480	0.540	0.600
5	0.300	0.450	0.600	0.750	0.900	1.050	1.200	1.350	1.500
10	0.600	0.900	1.200	1.500	1.800	2.100	2.400	2.700	3.000
15	0.900	1.350	1.800	2.250	2.700	3.150	3.600	4.050	4.500
20	1.200	1.800	2.400	3.000	3.600	4.200	4.800	5.400	6.000
25	1.500	2.250	3.000	3.750	4.500	5.250	6.000	6.750	7.500
30	1.800	2.700	3.600	4.500	5.400	6.300	7.200	8.100	9.000
50	3.000	4.500	6.000	7.500	9.000	10.50	12.00	13.50	15.00

7.2.5 INJECTING ACID

Acids are injected into irrigation water to treat plugging caused by calcium carbonate (lime) and magnesium precipitation. Water with a pH of 7.5 or higher and a bicarbonate level higher than 100 ppm poses a risk of mineral precipitation, depending on the hardness of the water. Hardness of water, determined by the concentrations of calcium and magnesium, is classified as follows: soft (0 to 60 ppm of Ca and Mg); moderate (61 to120); hard (121 to180); very hard (more than 180 ppm). Moderate, hard and very hard water warrant acid injection.

Sulfuric, phosphoric, urea-sulfuric, or citric acid can be used. The type most commonly used in drip irrigation is 98% sulfuric acid. Acetic acid, or vinegar, can be used in organic farming, although it is much more expensive. If the irrigation water has more than 50 ppm of calcium, phosphoric acid should not be injected, unless the injection rates are high to lower the pH below 4.

Acid is usually injected after the filter so that it does not corrode the filter. If the filter is made of polyethylene, which resists corrosion, acid can be injected before the filter. The amount of acid to use depends on the characteristics of the acid you are using and the chemical characteristics of the irrigation water. A titration curve of the well water used for drip irrigation can be developed by a laboratory showing the amount of acid needed to reduce the pH to a certain level. If a titration curve is not available, use a trial and-error approach until the pH is reduced to 6.5. Colorimetric kits or portable pH meters can be used to determine the water pH at the end of lines. Many farmers inject 1 to 5 gallons of sulfuric acid per hour, depending on the water pH, water quality, and well capacity.

Most chemicals used in drip system maintenance are extremely hazardous. Sulfuric acid is very corrosive and must be handled with proper personal protection equipment. Store sulfuric acid in polyethylene or stainless steel tanks with extra heavy walls. *Always add acid to water; do not add water to acid.* Never mix acid and chlorine or store them together in the same room; a toxic gas will form.

Besides clearing clogged emitters, acid injected into irrigation water may improve infiltration characteristics of some soils and releases micronutrients by lowering the soil pH. To reduce the cost, acid can be injected during the last third of the irrigation time.

7.2.6 ADDITIONAL NECESSARY MAINTENANCE

7.2.6.1 KEEP OUT PLANT ROOTS

It is important to keep plant roots from penetrating the drip emitters (Fig. 4 shows a root intrusion problem). Metam sodium and trifluralin are two compounds that control roots. In cotton, metam sodium is generally used at defoliation to keep roots out as the soil dries, while trifluralin is used before harvest. Super-chlorination at a dosage of 400 ppm chlorine also will keep roots out. Fill the tapes with chlorine and leave it overnight.

FIGURE 4 MRoots penetrating a drip emitter.

7.2.6.2 PREVENT BACK-SIPHONING

Back-siphoning is the backflow of water from the soil profile back into the tape at the end of an irrigation cycle caused by a vacuum developed as residual water in the tape moved to the lower elevations in the field. Back-siphoning may pull soil particles and other debris through emitters into the tape. Figure 5 shows some live worms that were flushed from SDI lines during normal maintenance. It is hypothesized that the eggs or cocoons of worms were pulled into the drip-lines at the higher elevations in the field when zone valves were closed. Once in the drip-lines, the eggs may have hatched and the worms started to grow. Worms and other contaminants were removed during normal flushing cycles (every 2 weeks).

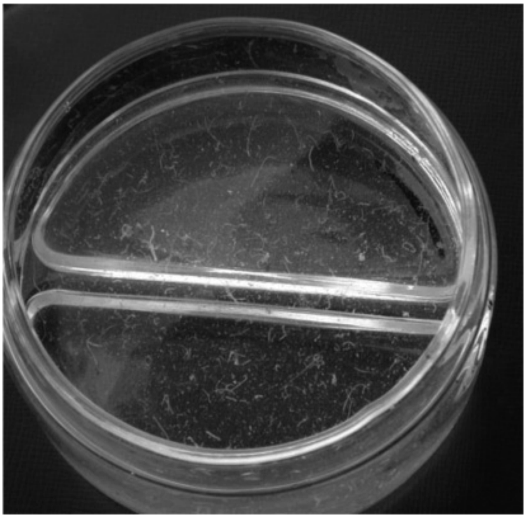

FIGURE 5 Worms flushed from an SDI system. Flushing twice a week solved the problem.

7.3 SUMMARY

Drip irrigation, micro irrigation and subsurface drip irrigation (SDI) systems can deliver water at low flow rates very uniformly. A permanent system, properly designed and maintained, should last more than 20 years. A maintenance program includes cleaning the filters, flushing the lines, adding chlorine, and injecting acids. These preventive measures will reduce the need for major repairs and extend the life of the system. This chapter describes and provides ideas on how to conduct preventive maintenance, evaluate a drip irrigation system, inject chlorine and sulfuric acid, and provides some other considerations for maintaining these irrigation systems.

KEYWORDS

- **Algae**
- **Backflush valve**
- **Backflushing**
- **Bicarbonates**
- **Biological clogging**
- **Calcium**
- **Center pivot sprinkler irrigation systems, CP**
- **Centrifugal separator**
- **Chemical clogging**
- **Chemigation**
- **Chlorination**
- **Clogging**
- **Cyclonic filter**
- **Disk filters**
- **Distribution uniformity**
- **Distribution uniformity of emitter discharge, DUlq**
- **Emitter**
- **Emitter discharge variation, qvar**
- **Flush valve**
- **Free chlorine**
- **Goof plug**
- **Hydrogen sulfide**
- **Magnesium**
- **Manganese**
- **Media filter**
- **Micro-irrigation**
- **Microsprinkler**

- **Municipal effluent**
- **pH**
- **pH meter**
- **Phosphoric acid**
- **Physical clogging**
- **Pressure compensating emitter**
- **Protozoa**
- **Root intrusion**
- **Screen filter**
- **Sodium hypochlorite**
- **Subsurface drip irrigation, SDI**
- **Sulfuric acid**
- **Super-chlorination**
- **Total iron**
- **Trifluralin**
- **Urea-sulfuric-acid**

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PART II

MANAGEMENT OF MICROIRRIGATION SYSTEMS

CHAPTER 8

ESTIMATION OF PAN EVAPORATION COEFFICIENTS

ERIC W. HARMSEN, ANTONIO GONZÁLEZ-PÉREZ,
and AMOS WINTER

CONTENTS

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8.1 INTRODUCTION

The pan evaporation method is widely used to schedule irrigation because it is easy and inexpensive. The University of Puerto Rico Agricultural Experiment Station (UPR-AES) is currently promoting this method in the "Technological Package [Spanish]" guidance publications for various crops [1]. A number of studies have been performed to determine optimal irrigation rates based on pan evaporation data in Puerto Rico for several crops, such as: Tanier [2], bananas under mountain conditions [3], bananas under semiarid conditions [4], plantains under semiarid conditions [5], watermelon under semiarid conditions [6], and sweet peppers under humid conditions [7, 8]. Harmsen [9] presented a summary of these studies.

The evapotranspiration (ET) can be estimated using pan evaporation method with the following equations:

$$ET_{pan} = K_c * Et_{o\text{-}pan} \tag{1}$$

$$Et_{o\text{-}pan} = K_p * E_{pan} \tag{2}$$

where: ET_{pan} = Actual crop ET, based on the pan-derived reference ET, $Et_{o\text{-}pan}$; K_p = Pan coefficient; E_{pan} = Class A pan evaporation; and K_c = Crop coefficient. According to Allen et al. [10], estimates of ET from pan data are generally recommended for periods of 10 days or longer. It is recommended that the Eqs. (1) and (2) should be used for ET estimations usually for periods of four to seven days in Puerto Rico. Most of the studies have recommended applying water to plants at a rate equal to 1 to 1.5 times the pan-estimated ET rate to maximize crop yield. Because this approach is easy and inexpensive, these studies represent valuable contributions to agricultural production in the tropics.

Problems, however, may result from this approach because of the inherent differences in water loss from an open water surface and a crop [10]. Another potential limitation is that only a single value of crop coefficient is commonly used, and by definition the crop coefficient varies throughout the season. The magnitude of the crop coefficient depends on crop height, leaf area, crop color, stomatal resistance, and crop maturity.

Although recommended irrigation application rates by this method may maximize crop yields, the method may also result in the over application of water early in the crop season, leading to the degradation of groundwater resources from leaching of agricultural chemicals.

In Puerto Rico, the K_p values commonly used were derived from a study by Goyal and González [11] using data from the seven agricultural substations located at Adjuntas, Corozal, Juana Díaz (Fortuna), Gurabo, Isabela, Lajas, and Río Piedras. Figure 1 shows the location of the substations and the Climate Divisions established by the National Oceanic and Atmospheric Administration (NOAA). These data were developed on the basis of the ratio of long-term monthly average reference evapotranspiration (estimated from an equation) to pan evaporation:

$$K_p = ET_o / E_{pan} \tag{3}$$

where: K_p is the pan coefficient; ET_o is reference or potential ET; and E_{pan} is the pan evaporation rate. Mean daily values of pan evaporation were derived from a University of Puerto Rico Agricultural Experiment Station document *Climatological Data from the Experimental Substations of Puerto Ric*o [12]. Goyal and González [11] estimated the potential ET by using the Soil Conservation Service (SCS) Blaney-Criddle method [13]. In a recent study by the American Society of Civil Engineers (ASCE), the SCS Blaney-Criddle method was found to produce large errors relative to weighing lysimeter data indicating overestimation on average by 17% in humid regions and underestimation on average by 16% in arid regions [14].

In a study that compared seasonal consumptive use for pumpkin and onion at two locations in Puerto Rico, Harmsen et al. [15] reported large differences between the SCS Blaney-Criddle method [estimates obtained from Goyal 1989, 11] and the Penman-Monteith method. The Penman-Monteith approach used crop coefficients as determined by the FAO procedure [10]. Crop stage durations, used to construct the crop coefficient curves, were based on crop growth curve data presented by Goyal [16]. The maximum observed differences in the estimated seasonal consumptive use were on the order of 100 mm per season. The study concluded that large potential differences can be expected between the SCS Blaney-Criddle and the Penman-Monteith methods, with under-estimations in some months and overestimations in other months.

Because of inherent errors associated with the SCS Blaney-Criddle method, the published values of K_p for Puerto Rico may not be accurate. The United Nations Food and Agriculture Organization (FAO) currently recommends using the ratio of pan evaporation divided by the Penman-Monteith-estimated reference ET for calculating the pan coefficient [10]. The Penman-Monteith based reference ET was found to have a high degree of accuracy in the above-mentioned ASCE study [14], with errors not exceeding ±4%.

This chapter indicates how to update pan coefficient values for the seven substations in Puerto Rico using the Penman-Monteith reference ET, and to incorporate 20 years of additional pan evaporation data. As part of the study, long-term trends in pan evaporation data were evaluated.

8.2 MATERIALS AND METHODS

8.2.1 PAN EVAPORATION DATA

Historical pan evaporation data were evaluated to determine whether decreasing or increasing trends existed in the data. Roderick and Farquhar [17] and Ohmura and Wild [18] have reported that pan evaporation rates have been decreasing globally. The cause of the decrease has been attributed to the decrease in solar irradiance (during the last decade) and changes in diurnal temperature range and vapor pressure deficit [17]. If in fact pan evaporation is changing in Puerto Rico, then the more recent data (e.g., for the last 20 years) may provide better estimates of the pan coefficient than would longer term average data. Updated pan evaporation data were obtained from NOAA's Climatological Data Sheets. To evaluate possible trends, pan evaporation data were plotted graphically, and regression analysis was used to determine whether the regression coefficient (i.e., the slope) of the best-fit linear model was significantly different from zero. All statistical analyzes were performed by using the statistical software package StatMost Version 3.6 [19].

8.2.2 REFERENCE EVAPOTRANSPIRATION (ET)

The long-term monthly reference ET was estimated by using the Penman – Monteith equation [10]:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{4}$$

where: ET_0 = ET (mm day^{-1}); Δ = Slope of the vapor pressure curve (kPa°C^{-1}); R_n = Net radiation at the crop surface (MJ m^{-2}day^{-1}); G = Soil heat flux density (MJ m^{-2} day^{-1}); ρa = Mean air density at constant pressure (kg m^{-3}); Cp = Specific heat at constant pressure (MJ kg^{-1}°C^{-1}); e_s–e_a = Vapor pressure deficit (kPa); e_s = Saturation vapor pressure (kPa); e_a = Actual vapor pressure (kPa); r_a = Aerodynamic resistance (s m^{-1}); r_s = The bulk surface resistance (s m^{-1}); λ = Latent heat of vaporization (MJ kg^{-1}); γ = The psychrometric constant (kPa°C^{-1}).

Equation (4) applies specifically to a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m and a solar reflectivity of 0.23. The FAO recommends using the Penman-Monteith method over all other methods even when local data are missing. Studies have shown that using estimation procedures for missing data with the Penman–Monteith equation will generally provide more accurate estimates of ET_O than will other available methods requiring less data input [10].

Of the various climate parameters needed to calculate ET_0 with Eq. (4), only air temperature (T) and wind speed (u) were available for all seven experimental substations in Puerto Rico; however, wind speed was not measured consistently. For example, in the case of Lajas, wind speed data were available only during the following years: 1963, 1966 to 1969, 1971 to 1978, 1983 to 1985 and 1987 to 1990. Wind speeds were measured at 0.33 m above the ground and therefore needed to be adjusted to the two-meter value (u_2) using the logarithmic adjustment equation presented by Allen et al. [10].

Relative humidity (needed to estimate actual vapor pressure) is measured at the substations by using a sling psychrometer, but only once in 24 h; thus, these data do not represent daily average values. Therefore, the actual vapor pressure was derived from the dew point temperature (Tdew). Long-term average dew point temperature was estimated from the minimum air temperature plus or minus a temperature correction factor. Temperature correction factors, developed for the six NOAA Climate Divisions for Puerto Rico (See Fig. 1), were obtained previously from Harmsen et al. [20]. Net radiation was estimated from solar radiation (Rs.) by using the method presented by Allen et al. [10] involving the use of a simple equation for island settings (elevations < 100 m) or by the Hargreaves radiation equation (elevations > 100 m), based on air temperature differences. Pan coefficients were estimated from Eq. (3). Statistical comparisons were made between Kp from average pan evaporation data collected between 1960 and 1980 and Kp from data collected between 1981 and 2000.

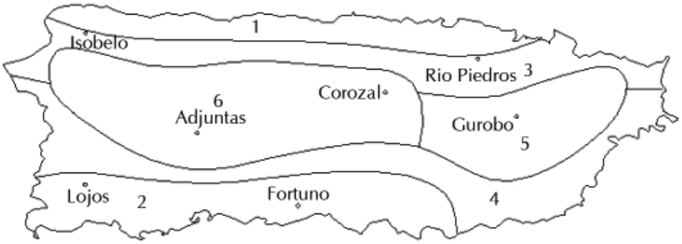

FIGURE 1 MUPR Agricultural Experiment Substation locations and NOAA climate divisions of Puerto Rico: 1, North Coastal; 2, South Coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6, Western Interior.

8.3 RESULTS AND DISCUSSION

Figure 2 shows the monthly average pan evaporation for the seven experimental substations, based on approximately 40 years of pan evaporation data. Note that pan evaporation was highest for Fortuna and lowest for Adjuntas for most months of the year. Figures 3, 4 and 5 show the average monthly pan evaporation with time. Figure 3 shows the sites that had significant decreasing pan evaporation with time; Figure 4 shows the sites that had significant increasing pan evaporation with time; and Fig. 5 shows the sites that had no significant increase or decrease in pan evaporation with time. Increases and decreases, as expressed by the linear regression coefficients, associated with Figs. 3 and 4, were significant at or below the 5% probability level.

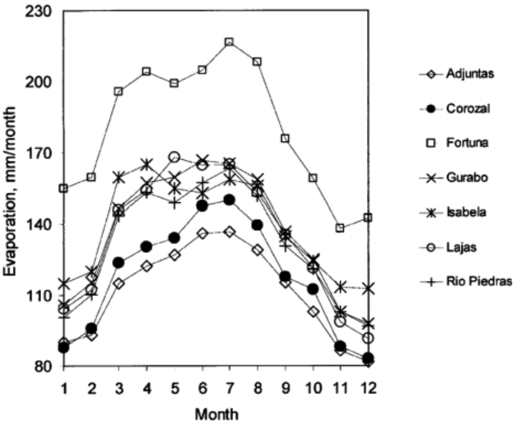

FIGURE 2 Long-term average monthly pan evaporation for the seven substations in Puerto Rico.

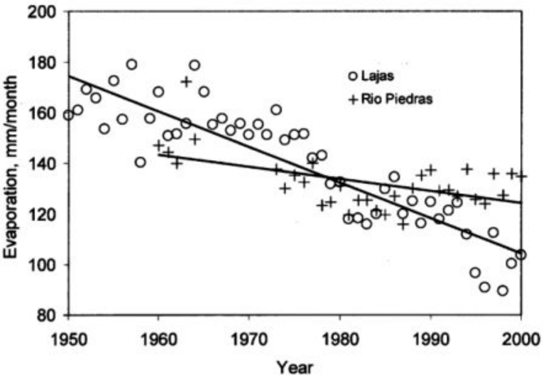

FIGURE 3 Average monthly pan evaporation with time at Lajas and Río Piedras, Puerto Rico.

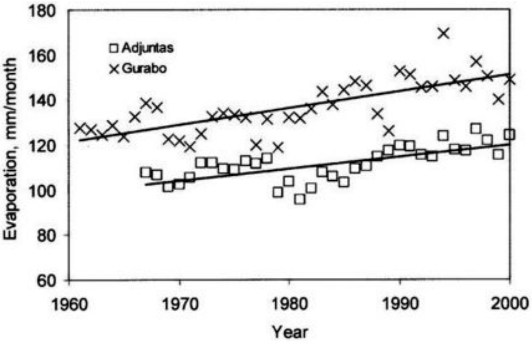

FIGURE 4 Average monthly pan evaporation with time at Adjuntas and Gurabo, Puerto Rico.

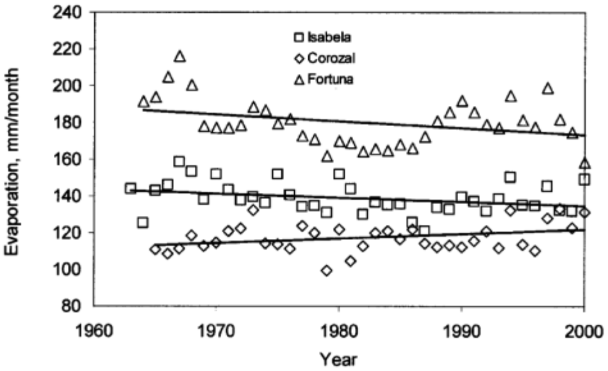

FIGURE 5 Average monthly pan evaporation with time at Corozal, Isabela and Fortuna, Puerto Rico.

TABLE 1 Linear regression results for the pan evaporation data from the seven substations.

Station	Latitude	Elevation (m)	NOAA Climate Division	Regression Coefficient (slope of line)	r^2	Significant at the 5% level	Trend
Gurabo	18°15'N	48	5	0.029	0.55	Yes	Increasing
Adjuntas	18°11'N	549	6	0.021	0.47	Yes	Increasing
Corozal	18°20'N	195	6	0.010	0.11	No	Increasing
Isabela	18°28'N	126	3	–0.008	0.08	No	Decreasing
Fortuna	18°01'N	21	2	–0.015	0.10	No	Decreasing
Río Piedras	18°24'N	100	3	–0.019	0.28	Yes	Decreasing
Lajas	18°03'N	27	2	–0.055	0.81	Yes	Decreasing

Regression coefficients associated with the linear regression lines shown in Fig. 5 were not statistically significant. The linear regression results are summarized in Table 1. Following noteworthy results can be summarized from Figs. 3 to 5 and Table 1:

- Lajas had the greatest decrease in the average monthly pan evaporation: 1.4 mm per month (average) per year. This amount is equivalent to a drop of 56 mm per month in the pan evaporation in 40 years. This is a very significant reduction considering that the average pan evaporation in 2002 was only 103.9 mm per month in Lajas. It will be interesting to see whether this trend continues in the future or whether it begins to level off.

- The decreasing pan evaporation observed at Lajas and Río Piedras is consistent with the observed decreasing trend globally.
- Pan evaporation at two sites (Adjuntas and Gurabo) increased. These results are contrary to the observed global decrease in pan evaporation. Both sites are located in humid areas. It is interesting to note that Adjuntas is at a relatively high elevation (549 m), whereas Gurabo is at a relatively low elevation (48 m).

Figure 6 shows the estimated long-term average monthly reference ET for each substation. As with pan evaporation (Fig. 2), Fortuna shows the highest ET_o, and Adjuntas shows the lowest values during most of the year. However, ET_o for Lajas was essentially identical to that of Fortuna, whereas the Lajas pan evaporation (Fig. 2) was lower than that of Fortuna. There are two possible explanations for this:

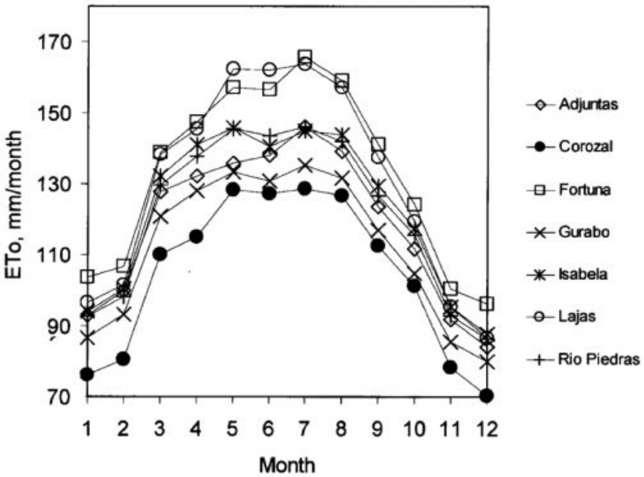

FIGURE 6 Long-term average monthly reference ET for the seven substations.

1. The local environment may have gradually changed in the vicinity of the evaporation tank in Lajas. For example, installation of new structures, establishment of trees, or relocation of the evaporation tank. Development of the Lajas Valley may also have influenced a change in pan evaporation at the substation.
2. Pan evaporation and reference ET may not be directly comparable. Allen et al. [10] list the following factors that may cause significant differences in loss of water from a water surface and from a cropped surface:

- Reflection of solar radiation from the water surface might be different from the assumed 23% for the grass reference surface.
- Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime.
- There are differences in turbulence, temperature and humidity of the air immediately above the respective surfaces.
- Heat transfer occurring through the sides of the pan can affect the energy balance.

Monthly average pan coefficients were estimated for each month at each of the seven experimental substations on the basis of pan evaporation data from 1960 (approximate) to 1980 and from 1981 to 2000. (For convenience, hereafter the earlier period will be referred to as 1960 to 1980 and the latter period as 1981).

A Student t-Test analysis indicated that the difference between the mean K_p based on the two time periods was highly significant. Table 2 presents the results of the t-Test. The difference in the mean K_p for all locations for the two time periods was 0.15. The average K_p equaled 0.75 for 1960 to 1980 and 0.91 for 1981 to 2000. A comparison was also made between the K_p values of Goyal and González [11] and the 1981 to 2000 K_p values from this study (See Table 5).

A significant difference was observed between the two datasets at the 0.01% probability level, with a difference in the mean K_p of 0.08. The average value of the K_p of Goyal and González [11] was 0.82.

To understand whether the difference in the mean pan evaporation between the two periods [1960 to 1980 and 1981 to 2000] is significant on a practical level (independent of statistical significance), Eq. (2) was used to estimate the difference in the reference ET for a given amount of pan evaporation. Suppose the annual pan evaporation for a certain location was 1500 mm; then the K_p difference of 0.15 is equivalent to [0.15 × 1500 mm] = 225 mm in the annual reference ET. For an average farm size of 18 hectares in Puerto Rico [21], this is equivalent to 40,500 m^3 of water (or 10.7 million gallons).

Because there was a significant difference between the mean K_p for the last 20 years and that of the subsequent 20-year period, this study recommends that crop water use estimates use K_p values from the most recent 20 years. Tables 3, 4 and 5 give the average monthly reference ET, pan evaporation and pan coefficients, respectively.

The methodologies used in this paper can be considered sufficiently general and therefore could be applied at other locations throughout the world.

TABLE 2 Results of a Student t-test comparing monthly pan coefficients based on pan evaporation data from 1960 (approximate) to 1980 and 1981 to 2000.

t-Test Analysis Results

Confidence Level = 0.95 (Two Tail Test)

1960 to 1981 vs. 1981 to 2000:

	1960 to 1981	1981 to 2000		
Sample Size	84	84		
Number of Missing	0	0		
Minimum	0.5694	0.6732		
Maximum	1.1579	1.2473		
Standard Deviation	0.1398	0.1319		
Standard Error	0.0153	0.0144		
Coeff of Variation	18.5924	14.5441		
Mean	0.7520	0.9067	Difference = 0.1547	
Variance	0.0196	0.0174	Ratio = 1.1242	
Paired	t-Value	Probability	DF	Critical t-Value
	9.5097	6.24516E-015	83	1.9890

Co-Variance = 0.0074, Std Deviation= 0.0163

TABLE 3 Long-term average reference ET (ET_o) in mm/month for the seven experimental substations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adjuntas	93	100	128	132	136	138	146	139	124	112	92	84
Corozal	76	80	110	115	128	127	129	127	112	101	78	70
Fortuna	104	107	139	147	157	156	166	159	141	124	100	96
Gurabo	87	93	121	128	133	131	135	132	117	105	85	80
Isabela	94	100	132	141	146	141	145	144	129	118	95	88
Lajas	97	102	138	145	162	162	164	157	137	120	95	87
Río Piedras	93	98	130	138	145	143	146	142	127	116	93	86
Average	93	100	128	132	136	138	146	139	124	112	92	84

TABLE 4 Average monthly pan evaporation (E_{pan}) based on 1981 through 2000 pan evaporation data for seven experimental substations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adjuntas	93	100	128	132	136	138	146	139	124	112	92	84
Corozal	76	80	110	115	128	127	129	127	112	101	78	70
Fortuna	104	107	139	147	157	156	166	159	141	124	100	96
Gurabo	87	93	121	128	133	131	135	132	117	105	85	80
Isabela	94	100	132	141	146	141	145	144	129	118	95	88
Lajas	97	102	138	145	162	162	164	157	137	120	95	87
Río Piedras	93	98	130	138	145	143	146	142	127	116	93	86
Average	93	100	128	132	136	138	146	139	124	112	92	84

TABLE 5 Pan Coefficients (K_P) based on 1981 through 2000 pan evaporation data, for seven experimental substations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adjuntas	1.02	1.05	1.05	1.03	1.04	0.97	1.04	1.02	1.00	1.00	0.99	0.98
Corozal	0.84	0.80	0.85	0.85	0.94	0.86	0.85	0.87	0.92	0.88	0.87	0.81
Fortuna	0.68	0.67	0.72	0.74	0.81	0.78	0.78	0.76	0.80	0.77	0.72	0.69
Gurabo	0.74	0.77	0.78	0.77	0.80	0.74	0.77	0.77	0.80	0.79	0.77	0.76
Isabela	0.84	0.84	0.86	0.86	0.95	0.92	0.89	0.91	0.97	0.93	0.88	0.82
Lajas	1.08	1.10	1.15	1.14	1.17	1.22	1.25	1.16	1.02	1.10	1.08	1.07
Río Piedras	0.95	0.90	0.92	0.90	1.00	0.95	0.91	0.96	0.97	0.95	0.93	0.92

8.4 SUMMARY

The objective of the research in this chapter was to update pan evaporation coefficient (K_p) values for the seven University of Puerto Rico – Agricultural Experimental Substations, based on updated pan evaporation data and the Penman-Monteith reference ET. Therefore, historical pan evaporation data for seven experimental substations were evaluated to determine whether increasing or decreasing trends existed. Significant decreasing pan evaporation was observed at Lajas and

Río Piedras. Significant increasing pan evaporation was observed at Gurabo and Adjuntas. No significant trends were observed at Fortuna, Isabela or Corozal. A significant difference was found to exist between the mean K_p calculated with pan evaporation data from 1960 to 1980 and that with data from 1981 to 2000. An updated table of monthly average pan coefficients is provided (Table 5) that can be used to estimate ET_{pan} for the seven substations.

Additional research is needed to help explain the significant reduction in the pan evaporation observed at Lajas as compared to that of other locations. The K_p data presented in Table 5 are valid for data obtained from the pan located at the Lajas Experiment Station. However, if pan evaporation is obtained from another source in the vicinity of Lajas, these data should be compared with the experiment station evaporation data to verify consistency between the two data sources. If large differences exist, then an adjustment should be made in the Lajas K_p values presented in Table 5. Further research is also needed to investigate the reason for the observed variations in the trends in pan evaporation (i.e., increasing at some locations and decreasing at other locations).

KEYWORDS

- **Blaney – Criddle method**
- **Crop water use**
- **Reference Evapotranspiration**
- **Evapotranspiration**
- **Food and Agriculture Organization, FAO**
- **Pan coefficient**
- **Pan evaporation**
- **Penman – Monteith method**
- **Puerto Rico**
- **Regression analysis**
- **Water management**

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CHAPTER 9

ALTERNATE PARTIAL ROOT-ZONE SURFACE DRIP IRRIGATION FOR TOMATO: HYDRUS-2D

TAREK SELIM ABOU LILA, RONNY BERNDTSSON,
MAGNUS PERSSON, and MOHAMED SOMAIDA

CONTENTS

Modified and printed from, "Assessment of interplant emitter distances and effects of irrigation water salinity on APRDI using HYDRUS-2D by Abou Lila Tarek Selim, Ronny Berndtsson, Magnus Persson and Mohamed Somaida, (2011). European Journal of Scientific Research, 58:266–277.

9.1 INTRODUCTION

Due to population growth, the demand on water resources increases. One option for coping with this is to minimize the use of irrigation practices that are wasteful in their water consumption as well as using brackish water as alternative irrigation water resources especially in arid and semiarid areas. Egypt is considered one of the water scarce arid countries in the Middle East. Water scarcity is forcing Egypt to use brackish water as an alternative source for crop irrigation. The El-Salam Canal is one of the five mega irrigation projects in Egypt and used to irrigate 2.6 billion m^2 of new reclaimed areas in the Eastern Delta and North Sinai. Canal water is a mixture of 1.9 billion m^3/year of drainage water and 2.1 billion m^3/year of fresh water from the river Nile. Recently in Egypt, modern irrigation techniques are being called on to produce more food with less irrigation water. Conventional deficit irrigation (CDI), considering crop tolerance to water stress during its growing stages, is one approach that can diminish water use without distinct yield reduction [15]. Alternate partial root irrigation (APRI) is another water-saving irrigation technique in which irrigation amount can be reduced without significant reduction in crop yield [16]. In this technique, approximately half of the root system is always exposed to drying soil while the remaining half is irrigated as in full irrigation. The wetted and dry sides of the root system are alternated with a frequency according to soil water balance and crop water requirement [13]. Zhang et al. [26] demonstrated that plants with two halves of their roots under alternating drying and wetting cycles developed normally with reduced stomatal opening and without considerable leaf water deficit. Laboratory studies conducted by many researchers [18, 26, 27, 28] manifested that stomatal regulation is managed through chemical signals from plant roots to leaves. These signals depended mainly on the development of abscisic acid (ABA) in plant roots in the drying soil. ABA transported through the transpiration streams and the augment of ABA concentration in plant xylem causes closure of stomata. Thereby, the luxury transpiration was reduced without any effect on photosynthesis [11, 22].

Many field experiments have been conducted to study the behavior, yield, and water use efficiency of different plant species under APRI and the effectiveness of APRI over other irrigation methods as a water-saving technique. Kang et al. [13] compared three furrow irrigation techniques (alternate, fixed, and conventional furrow irrigation) for growing maize in an arid area. They concluded that root development was significantly improved by alternate furrow irrigation. Primary root numbers, root density, and total root dry weight were higher than in other techniques. Moreover, alternate furrow irrigation sustained high grain yield with up to 50% reduction in the amount of irrigation.

Kirda et al. [17] assessed the crop yield differences under CDI, APRI, and full irrigation for different crops (e.g., cotton, tomato, and pepper) in a heavy clay soil under Mediterranean climate conditions. They demonstrated that there was no significant difference in tomato yield between the APRI and full irrigation but the APRI had about 10% additional tomato yield over CDI. On the other hand, the water use efficiency was approximately the same in all irrigation methods in pepper crop. They also concluded that no reduction in seed yield for cotton was observed with deficit treatments compared with full irrigation. The effect of conventional drip irrigation and alternate partial root-zone subsurface drip irrigation on potato yield and irrigation water use efficiency was investigated by Huang et al. [10]. They concluded that no significant difference in potato yield occurred in the two irrigation methods while the alternate partial root-zone subsurface drip irrigation increased irrigation water use efficiency by 27.5%. Kaman et al. [12] investigated soil salinization under APRI and compared it with conventional drip irrigation for growing tomato in a greenhouse and with conventional furrow irrigation when growing cotton in the field. They revealed that differences in salt accumulation were limited to the top 30 cm of soil profile. In addition, the soil salinity at harvest under the APRI was 35% higher than full irrigation but soil salinity levels remained below the salt tolerance threshold levels for both crops. Wang et al. [25] investigated the relation between soil water content and microbial population and distribution responses under three irrigation methods (APRI, conventional irrigation, and fixed partial root-zone irrigation). The experiments were carried out in a greenhouse with loam soil. They concluded that APRI maintained the best aeration and soil moisture condition and improved the activities of soil microorganisms as compared to other irrigation methods.

Numerical modeling is considered inexpensive, fast, and labor saving tool for simulating water and solute dynamics under different irrigation techniques. Skaggs et al. [21] and Gärdenäs et al. [7] showed that HYDRUS-2D model can be used as an effective tool for investigating and designing different irrigation management practices. Although few numerical simulation studies focused on soil moisture distribution under APRI [29, 30], simulation of soil salinity distribution under APRI with brackish irrigation water does not appear to have caught researcher's attention so far. Most of the past research related to APRI dealt with the physiology and technical perspective. Therefore, there is a need for more studies focusing on the effect of using brackish water and APRI design aspects on soil moisture and salinity distribution as well as on water balance components.

In the view of the above, this chapter discusses the research results to quantify: 1) the effect of inter plant emitter distance on soil moisture and salinity distribution under APRDI, 2) the effect of irrigation water salinity levels on soil salinity distribution under APRDI, and 3) the possibility of using brackish irrigation water in APRDI. Overall, authors believe that this study provides insights to develop clear guidelines for proper design and management of alternate partial root-zone drip irrigation systems.

9.2 METHODS AND MATERIALS

HYDRUS-2D [20] numerical model was used to study the effects of interplant emitter distance and irrigation water salinity levels on the soil moisture and soil salinity distribution as well as water balance components for tomato under APRDI of growing on loamy sand soil. The software can simulate water, heat, and solute movement in two and three-dimensional variably saturated media. In addition, it can describe a wide range of boundary conditions and soil heterogeneities. Water flow in isotropic variably saturated porous media was described using modified form of Richards' equation incorporating a sink term to account for water uptake by plant roots as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial r}\left(K_r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z} - S \qquad (1)$$

where: θ is volumetric soil water content (L^3L^{-3}), h is the soil water pressure head (L), t is the time (T), r is the lateral coordinate (L), *z* is the vertical coordinate positive downwards (L), K is the unsaturated hydraulic conductivity (LT^{-1}), and S is the sink term accounting for root water uptake (T^{-1}). On the other hand, the solute transport was described using the advection-dispersion Eq. (9) considering advection-dispersion in the liquid phase, as well as diffusion in the gaseous phase.

9.2.1 SDI SYSTEM AND EXPERIMENTAL AREA

In the present study, the simulated APRDI system was set up to irrigate tomato (a typical crop in the study area) through two surface drip lines per tomato row spaced 40, 60, and 80 cm. The distance between emitters was 35 cm and the spacing between tomato rows was 140 cm. El-Salam Canal cultivated land is characterized by low annual rainfall, approximately 150 mm/year, and high annual potential evapotranspiration. Maximum temperatures in the study area during July–August range from 41 to 46 °C and minimum temperature during December–January vary from 8 to 19 °C.

9.2.2 MODELING DOMAIN GEOMETRY

The simulated domain for water flow and solute transport was rectangular, 100 cm deep and 140 cm wide with a tomato plant located in the middle of flow domain and with a trickle emitter placed at soil surface in the location of drip line. The drip line was assumed as a line source with equal flow between emitters [21] and the flux radius was taken equal to 6 cm as neither ponding nor surface runoff was assumed to occur. Unstructured triangular mesh with 3239 2-D elements was used to spatially discretize the transport domain. Mesh refinement was done closer to the soil surface where rapid change in flux occurs. Figure 1 shows a conceptual diagram of the simulation domain.

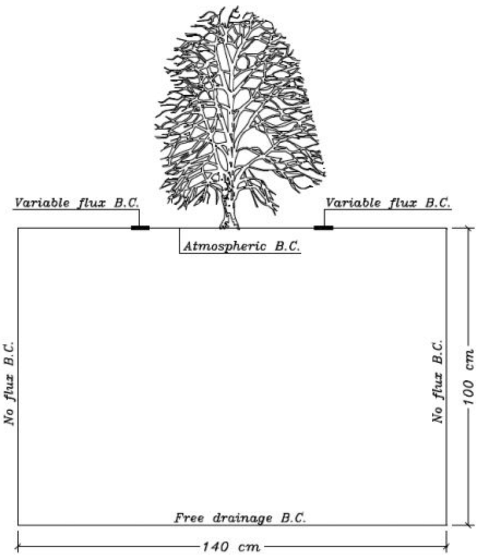

FIGURE 1 Conceptual diagram of simulated area.

9.2.3 BOUNDARY CONDITIONS

No flux was allowed through the vertical sides of the soil domain due to symmetry. A free drainage boundary was set at the bottom boundary because the water table is situated far below the domain of interest (about 1.50 m below the soil surface). Variable flux boundary condition was assumed at the top boundary in the location of trickle emitter during irrigation time and no flux in fallow time. The remaining part of the top boundary was assigned atmospheric boundary condition allowing for crop evapotranspiration (ETc). Crop ETc was calculated with the Penman-Monteith equation for a reference crop (ETo) values obtained from the weather conditions and crop coefficient (Kc) value. ETc was computed from the product of ETo and the crop coefficient (for tomato, Kc = 1.05 from FAO, 5). During simulation, potential evapotranspiration was partitioned into potential evaporation (Ep = 0.05ETc) and potential transpiration (Tp = 0.95ETc).

Bonchela et al. [3] concluded that evaporation from emitter zone in olive orchards with 36% ground cover ranged from 4 to 12%. The effect of saline irrigation water was simulated by assuming a third-type boundary condition at the emitter location and the solute was accompanied with the irrigation water. In this study, the salinity of irrigation water was taken equal to 0, 1.00, and 2.00 dS/m (the salinity of El-Salam Canal water ranges from 1.00 to 2.00 dS/m).

9.2.4 INITIAL CONDITIONS

Uniform initial water content of 0.199 $m^3 m^{-3}$ was set throughout the flow domain and initial solute concentration was set equal to 2.00 dS/m. Soil salinity measurements in El-Salam Canal cultivated land (study area) in previous field experiments were conducted by Abou Lila et al. [1] and they found the soil salinity range of 0.70 to 3.50 dS/m.

TABLE 1 Hydraulic parameters of simulated soil.

Soil Type	θr	θs	α	n	ks (cm/day)	L
Loamy sand	0.074	0.453	0.045	1.72	288.5	0.5

9.2.5. SOIL PROPERTIES

Soil hydraulic properties used for model execution (Table 1) were estimated using standard laboratory methods (Pressure plate extractor set) for soil samples collected from El-Salam Canal cultivated land. The soil hydraulic properties in HYDRUS-2D are based on the van Genuchten-Mualem model [23]:

$$h \begin{cases} \theta_r + \dfrac{\theta_{s-\theta_r}}{\left[1+|\alpha h|^n\right]^m} \text{h}< 0 \\ \\ \theta_s \text{h} \geq 0 \end{cases} \qquad (2)$$

$$K(h) = K_s\, S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad (3)$$

where: θ (h) is the soil water retention (L^3L^{-3}), θ_s is the saturated water content (L^3L^{-3}), θr is the residual water content (L^3L^{-3}), α is related to the inverse of a characteristic pore radius (L^{-1}), l is shape parameter, n is a pore-size distribution index, m = 1–1/n, and ***Se*** is the effective saturation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (4)$$

9.2.6 SOLUTE PARAMETERS

Longitudinal dispersivity (ε_L) was approximated to one-tenth of the profile depth [2, 4]. The transversal dispersivity ε_T was set to = 0.1(ε_L). Adsorption isotherm and molecular diffusion were ignored during simulation. Salinity transport was simulated based on the hypothesis that the solutes were nonreactive and there was neither net solubilization nor dissolution.

9.2.7 ROOT WATER UPTAKE PARAMETERS

Root water uptake has a crucial effect on the spatial distribution of water and soil water salinity in the flow domain. Feddes et al. [6] presented a threshold water stress response function that describes the water uptake from the soil. The following parameters by Feddes et al. [6], model were used in simulation: $P_o = -1$, $P_{opt} = -2$, $P_{2high} = -800$, $P2_{low} = -1500$, $P_3 = -8000$ cm, $r_{2high} = 0.5$ cm.d^{-1}, $r_{2low} = 0.1$ cm d^{-1}. The osmotic effects were included using threshold model [19] with threshold = 2.5 dS.m^{-1} and a slope of 9.9%. The Vrugt model [24] was used to illustrate the root distribution for tomato. The root distribution for tomato crop was set as reported by Hanson et al. [8]. It is worthwhile to observe that the assumed root distribution was used for all simulation scenarios because of the lack of information for root distribution under certain scenarios.

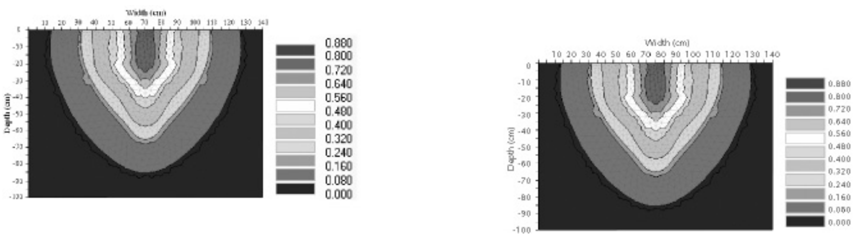

FIGURE 2 Root distribution (percentages of the total roots) used for HYDRUS-2D simulation.

9.2.8 SIMULATION SCENARIOS

Series of simulations were performed including two varying factors; salinity of irrigation water and the interemitter plant distance. Simulations were conducted for loamy sand during a 40-day period (summer season) considering three IPED (20, 30, and 40 cm) and three irrigation water salinity levels (0, 1, and 2 dS/m). The applied irrigation water was assumed 25% less than conventional surface drip irrigation system. The irrigation period was calculated according to emitter discharge of 1.0 L per hour and crop water requirements. Table 2 shows the different scenarios used in this chapter.

TABLE 2 Simulation scenarios for a sandy loam soil.

Scenario number	Inter-plant emitter distance cm	Salinity of irrigation water dS/m	Irrigation interval (days)	Irrigation period (days)
1	20	0	40	0.115
2	20	1	40	0.115
3	20	2	40	0.115
4	30	0	40	0.115
5	30	1	40	0.115
6	30	2	40	0.115
7	40	0	40	0.115
8	40	1	40	0.115
9	40	2	40	0.115

9.3 RESULTS AND DISCUSSION

9.3.1 WETTING PATTERNS

9.3.1.1 EFFECT OF INTERPLANT EMITTER SPACING ON WATER CONTENT DISTRIBUTION

For all simulation scenarios, at the beginning of each irrigation event, the soil moisture content increased in the region close to the emitter, after that, the wetting front extended laterally and in depth. Figure 3 shows the evolution of the wetting front at three elapsed time periods (after the first two irrigation events and after last irrigation event) for simulation scenarios 1, 4, and 7. It was noted that the size of the wetted zone around the emitter was approximately the same in all simulation scenarios. Due to gravity, the vertical spread of the water was larger than the lateral. Wetted radius at soil surface was about 20 cm while wetted depth was about 25 cm directly below the emitter. Therefore, for different IPED, approximately half of plant root system was always exposed to drying cycle.

For all simulation scenarios, just before the next irrigation event, substantial reduction in moisture content occurred around the emitter because of the water uptake by the plant roots. Similar wetting and drying cycles occurred during the entire simulation period. Figure 3 also manifests that after the end of last irrigation event, the water content values in the zone of maximum root density especially beneath the plant trunk were higher in case of short IPED (20 cm) than long IPED (30 and 40 cm). This is due to the limited lateral extension of the wetted area around emitter in case of long IPED.

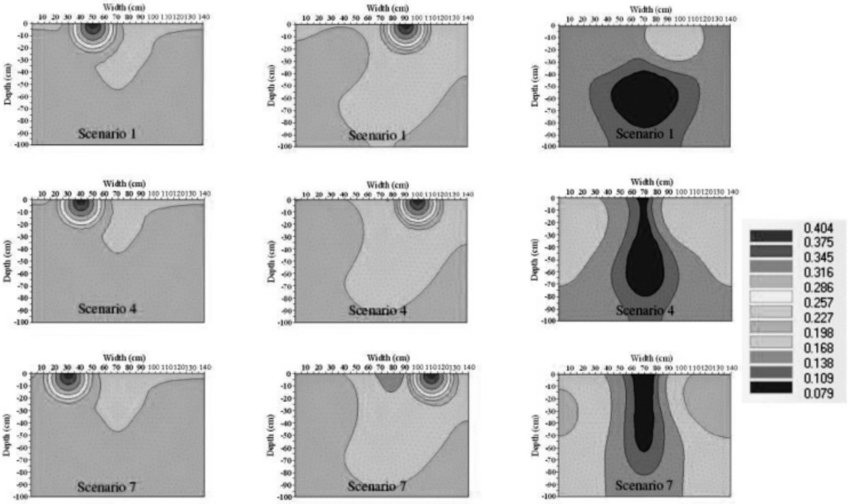

FIGURE 3 Simulated water content distribution around the emitter [$m^3.m^{-3}$] (left column: after first irrigation event, middle column: after second irrigation event, and right column: after last irrigation event).

Figure 4 visualizes the progress of the water content for an observation point at the soil surface 10 cm laterally from the plant trunk for simulation scenarios 1, 4, and 7. The water content fluctuations are more pronounced in case of short IPED. The water content reached its highest value (0.30 $m^3 m^{-3}$) due to the large amount of water added to the soil at the end of each irrigation event, thereafter, it decreased to its lowest value (0.14 $m^3 m^{-3}$) due to water extracted by plant roots during the period between the two successive irrigation events. On the other hand, for the longest IPED (40 cm), the fluctuations in water content were less distinct changing from 0.12 to 0.09 $m^3 m^{-3}$ reflecting the limited root water uptake. This is attributed to the limited extension of wetted area that causes limited available amount of water in the zone of maximum root density. Therefore, it is preferable to regulate the IPED according to soil hydraulic properties.

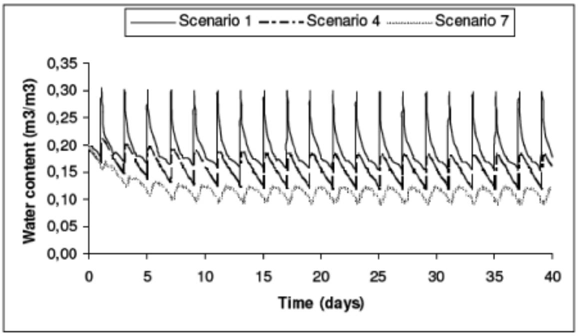

FIGURE 4 Temporal variation in water content at an observation point and 10 cm laterally from the trunk of a plant.

9.3.2 ROOT WATER UPTAKE

9.3.2.1 EFFECTS OF INTERPLANT EMITTER DISTANCE ON ROOT WATER UPTAKE

Figure 5a shows the temporal variation in water extracted by plant roots during the simulation period for simulation scenarios 1, 4, and 7. The Fig. 5a shows that root water uptake rate was higher in case of short IPED compared to the case of long IPED. This is due to the large soil moisture content near the zone of maximum root density for short IPED compared to other cases. And for simulation scenario 7, although the wetting bulb was away from the zone of maximum root density the rate of water extracted by plant root was high at the beginning of simulation period (first 5 days). This is attributed to the high value of antecedent water content (0.199 m3.m^{-3}) that provided more available water at the beginning of simulation period. Thus the antecedent water content value and root distribution play a major role in controlling root water uptake rates. Short IPED is preferable especially for root system with limited lateral extension.

9.3.2.2 EFFECTS OF IRRIGATION WATER SALINITY ON ROOT WATER UPTAKE

The root water uptake rate depends mainly on the soil moisture content in the root zone and the plant salt tolerance. Figure 5b shows the temporal variation in water uptake by plant roots during the simulation period for simulation scenarios 1, 2, and 3. The figure shows that the salinity of irrigation water has an obvious effect on root water uptake rate. As the salinity of irrigation water increased root water uptake rates decreased. For irrigation water salinity of 1 dS/m and 20 cm IPED, the rate of root water uptake decreased from 0.71 to 0.51 cm/day by the end of the simulation period. However, for irrigation water salinity of 2 dS/m, the rate of root water uptake decreased from 0.71 to 0.44 cm/day compared with 0.57 cm/day for the case of nonsaline irrigation water. On the other hand, for irrigation water salinity of 2 dS/m, the root water uptake rate reached 0.40 and 0.37 cm/day by the end of the simulation period for 30 and 40 cm IPED, respectively, (results not shown). The lower values of root water uptake rate were attributed to the high salinity values in root zone that in some parts exceeded the crop salinity tolerance threshold levels. Therefore, short IPED is more suitable in APRDI when using brackish irrigation water taking into account the crop salinity tolerance.

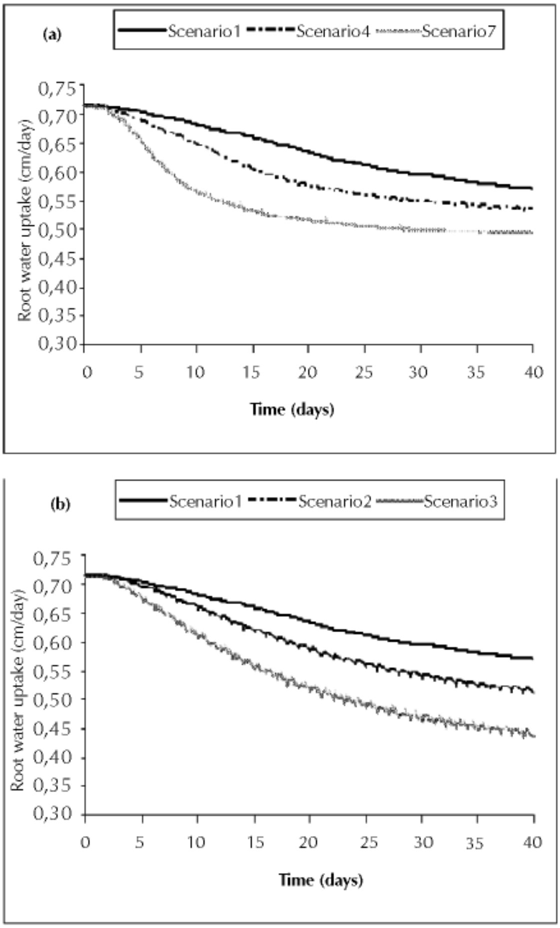

FIGURE 5 Temporal variation in root water uptake: a) scenarios 1, 4, and 7; and b) scenarios 1, 2, and 3.

9.3.3. SOIL WATER SALINITY

Excess salinity in the root zone generally has a harmful effect on plant growth since it causes reduction in transpiration and growth rates. At the end of the first irrigation event in all scenarios, substantial salt leaching occurred near the emitter. Soil salinity decreased to levels lower than initial values near the emitter and increased with distance from the emitter in both lateral and vertical direction. Figure 6 shows the salinity distribution at the end of the simulation period at the soil surface for all simulation scenarios. It was noted that for all simulation scenarios, the soil salinity reached its highest values in the middle of the flow domain (at the location of plant) followed by the edges of the flow domains except in the case of 20 cm IPED with nonsaline irrigation water. Therefore, APRDI with short IPED is recommended when using nonsaline irrigation water. This will reduce the harmful effect of initially saline soil on seed germination. Figure 6 shows also that the effect of using brackish irrigation water was less pronounced in case of 20 cm as compared to 30 and 40 cm IPED, respectively. Nevertheless, soil salinity levels at the middle of the flow domain in case of 20 cm IPED with irrigation water salinity = 2 dS/m was approximately the same as in case of 30 cm IPED with nonsaline irrigation water. Therefore, the IPED has a great impact on salinity values at soil surface especially at the location of plant trunk. Using brackish irrigation water in case of long IPED increased significantly the soil salinity at the soil surface especially at the location of plant trunk that may affect the seed germination. Periodic leaching is necessary to remove the salt accumulated near the soil surface when using brackish irrigation water especially for long IPED.

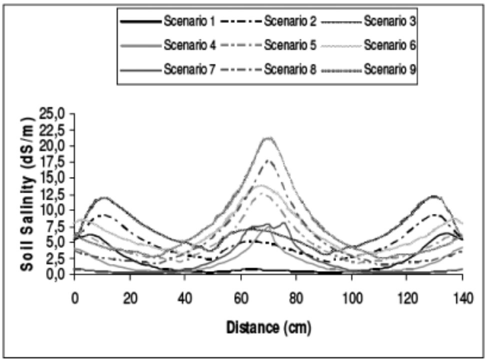

FIGURE 6 Soil salinity distribution along soil surface.

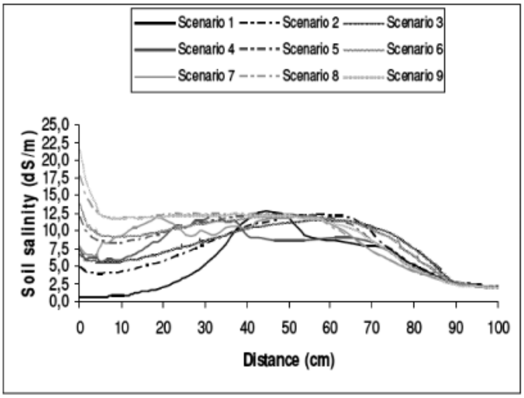

FIGURE 7 Soil salinity distribution along vertical section across the plane of symmetry of flow domain.

Figure 7 shows the salinity distribution by the end of the simulation period along a vertical section across the plane of symmetry of flow domain for all simulation scenarios. It was noted that for 20 cm IPED, soil salinity reached its highest levels in the region located between the 40 and 65 cm depths. This is attributed to the relatively high initial soil salinity (2 dS/m) and the limited vertical extension of the wetting bulb. On the other hand, for 30 and 40 cm IPED, soil salinity reached its highest values at the top soil layer. Although long IPED shows higher salinity levels at the soil surface, soil salinity was approximately the same in the region between the 40 and 65 cm depths for both short and long IPED. Using long IPED with brackish irrigation water in APRDI is not suitable for plants with shallow root system. However, short IPED is more suitable for plants with shallow root system even when using brackish irrigation water as compared to plants with deep root system taking into consideration crop salinity tolerance.

9.3.4 WATER BALANCE

Water balance for all simulation scenarios is shown in Table 3. Water balance was expressed in percent of total applied water during the simulation period. Soil evaporation was approximately the same in all simulation scenarios. In addition, plant roots extracted more than 85% of the applied irrigation water. Consequently, most of the applied irrigation water was effectively used through the root system. Maximum root water uptake occurred in simulation scenario 1.

TABLE 3 Water balance components in different simulation scenarios in percent of total applied water.

Scenario number	Root water uptake	Drainage	Soil evaporation	Root zone storage
1	113.12	7.44	6.08	- 26.64
2	106.46	7.56	6.09	- 20.11
3	96.65	8.17	6.09	- 10.90
4	106.03	8.65	6.03	- 20.71
5	99.32	8.90	6.09	- 14.30
6	90.87	9.64	6.07	- 6.58
7	97.20	11.94	5.54	- 14.68
8	91.93	12.26	5.88	- 10.07
9	85.04	13.09	5.96	- 4.10

IPED played a major role in controlling root water uptake. Although the applied water was less than crop ET_{pot}, deep percolation below the root zone occurred. Maximum drainage took place in simulation scenario 9. This is due to the higher salinity values in the zone of maximum root density that reduced the amount of water extracted by plant roots. In contrast, minimum drainage occurred during the 20 cm IPED scenarios. Using brackish irrigation water had insignificant effect on drainage in case of short IPED. Therefore, short IPED with or without brackish irrigation water is preferable to reduce groundwater contamination risk. It is worth noting that the root zone storage values were negative in all simulation scenarios and the root water uptake in some simulation scenarios exceeded the amount of applied irrigation water. This is attributed to the deficit in applied irrigation water and thus the crop is under stress throughout the simulation period. Thereby, the deficit in applied irrigation water was compensated by soil water contribution. Thus, antecedent water content value has a significant effect on the water balance components.

9.4 CONCLUSIONS

Understanding of soil moisture dynamics and salinity distribution is essential when selecting appropriate irrigation method that help saving water without crop yield reduction. In this study, HYDRUS-2D was used to simulate water and salinity movement under APRDI for growing tomato with two varying factors namely, IPED and irrigation water salinity. Simulations were conducted for loamy sand during a 40-day period considering three IPED (20, 30, and 40 cm) and three irrigation water salinity levels (0, 1, and 2 dS/m). The applied irrigation water was assumed 25% less than conventional surface drip irrigation system.

Simulation results revealed that due to the limited extension of wetting bulb, water content in the zone of maximum root density by the end of simulation period was higher in case of short IPED (20 cm) than in long IPED (30 and 40 cm). Thereby, root water uptake rate was higher in case of short IPED. Therefore, it is preferable to regulate the IPED according to soil hydraulic properties and plant root system. IPED shows a great impact on surface soil salinity at plant location when using APRI with nonsaline irrigation water in initially saline soil. Only 20 cm IPED did not show any response to the relatively high initial soil salinity value (2 dS/m). Surface soil salinity was lower than the initial values. Therefore, APRDI with short IPED is recommended when using nonsaline irrigation water in initially saline soil to reduce the salinity effects on seed germination. The effect of irrigation water salinity on root water uptake increased as the IPED increased. As irrigation water salinity increased the root water uptake decreased. Simulation results also showed that the effect of using brackish irrigation water on soil salinity values was less distinct in case of 20 cm compared to 30 and 40 cm IPED, respectively. Nevertheless, soil salinity levels at the middle of the flow domain in case of 20 cm IPED with irrigation water salinity = 2 dS/m was approximately the same as in case of 30 cm IPED with non saline irrigation water. Thus, IPED has a great impact on salinity values at soil surface and plays a major role in controlling root water uptake.

Soil salinity reached its highest values at the top soil layer followed by the soil layer between the 40 and 65 cm depths in case of long IPED (30 and 40 cm). However, highest soil salinity values were between depths 40 and 65 cm in case of 20 cm IPED. Therefore, using long IPED with brackish irrigation water in APRDI is not suitable especially for plants with shallow root systems. However, short IPED can be used for plants with shallow root system even using brackish irrigation water if the crop salinity tolerance is considered.

Water balance calculations revealed that minimum drainage occurred during the 20 cm IPED scenarios. Using short IPED with or without brackish irrigation water in APRI thus can reduce groundwater contamination risk. It was noted also that the deficit in applied irrigation water was compensated by soil water contribution. The antecedent water content value plays a major role in controlling root water uptake rates.

9.5 SUMMARY

Modern irrigation techniques are becoming increasingly important in water-scarce countries. In this study, a two-dimensional water and solute transport model, HYDRUS-2D, was used to assess the impact of interplant emitter distance (IPED) and irrigation water salinity on soil moisture and salinity distribution as well as on water balance components under alternate partial root-zone surface drip irrigation (APRDI) of tomato growing in loamy sand soil. Three IPED (20, 30, and 40 cm) and three irrigation water salinity levels (0, 1, and 2 dS/m) were used to execute different simulation scenarios. Simulation results indicated that the fluctuations in water content within the root zone were more pronounced in case of 20 cm IPED. The root water uptake increased as the IPED decreased. Using brackish irrigation water in APRDI caused significant augmentation in soil salinity in the top soil layer especially at the location of plant. The impact of irrigation water salinity on root water uptake increased as the IPED increased. As irrigation water salinity increased the root water uptake decreased. At plant location, soil salinity reached its highest values at the top soil layer in case of 30 and 40 cm IPED with brackish irrigation water. However, high soil salinity values were observed between the 40 and 65 cm depths in case of 20 cm IPED. Based on the results, it appears that APRDI with nonsaline irrigation water is more effective with short IPED considering that approximately half of the root system was exposed to drying cycle. In addition, short IPED is recommended in APRDI when using brackish irrigation water especially for plants with shallow root system taking into account crop salinity tolerance.

KEYWORDS

- **abscisic acid**
- **Alternate partial root-zone surface drip irrigation**
- **Alternate partial root-zone irrigation**
- **Brackish irrigation water**
- **Brackish water**
- **Conventional deficit irrigation**
- **Egypt**
- **El-Salam Canal, Egypt**
- **Hydraulic conductivity**
- **HYDRUS-2D**

- **Inter-plant emitter distance**
- **Irrigation water salinity**
- **Lund University**
- **North Sinai**
- **Penman-Monteith**
- **Potential evapotranspiration**
- **Root zone**
- **SDI, Subsurface drip irrigation**
- **Soil depth**
- **Soil moisture**
- **Soil salinity**
- **Surface drip irrigation**
- **Water balance**
- **Xylem**

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CHAPTER 10

SOIL MOISTURE DISTRIBUTION UNDER MICRO IRRIGATION

MUKESH KUMAR

CONTENTS

10.1 INTRODUCTION

Water is an important or perhaps the most important natural resource for survival of life on the earth. Geographical area of India is 3.29 million km^2, which is only 2.4% of total geographical area of the world and has only 4% share of the world fresh water to support over 16% of the world population. India receives annual average rainfall of about 119 cm, which is highly variable temporally and spatially. Maximum rainfall received during three to four monsoon months is spatially highly variable. The areas receiving heavy rainfall during monsoon months invariably face water scarcity during the nonrainy season every year. Therefore, it is absolutely essential that every drop of water is conserved and efficiently used for long-term sustainability of scarce water resource for survival of mankind.

Agriculture sector is the major consumer of water but its share is declining due to its increasing demand for industrial and urban sectors due to ever growing population. Consequently the share of water for agriculture is expected to reduce from the present 85 to 69% by 2025 [8]. Irrigation, one of the most important agricultural operations performed in crop production consumes around 70% of the total available and usable water resources. There is a considerable scope to increase the water use efficiency and agricultural productivity. Therefore, it is of paramount importance to maximize irrigation efficiency in order to use the available water resource for long-term sustainability.

Micro-irrigation is an efficient and advanced irrigation method to enhance water use efficiency (WUE). The highest water application efficiency (WAE) of about 90% may be achieved in drip irrigation methods resulting in 50–100% water saving as compared to surface irrigation. Drip irrigation, which allows frequent application of shallow irrigation depths, helps reduce soil moisture stress and achieve optimum moisture regime leading to higher water use efficiencies and better quality of produce. In depth understanding of water application rate and soil properties, that affect the soil wetting zone developed around the crop root zone, is important for proper designing and management of drip irrigation system [3]. Water application rate is an input factor in determining the soil water content around the dripper and the water uptake pattern by plant [5, 7].

Moisture distribution pattern under a drip source is one of the basic requirements for efficient design of drip irrigation. The extent of soil wetted volume in drip irrigation system determines the optimal amount of water needed to wet the effective root zone. The amount of soil water stored in the root zone can be estimated by the volume of wetted soil. Design parameters, such as percent of root zone to be wetted, spacing and location of drippers, application rates, frequency and amount of irrigation, etc. are governed by the moisture distribution patterns in the soil profile in drip irrigation which need to be thoroughly investigated. The wetting of soil volume is mainly a function of the soil texture, structure, water application rate as well as the quantity of water applied. The depth of the wetted volume should coincide with the depth of the root system while its width is related to the spacing between drippers and drip laterals [10]. Water movement in soil under drip irrigation is influenced by the type of soil and rate of water application [9]. The soil hydraulic properties, number of drippers, dripper discharge and irrigation frequency greatly affect the shape of the wetted volume of soil. The exact wetted volume of the soil needs to be determined for providing the adequate amount of water required by the crop [2, 6].

Therefore, one of the basic needs for an accurate design of drip irrigation system is precise information about the water movement and distribution patterns in soil. Keeping this in view, the present investigation was carried out to study the movement of soil moisture under different drip discharges at different system operating pressures.

10.2 MATERIAL AND METHODS

The experiment was conducted at the research farm of Water Technology Centre, Indian Agricultural Research Institute (IARI), New Delhi, India (Latitude 28°37′30″–28°30′0″ N, Longitude 77°88′45″–77°81′24″ E and amsl 228.61 m) during 2010–2011. The soil samples were collected at 0.0–15.0, 15.0–30.0, 30.0–45.0, 45.0–60.0 cm soil depths below the soil surface. The soil at the experimental area was deep loam soil comprising of 36.9% sand, 41.00% silt and 22.10% clay. The average bulk density, average field capacity and average saturated hydraulic conductivity of soil were 1.60 g cm^{-3}, 0.21 and 1.19 cm h^{-1}, respectively. The average bulk density and saturated hydraulic conductivity were 1.53 g cm^{-3} and 1.67 cm h^{-1}, respectively The physical and chemical properties of the soil samples were also determined and are presented in Table 1.

TABLE 1 Soil characteristics at the experimental site.

Soil depth	Soil comparison			Soil Texture	FC,	PWP	BD	Ks
	Sand	Silt	Clay					
cm	%	%	%	—	%	%	g cm^{-3}	cm h^{-1}
0–15	38.72	40	21.28	Loam	19.8	6.78	1.57	1.65
15–30	36.72	42	21.28	Loam	20.3	7.53	1.65	1.74
30–45	34.72	42	23.28	Loam	22.5	7.60	1.63	1.58
45–60	37.44	40	22.56	Loam	22.8	8.10	1.58	1.74

A field plot of 21 m × 50 m was selected for the experiment. The drip irrigation system was installed with the main station, which includes one hydro cyclone filter (flow rate 27 m^3.h^{-1}, 75 mm size), one sand media filter (flow rate 25 m^3.h^{-1}, 50 mm size, silica sand 0.7 mm) with back flush mechanism. Main lines (PVC pipes of 60 mm diameter) were connected to submains (PVC pipes of 40 mm diameter) for each seven rows plot through a valve tree, ball valve connector and pressure release valve. Flush manifolds were connected at the lower end of each block.

Experiment was designed to determine the soil moisture movement with different dripper discharges under different system operating pressures. The thin-walled drip line (Azud line, 16 mm diameter with 30 cm dripper spacing and dripper discharge of 1.4 l h^{-1}) with 16 mm nominal diameter was used for the experiment. The system was operated at three operating pressures (0.5 kg cm^{-2}, 1.0 kg cm^{-2} and 1.5 kg cm^{-2}). The field was divided into three equal subunits. The discharge rates of the dripper at different system operating pressure were determined by collecting the volume of water in the catch cans for a particular duration.

Wetting patterns in the soil were observed at different system operating pressures (0.5 kg cm^{-2}, 1.0 kg cm^{-2} and 1.5 kg cm^{-2}). The drip irrigation system was operated continuously for one hour duration to supply water at 0.5, 1.0 and 1.5 kg.cm^{-2} operating pressures without crop. Soil moisture content was estimated by gravimetric method by collecting the soil samples in both horizontal (0, 15, 30 cm) and vertical (0–15, 15–30, 30–45 and 45–60 cm) direction across the dripper (Fig. 1) after 1.0 h, 1 day, 3 day and 7 days after the operation of the system.

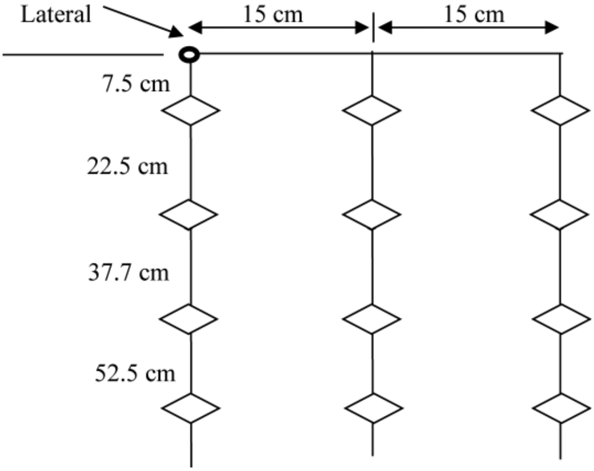

FIGURE 1 Locations of soil samples below the lateral line.

The soil samples were collected with the pipe auger to observe water movement in the soil. The wetting front was recognized by the color difference of the wetted and surrounding soils (Fig. 2). The horizontal and vertical wetting distances on the wetted face were recorded by ordinary meter scale.

FIGURE 2 Soil wetting front under drip irrigation.

10.3 RESULTS AND DISCUSSION

10.3.1 SPATIO-TEMPORAL DISTRIBUTION OF SOIL MOISTURE

Wetting patterns are characterized by the radial distance of the wetting front and the depth from the emitting source. Spatial distribution of soil moisture was measured by collecting the soil samples at different depths (15 cm interval, up to 60 cm) below the dripper and away from the dripper at an interval of 15 cm, up to 30 cm under different system operating pressures. The soil samples were also collected after 1 h, 1, 3 and 7 days of irrigation for temporal soil moisture distribution. The soil samples from different depths were also collected initially for determining the initial soil moisture content.

10.3.2 SPATIAL DISTRIBUTION OF SOIL MOISTURE

The spatial distribution of soil moisture after 1 hr. duration under different system operating pressures were measured and are presented in Fig. 3. The spatial distribution of soil moisture was significantly ($P<0.05$) different at different locations in horizontal and vertical directions from the dripper 1 hr. after the irrigation. However, it was not significantly ($P<0.05$) different at different locations 3 and 7 days after irrigation. The highest value of soil moisture content was observed below the dripper (a saturated condition), which decreased as the distance increased from the dripper. Maximum (25.4%) value of moisture content was observed near the dripper with 1.71 l h^{-1} dripper discharge at operating pressure of 1.5 kg cm^{-2} while minimum value (20.9%) of soil moisture content was observed below the dripper with 0.94 l h^{-1} dripper discharge at system operating pressure of 0.5 kg cm^{-2}.

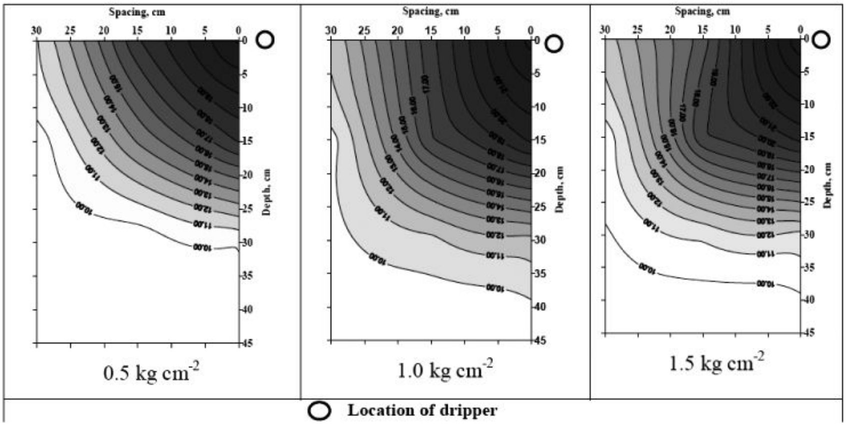

FIGURE 3 Soil moisture distribution 1 h after irrigation at 0.5, 1.0 and 1.5 kg.cm^{-2} system operating pressure.

10.3.3 TEMPORAL DISTRIBUTION OF SOIL MOISTURE

The temporal distribution of soil moisture below 15 and 30 cm away from the dripper after 1, 3 and 7 days at different locations away from the dripper under different system operating pressures are presented in Fig. 4.

It is clear from Fig. 4 that highest value of moisture content was observed below the drippers after 1 h at all operating pressures. Soil moisture moved in the soil 1 day after irrigation and higher values of soil moisture contents were observed at 15–30 cm soil depth. The higher values of soil moisture were present at upper soil layer (15–30 cm soil depth) at higher dripper discharges even after 3 days after irrigation. However, almost similar values of soil moisture were recorded in all the soil layers 7 days after irrigation.

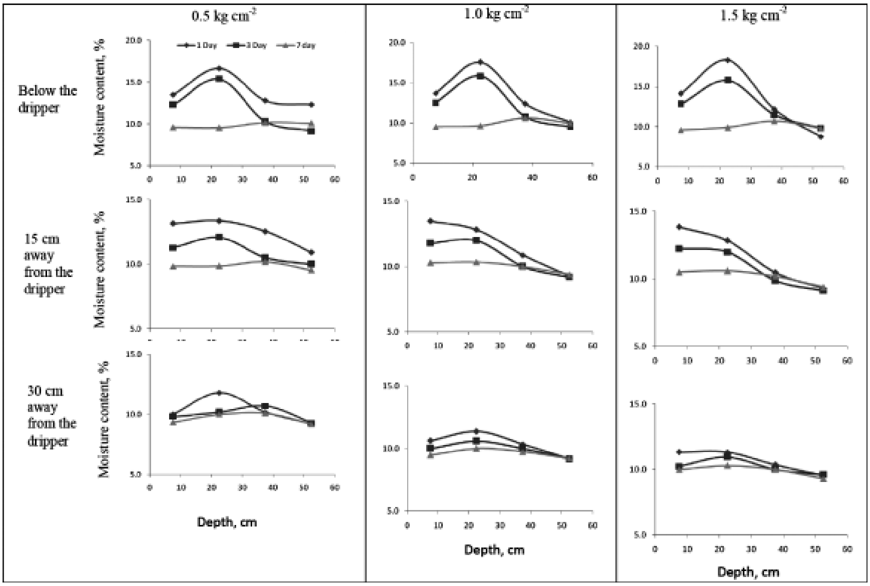

FIGURE 4 Temporal distribution of soil moisture distribution 1, 3 and 7 days after drip irrigation at different locations away from the dripper with different dripper discharges at 0.5, 1.0 and 1.5 kg.cm^{-2} system operating pressures.

Figure 4 shows that wetting front extended up to 15 cm horizontally and 30 cm vertically with 0.94 l h^{-1} dripper discharge at 0.5 kg cm^{-2} system operating pressure whereas, it extended up to about 20 cm horizontally and about 30 cm vertically at with 1.41 l h^{-1} dripper discharge at 1.0 kg cm^{-2} operating pressure after 1 day of irrigation. However, it reached to about 24 cm vertically and 26 cm horizontally with 1.71 l h^{-1} dripper discharge at 1.5 kg cm^{-2} operating pressure after 1 day of irrigation. Similar trends of wetted fronts were reflected from the observations taken after 3 days of irrigation.

At higher discharge rates, horizontal distances of water front were relatively larger as compared to vertical distances which may be attributed to less resistance to water flow in horizontal direction as compared to the vertical and negligible gravity forces for horizontal flow of water. Similar results have been reported in the past [1, 4]. Koon et al. [1] and Badr and Taalab [4] investigated the effect of drip discharge rate on the soil water distribution in soil and reported that increasing in the discharge rate of dripper resulted in an increased lateral movement of water and a decrease in wetted soil depth.

10.4 CONCLUSIONS

Soil moisture distribution in soil is one of the most important parameters for efficient design of drip irrigation system. Extent of wetting front in soil mainly depends on soil texture, structure, initial soil moisture, and dripper discharge. The effect of dripper discharge at different system operating pressures on spatio-temporal soil moisture movement was investigated and following conclusions were drawn based on the present study:

- Highest values of soil moisture contents were observed below the drippers, which decreased as the distance increased in both horizontal and vertical directions from the dripper.
- The value of moisture contents varied significantly ($P<0.05$) under different operating pressures (0.5, 1.0 and 1.5 kg cm^{-2}) and at different locations below and away from the dripper.
- Higher values of moisture content were present just below the dripper. However, it decreased as distance increase in both directions (horizontal and vertical) from the dripper.
- 9.4% and 14.3% higher soil moisture just below the dripper were observed with dripper discharges of 1.41 and 1.71 l h^{-1} at 1.0 and 1.5 kg cm^{-2} system operating pressures as compared to 0.94 l h^{-1} dripper discharge at 0.5 kg cm^{-2} system operating pressure.
- Wetting front extended up to 15 cm horizontally and 30 cm vertically with 0.94 l h^{-1} dripper discharge at 0.5 kg cm^{-2} system operating pressure whereas, it extended up to about 20 cm horizontally and about 30 cm vertically at with 1.41 l h^{-1} dripper discharge 1.0 kg cm^{-2} system operating pressure after 1 day of irrigation. However, it reached to about 24 cm vertically and 26 cm horizontally with 1.71 l h^{-1} dripper discharge at 1.5 kg cm^{-2} system operating pressure after 1 day of irrigation.

10.5 SUMMARY

Drip irrigation is an advanced and efficient method irrigation to use water efficiently. Water distribution in soil is one of the most important parameters to design efficient drip irrigation system. Soil texture, structure, initial soil moisture, and dripper discharge are the important factors on which extent of wetting front in soil mainly depends. An actual field research was conducted to investigate the effect of dripper discharge at different system operating pressures on spatio-temporal soil moisture movement. The value of moisture contents varied significantly ($P<0.05$) under different operating pressures (0.5, 1.0 and 1.5 kg cm^{-2}) and at different locations below and away from the dripper. Highest values of soil moisture contents were observed below the drippers, which decreased as the distance increased in both horizontal and vertical directions from the dripper. The values of moisture content in soil decreased as distance increase in both directions (horizontal and vertical) from the dripper. 9.4% and 14.3% higher values of soil moisture just below the dripper were observed with dripper discharges of 1.41 and 1.71 l h^{-1} at 1.0 and 1.5 kg cm^{-2} system operating pressures as compared to 0.94 l h^{-1} dripper discharge at 0.5 kg cm^{-2} system operating pressure. Wetting front extended up to 15, 20, and 26 cm horizontally and 30, 30, and 24 cm and extended vertically up to 0.94, 1.41, and 1.71 l h^{-1} dripper discharge at 0.5, 1.0, and 1.5 kg cm^{-2} system operating pressure, respectively, after 1 day of irrigation.

KEYWORDS

- **Drip irrigation**
- **Dripper discharge**
- **Dripper spacing**
- **Emission rate**
- **Indian Agricultural Research Institute**
- **Indira Gandhi National Open University**
- **India**
- **Moisture distribution**
- **Operating pressure**
- **Rainfall**
- **Soil water distribution**
- **Spatial distribution**
- **Surface irrigation**
- **Temporal distribution**
- **WAE, water application efficiency**
- **WUE, water use efficiency**
- **Wetting front**
- **World population**

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CHAPTER 11

WEB-BASED IRRIGATION SCHEDULING

ERIC W. HARMSEN

CONTENTS

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11.1 INTRODUCTION

There is antidotal evidence that many farmers in Puerto Rico and the developing countries do not employ scientific methods for scheduling irrigation for their crops. Instead, the pump is turned on for an arbitrary amount of time without knowing whether the amount of water applied is too much or too little. Over application of water can lead to the waste of water, energy, chemicals and money, and also may lead to the contamination of ground and surface waters. Under application of irrigation can lead to reduced crop yields and a loss of revenue to the grower.

There are various approaches for scheduling irrigation. One approach is to supplement rainfall with enough irrigation so that the cumulative rainfall and irrigation, over a specific period of time (e.g., one day, one week, one season), matches the estimated potential evapotranspiration, which is equivalent to the crop water requirement. Potential evapotranspiration (ET_c) can be estimated by the product of a crop coefficient (K_c) and the reference evapotranspiration (ET_o). Traditionally, potential evapotranspiration is derived from pan evaporation data or meteorological data from weather stations. Another approach involves monitoring the soil moisture and applying irrigation sufficient to maintain the soil moisture content within a predetermined range. In this paper we present an approach based on applying irrigation to the crop to meet the crop water requirements (i.e., potential evapotranspiration), but instead of using pan evaporation or meteorological data, we use a remote sensing technique. The advantage of the method is that reference evapotranspiration can be estimated at a 1 km resolution for the entire island each day. If the relatively simple approach presented in this chapter is used it can potentially lead to increased efficiency of water and energy use, and help to reduce crop water stress and losses in crop yields.

In this chapter, a set of steps are provided first to estimate the irrigation requirement for locations within Puerto Rico. A detailed example problem is then given to use of the method.

11.2 METHODS FOR IRRIGATION SCHEDULING

Potential crop evapotranspiration is estimated using Eq. (1):

$$ET_c = K_c\, ET_o \qquad (1)$$

where: ET_c and ET_o were previous defined and K_c is the crop coefficient. Reference evapotranspiration is obtained from the operational water and energy balance algorithm for Puerto Rico (GOES-PRWEB). Each day the operational algorithm produces a suite of 24 hydro-climate variables, which are available to the public on the internet. Estimates of reference evapotranspiration are available for three widely used methods, namely: Penman-Monteith [5], Priestly Taylor [10] and Hargreaves-Samani [5]. Of the three methods, the Penman-Monteith method is generally regarded as superior because it takes into account the major variables which control evapotranspiration [1], and the method has been rigorously validated under diverse conditions throughout the world [9]. The Penman- Monteith method is given by the Eq. (2):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{900}{T+273}\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{2}$$

where: ET_o = ET (mm day^{-1}); Δ = Slope of the vapor pressure curve (kPa°C^{-1}); R_n = Net radiation at the crop surface (MJ $m^{-2}day^{-1}$); G = Soil heat flux density (MJ m^{-2} day^{-1}); ρa = Mean air density at constant pressure (kg m^{-3}); Cp = Specific heat at constant pressure (MJ kg^{-1}°C^{-1}); e_s–e_a = Vapor pressure deficit (kPa); e_s = Saturation vapor pressure (kPa); e_a = Actual vapor pressure (kPa); r_a = Aerodynamic resistance (s m^{-1}); r_s = The bulk surface resistance (s m^{-1}); λ = Latent heat of vaporization (MJ kg^{-1}); γ = The psychrometric constant (kPa°C^{-1}).

Equation (1) applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 $sec.m^1$ and an albedo of 0.23. The crop coefficient, which changes throughout the crop season are shown in Fig. 1. During the initial crop growth stage, the value of the crop coefficient is $K_{c\ ini}$. During the mid season the crop coefficient is $K_{c\ mid}$, and at the end of the late season the crop coefficient is $K_{c\ end}$. The values of $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ can be obtained from published tables [1].

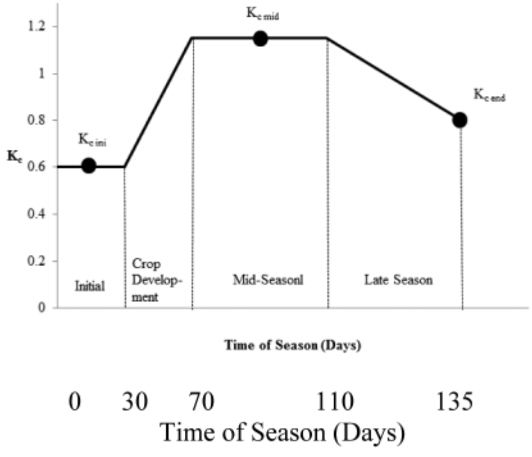

FIGURE 1 Crop Coefficient Curve [1].

11.2.1 STEPS TO ESTIMATE IRRIGATION REQUIREMENT

Step 1. Create an evapotranspiration crop coefficient curve for the crop. The following link to the Food and Agriculture Organization (FAO) Document No. 56 [1] provides tables of crop stage growth (Table 11) and K_c values (Table 12) for a large number of crops: http://www.fao.org/docrep/X0490E/x0490e00.htm. The K_c curve should look like Fig. 1 when step 1 is finished. Note that crop coefficient curves can also be created by using computer programs such as PRET [8] or CropWat [3].

Step 2. Go to the following website address to obtain the appropriate ET_o map(s) for the specific location: http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/reference_ET/. Note that if you are irrigating every day, then you need only to obtain the ET_o for yesterday's date. If, however, one is irrigating once per week, for example, then one will need to obtain the ET_o values from the maps for the previous week. In this latter example, one will need to sum up the daily values of ET_o to obtain a value of the weekly ET_o.

Step 3. From the K_c curve obtained in Step 1, determine a representative value of K_c for the current growth stage of the crop.

Step 4. Estimate the crop water requirement (crop evapotranspiration) using Eq. (1): $ET_c = K_c \times ET_o$.

Step 5. Estimate the required amount of irrigation in depth units: Irrigation = $[ET_c - \text{Rainfall}]$. If the estimated Irrigation is negative, then one does not need to irrigate.

It is recommended that rainfall be measured on the farm with a rain gauge, however, if measured rainfall is not available, the approximate value of the rainfall (derived from NEXRAD radar) can be obtained at the following website: http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/rainfall/. It will also be necessary to measure the irrigation volume. A digital or mechanical flow meter, which measures the cumulative volume in gallons, is recommended.

The irrigation scheduling approach described above is based on various simplifying assumptions (e.g., surface runoff and deep percolation are ignored). The FAO [1] has suggested corrections to $K_{c\ ini}$ for time interval between wetting events, evaporative power of the atmosphere and magnitude of the wetting events, and corrections to K_c mid and K_c end for air humidity, crop height and wind speed; however, these corrections have been ignored in order to preserve simplicity in the approach presented above. Despite the simplifying assumptions, the approach should significantly improve water management on a farm if currently there is no irrigation scheduling method being used.

11.3 DETAILED EXAMPLE PROBLEM

A detailed example problem is presented here to illustrate the use of the proposed methodology. In this problem, we will determine the irrigation requirement for the 5 day period [February 15–19, 2012] for a tomato crop being grown in Juana Diaz, Puerto Rico, USA. Table 1 summarizes the information used in the example problem. Table 2 provides the important web addresses necessary for obtaining data for use in the example problem.

Step 1: With the information in Table 1, it is now possible to construct the crop coefficient curve by consulting the FAO Document No. 56, Table 11. (Lengths of crop development stages for various planting periods and climatic regions) and Table 12 (Single time-averaged crop coefficients…). FAO Document No. 56 is available online at the web address given in Table 2. Table 3 summarizes the crop stage and crop coefficient information. The crop coefficient curve constructed from the data in Table 2 is shown in Fig. 2. The approximate average crop coefficient for February 15–19 (day of season 46–50) is approximately 0.85.

TABLE 1 Information for the example problem in this chapter.

Location	**Juana Diaz–Puerto Rico**
Site Latitude	18.02 degrees N
Site Longitude	66.52 degrees W
Site Elevation above sea level	21 m
Crop	Tomato
Planting Date	1–Jan–12
Rainfall Information	A rain gauge is not available on or near the farm
Type of irrigation	Drip
Approximate wetted area of the field	50%
Irrigation system efficiency	85%
Field size	10 acres
Pump capacity	300 gpm

TABLE 2 Web addresses used to obtain information for solving the example problem in this chapter.

Length of Growth Stages (Table 11) and Crop Coefficients (Table 12)	http://www.fao.org/docrep/X0490E/x0490e00.htm
Daily Reference ET Results for Puerto Rico*	http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/reference_ET/
Daily NEXRAD Rainfall For Puerto Rico	http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/rainfall/

*The web subdirectory contains Penman-Monteith, Hargreaves-Samani and Priestly Taylor ET_o data.

Table 3 Crop growth stage lengths and crop coefficient data for the example problem in this chapter (See Fig. 2).

Initial crop growth stage	30 days
Crop development growth stage	40 days
Mid-season growth stage	40 days
Late-season growth stage	25 days
Total length of season	135 days
$K_{c\ ini}$	0.6
$K_{c\ mid}$	1.15
$K_{c\ end}$	0.8

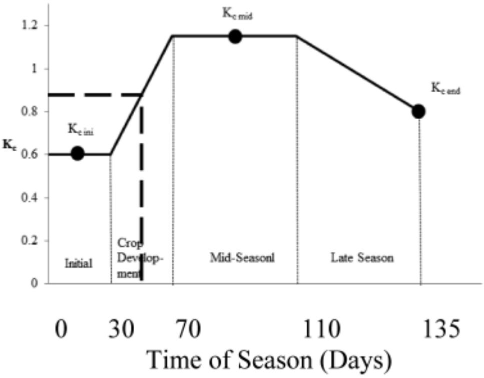

FIGURE 2 Crop coefficient curve with an example problem in this chapter. The heavy dashed line applies to the example problem with day of season 46–50 (horizontal axis) corresponding to an approximate crop coefficient of 0.85 (vertical axis).

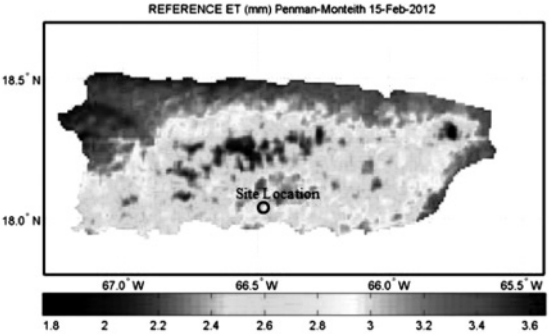

FIGURE 3 Estimated reference evapotranspiration (ETo) for Feb. 15, 2012. The approximate ETo at the site location is 2.95 mm.

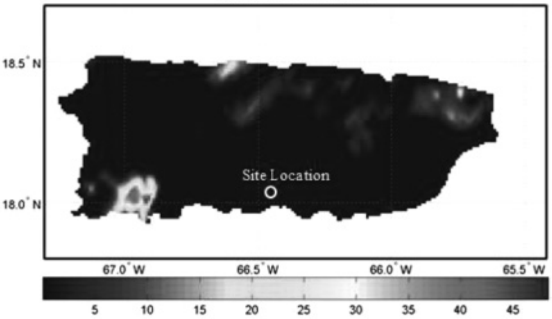

FIGURE 4 Estimated NEXRAD rainfall for Feb. 15, 2012.

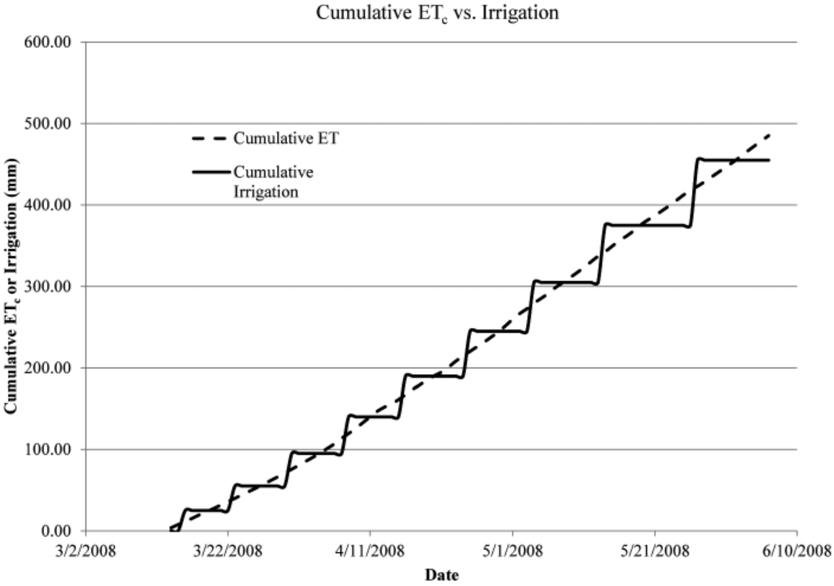

FIGURE 5 Example of the cumulative irrigation and ET_c plotted with time for a crop season.

***Note*:** **This** graph is not related to the example problem in this chapter.

Step 2: Determine the reference evapotranspiration for the five day period. Figure 3 shows the estimated reference evapotranspiration for Puerto Rico on February 15, 2012 obtained from the web address provided in Table 2. Note that the preferred reference evapotranspiration method is used (i.e., Penman-Monteith method). The estimated ET_o for the site location on Feb. 15, 2012 is 2.95 mm. Using a similar procedure, the ET_o for Feb. 16, 17, 18 and 19 is 2.8 mm, 3.1 mm, 3.5 mm and 3.7 mm, respectively. Summing up the ET_o values comes to a total crop water requirement (for the five days) of 16.1 mm.

Step 3: A rain gauge is not available on or near the farm for the example problem; therefore it is necessary to obtain rainfall information from the NEXRAD radar. Figure 4 shows the NEXRAD rainfall for Puerto Rico for February 15, 2012. At the site location no rainfall was estimated from the NEXRAD radar. Checking the other maps for the other days reveals that no significant rainfall occurred at the site. Therefore, all of the crop water requirement will have to be satisfied with irrigation.

Step 4: The crop water requirement for the time period can now be estimated as follows:

$ET_c = K_c\ ET_o = (0.85)(16.1\text{ mm}) = 13.\ 7\text{ mm}$ (slightly greater than one-half of an inch).

Step 5: Determine the number of hours that the pump should be run to apply the 13.7 mm of water. A form of the well-known irrigation Eq. (3) [2] can be used which is shown below:

$$T = 17.817 \times (D \times A)/(Q \times eff) \quad (3)$$

where: T is time in hours, D is depth of irrigation water in mm, A is effective field area in acres, Q is flow rate in gallons per minute and eff is irrigation system efficiency. Using D = 13.7 mm, A = 10 acres, Q = 300 gallons per minute and eff = 0.85, yields:

$$T = 17.817 \times (13.7 \times 10)/(300 \times 0.85) = 9.6 \text{ h}$$

11.4 IRRIGATION MANAGEMENT

To evaluate the irrigation management with the approach described in this chapter, construction of a graph similar to the one shown in Fig. 5 is recommended. The graph shows the cumulative depth of irrigation and ET_c plotted with time. The goal of irrigation scheduling is to try to match the applied irrigation with the ETc. By the end of the season, the cumulative irrigation (plus rainfall) should more or less equal the cumulative ETc. If these two curves stay close together, this is an indication that good irrigation management is being achieved. Note that the graph shown in Fig. 5 is not related to the example problem given above.

11.5 SUMMARY

Irrigation scheduling is critically important to avoid the loss of water, fuel and chemicals by over application of water, or a reduction in crop yield if too little water is applied. In this chapter a web-based irrigation scheduling approach is described. The approach is based on applying irrigation water at the rate of the estimated potential evapotranspiration, which is equivalent to the crop water requirement. Reference evapotranspiration is obtained from an operational water and energy balance algorithm (GOES-PREWEB), which produces a suite of hydro-climate variables on a daily basis for Puerto Rico. The algorithm produces daily estimates of the Penman-Monteith, Priestly Taylor and Hargreaves-Samani reference evapotranspiration. The crop coefficient curve is constructed per the methodology recommended by the United Nations Food and Agriculture Organization (FAO). Daily rainfall can be obtained from radar (NEXRAD) if rain gauge data is not available for the farm. A detailed example is provided for a farm growing tomato in Juana Diaz, PR, USA. The approach is relatively simple and the near-real time data is available to any farmer in Puerto Rico with internet access. Using the procedures described in this chapter, the approach could be developed at any location throughout the world.

KEYWORDS

- **Crop coefficient**
- **Crop water use**
- **Evapotranspiration**
- **FAO**
- **GOES-PRWEB**
- **Hargreaves-Samani**

- **Irrigation**
- **Irrigation management**
- **Irrigation scheduling**
- **NEXRAD**
- **Penman-Monteith**
- **Priestley-Taylor**
- **Puerto Rico**
- **Radar**
- **Web-based**

ACKNOWLEDGMENT

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PART III

APPLICATIONS OF MICRO IRRIGATION SYSTEMS

CHAPTER 12

BIOMETRIC RESPONSE OF CHILLI UNDER MICRO IRRIGATION PRACTICES

NADIYA NESTHAD, E. K. KURIEN, E. K. MATHEW,
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CONTENTS

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12.1 INTRODUCTION

Water resources in India are found to be getting deteriorated in terms of quality as well as quantity. Mark et al. [2] reported that by the year 2025 A.D., 33% of population in India will live under absolute water scarcity condition. The per capita water availability in terms of average utilizable water resources in the country was 6,008 cubic meters in 1947 and is expected to dwindle to 760 cubic meters by 2025 [1]. Water is a major input in agriculture. The water use efficiency of the crops has to be increased in order to reduce the water loss from the fields. With drip fertigation, nutrient use efficiency is increased and the loss of nutrients to the ground water is reduced. Soluble chemicals and nutrients move with the wetting front. Hence a precise scheduling of irrigation and fertilizer applications is essential for sustainable crop production.

Vegetable production in Indian agriculture has wider scope for increasing the income of the marginal and small farmers. Vegetables have vast potential in gaining foreign exchange through the export. The vegetable growers are looking for new ways to achieve superior quality produce with higher yields. Among the vegetables grown, chili is a spice cum vegetable crop of commercial importance.

The important components of a fertigation system include drip irrigation system of suitable layout and fertigation equipment. Crops are cultivated with fertigation system and the application of suitable mulch materials in order to reduce the water loss and weed infestation. The performance of crop may vary with the application rates and schedule of irrigation. The cost of the system will vary with the layout of the drip irrigation system as the use of laterals in each system of layout may vary.

This chapter will discuss effects of fertigation and drip system on performance of chili" at demonstration farm of Kelappaji College of Agricultural Engineering and Technology (KCAET), Tavanur, Malappuram – India.

12.2 MATERIALS AND METHODS

Kelappaji College of Agricultural Engineering and Technology (KCAET), Tavanur, Malappuram – India is situated at 10°51'23" N and 75°59'13" E and at msle of 29 ft. During 2011- 2012, the experiment was conducted to evaluate the response of chili (*Capsicum annum* var. Ujwala) to fertigation, drip system layout and mulching. The soil type of the experiment field was sandy loam. The field was plowed using tractor drawn disc plow and pulverized using rotavator. The plots of size 5×1 m^2 were drawn forming ridges around plot. A spacing of 45 cm × 45 cm was used, based on the recommendations for chili in the "*Package of Practices Recommendations: Crops (KAU, 2002).*"

12.2.1 INSTALLATION OF DRIP IRRIGATION SYSTEM AND FERTIGATION UNIT

Irrigation water was pumped through 7.5 kw motor pump set and conveyed through the main line of 63 mm diameter PVC pipes after filtering through the screen filter. From the main pipe, sub main of 40 mm diameter PVC pipes were installed.

From the sub main, laterals of 14 mm diameter LDPE were installed. Each lateral was provided with individual tap control for improving irrigation. Along the laterals, inline drippers were fixed at spacing of 50 cm. The number of laterals installed was based on the number of rows of crops grown. The discharge rate of single dripper is 4 L per hour.

Sub main and laterals were closed at the end with the end cap. Laterals were placed for each row per plot and in between two rows per plot, with 11 emitters in each lateral at a discharge rate of 4 L per hour. Irrigation scheduling at 65, 75, and 85% of irrigation requirement for each day was commenced after the transplanting.

12.2.2 EXPERIMENTAL DESIGN

The experiment was laid out with seven treatments, combination consisting of three irrigation levels and two drip system layouts. The experiment was laid out in randomized block design having seven treatment combinations and was replicated thrice. The treatment details are shown in Table 1.

Main plots	Irrigation levels
I1	65% of the daily irrigation requirement
I2	75% of the daily irrigation requirement
I3	85% of the daily irrigation requirement
Sub plots	**Drip system layout**
D1	One lateral in between two rows of crop in a bed
D2	One lateral for each row of crop in a bed.

TABLE 1 Treatment details.

Treatment	Description
T1	65% of the daily irrigation requirement, with one lateral for each row of crops in a bed.
T2	65% of the daily irrigation requirement, with one lateral in between two rows of crop in a bed.
T3	75% of the daily irrigation requirement, with one lateral for each row of crops in a bed.
T4	75% of the daily irrigation requirement, with one lateral in between two rows of crop in a bed.
T5	85% of the daily irrigation requirement, with one lateral for each row of crops in a bed.
T6	85% of the daily irrigation requirement, with one lateral in between two rows of crop in a bed.
T7	Control

12.2.3 IRRIGATION SCHEDULING

Irrigation scheduling was planned to provide the estimated water requirement of the crop. Irrigation was scheduled based on the daily crop water requirement. In order to determine the optimum water requirement for the crops, three irrigation levels were adopted. which were 65, 75 and 85% of water requirement of chili. The discharge rate of the emitter was 4 L per hour at a nominal pressure of 1.5 kg (f)/cm^2. Time required for each irrigation is shown in Table 2.

TABLE 2 Irrigation duration for each treatment.

Treatments	Time required for irrigation, min	Water required for irrigation, liters/day
T1	17.83	1.1
T2	35.66	1.1
T3	21.08	1.3
T4	42.16	1.3
T5	24.32	1.5
T6	48.64	1.5

12.2.4 FERTIGATION SCHEDULING

The fertigation was scheduled at weekly intervals. The entire phosphorous was applied as basal application. Nitrogen and potassium were applied through fertigation with 20 equal splits from third week to tenth week after planting. The recommended soluble fertilizers were applied simultaneously in a combined form to the root zone. The calculated amount of phosphorous was applied manually as a basal dose. Urea, poly feed (19:19:19) and Rajphos fertilizers were applied through fertigation. Fertilizer requirement for chili is shown in Table 3.

TABLE 3 Fertilizer requirement for chili.

Treatment	Fertilizer required (g)		
(%)	Urea	Polyfeed	Rajphos
100	1025	1243	709
Control	220	270	56

Recommended dose (kg per ha) of N: P: K is 75: 45: 20

12.3 RESULTS AND DISCUSSION

12.3.1 EFFECTS OF IRRIGATION AND DRIP SYSTEM LAYOUT ON BIOMETRIC RESPONSE

The data on plant height, number of leaves, number of branches and stem girth at 120 and 160 days after planting were observed different treatments, levels of irrigation and drip system layout. The results revealed that the plant height and number of leaves at both stages did not differ significantly with respect to the different levels of irrigation, to the different drip system layout and fertigation under plastic mulching. Figures 1 to 3 show the chili yield (g/plant) for different treatments, levels of irrigation and drip system layout.

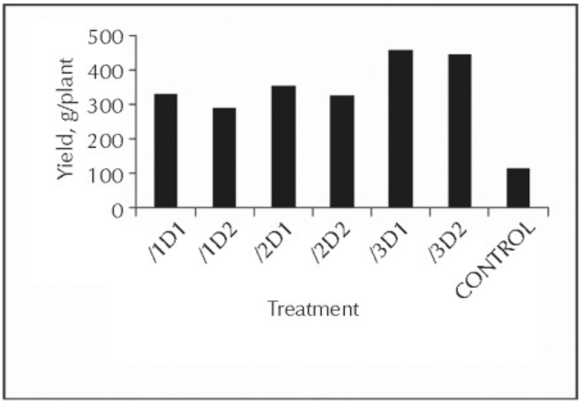

FIGURE 1 Yield in g/plant as influenced by different treatments.

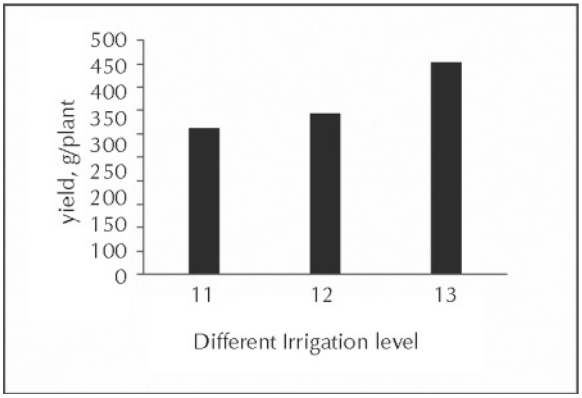

FIGURE 2 Yield in g/plant as influenced by different levels of irrigation.

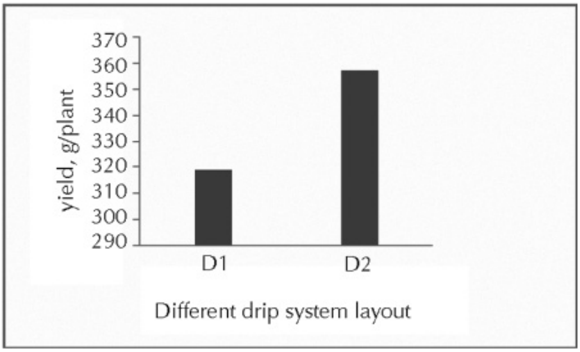

FIGURE 3 Yield in g/plant as influenced by different drip system layout.

With respect to the number of branches, it was observed that the maximum number of branches in the case of irrigation level was 8 in I3. In case of number of branches of 7, the level of irrigation I2 was on par with the irrigation level I3. The number of branches of 6 in the irrigation level I2 was on par with the I1. The minimum number of branches was observed for the irrigation level I1 at 120 days after planting.

For average yield, the different levels of irrigation and the drip system layout showed significant difference. The maximum yield value for irrigation level was observed in I3 (18.137 t/ha), 85% of the irrigation requirement. The minimum yield was observed for the irrigation level I1 (12.488 t/ha), 65% of the irrigation requirement. When different drip system layout were taken into consideration, the maximum yield was obtained for the drip system layout D1 (15.271 t/ha), one lateral for each row of crops and the minimum yield was obtained for the drip system layout, D2 (14.289 t/ha), one lateral in between two rows of crops. This can be attributed to the fact that high moisture level in one lateral for each row of crops helps in better fruit weight per plant as compared to the plants with one lateral in between two rows of crops.

12.3.2 WATER USE EFFICIENCY AND FERTILIZER USE EFFICIENCY

The highest water use efficiency of 25 kg/ha/mm was recorded in treatment T5 and T1. The reason for maximum water use efficiency in T1 was due to lesser water requirement as compared to T6. The water use efficiency of 25 kg/ha/mm for treatment T1 was higher than the water use efficiency of 23 kg/ha/mm for the treatment T3. This was due to lesser water requirement as compared with the treatment T3.

Increased FUE, such as Nitrogen use efficiency (NUE) and Potassium use efficiency (KUE), with the decreased levels of fertilizer doses were observed in the chili crop. The highest NUE of 244.26 kg of produce per kg of N was recorded in the treatment T5. Similar findings were observed by Vijayakumar, et al. [3]. For the treatment T6 the NUE of 239.36 kg of produce/ kg of N was recorded and for the control was about 60.5 kg of produce per kg of N.

The similar trend was observed in KUE in chili crop. The maximum KUE of 732.8 and 718.08 of kg of produce/ kg of K were observed in treatments T5 and T6, respectively. The WUE, NUE and KUE in chili crop are shown in Table 4.

TABLE 4 Water use efficiency (WUE), Nitrogen use efficiency (NUE) Potassium use efficiency (PUE) in chili crop.

Treatments	WUE (kg/ha/mm)	NUE ($kg.kg^{-1}$)	KUE $Kg.Kg^{-1}$
T1	25	176.42	529.28
T2	22	156.58	469.70
T3	23	190.10	570.32
T4	21	175.60	526.80
T5	25	244.26	732.80
T6	24	239.36	718.08

12.4 CONCLUSIONS

The effects of different irrigation levels and drip system layout under plastic mulch on the performance of Chilli (*Capsicum annum*) was studied. The number of branches, stem girth and yield showed significant differences among the treatments. The yield showed significant difference with different levels of irrigation and drip system layout. Maximum yield of 458 g/plant (18.32 t/ha) was observed for the treatment T5. The benefit cost ratio was 3.8 for treatment T5 at 85% of the irrigation requirement with one lateral for each row of crop and 3.9 for treatment T6 at 85% of the irrigation requirement with one lateral in between two rows of crop. Although the yield for the treatment T5 was high, yet the benefit cost ratio stands high for treatment T6. The high value of benefit cost ratio for treatment T6 was due to the reduction in the quantity of material for drip irrigation system.

12.5 SUMMARY

Field experiment on the effects of fertigation and drip system layout was conducted at KCAET, Tavanur – India. The experiment was laid out in a factorial randomized block design with treatments, which included three irrigation levels 85, 75 and 65% of daily irrigation requirement and two different drip system layout which were replicated thrice. In chili, maximum yield of 458 g/plant (18.32 t/ha) was observed for the treatment T5. The benefit cost ratio for treatment was 3.8 for T5, 85% of the irrigation requirement with one lateral for each row of crop and was 3.9 for treatment T6, 85% of the irrigation requirement with one lateral in between two rows of crop was 3.9. Even though the yield for the treatment T5 was high, the benefit cost ratio stands high for treatment T6. The high value of benefit cost ratio for treatment T6 was due to the reduction in the quantity of material for drip irrigation system.

KEYWORDS

- **Benefit cost ratio**
- **Biometric response**
- **Chilli**
- **Drip irrigation**
- **Fertigation**
- **fertilizer use efficiency**
- **India**
- **Kelappaji College of Agricultural Engineering and Technology India**
- **Kerala**
- **Micro-irrigation**
- **nitrogen use efficiency**
- **potassium use efficiency**
- **water use efficiency**

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CHAPTER 13

MICRO IRRIGATION AND FERTIGATION PRACTICES IN CHILLI (*CAPSICUM ANNUM*)

A. K. PANDEY, A. K. SINGH, A. KUMAR and S. K. SINGH

CONTENTS

13.1 INTRODUCTION

Water and fertilizer are the two costliest inputs in agriculture. Apart from the economics consideration it is also well known that the adverse effect of injudicious use of water and fertilizer on the environment can have far reaching implications. There is, therefore, a need for technological options, which will help in sustaining the precious resources and maximizing crop production without any detrimental impact on the environment. Micro-irrigation is the only option to replace the conventional irrigation method to achieve water-use efficiency.

Among the various technique developed for application of water, drip irrigation also referred to as trickle irrigation or micro irrigation is gaining popularity as perhaps the most efficient method of water application [4]. The area under drip irrigation was over 355,000 hectares in 2002. Presently, adoption of drip irrigation in India is increasing and about 600,000 hectares area is covered under drip irrigation under various crops [2]. As water, labor and land preparation becomes costlier; this technique of water application is bound to replace conventional systems. It has been reported that the savings is irrigation water using this technique over conventional methods can range from 40 to 70% [6].

Globally, India is leading country in context of area covered in chili production making it most dominant player in the world chili market. Water is an important input for growing this crop during this season. Pepper is most susceptible horticultural plants to drought stress because of the wide range of transpiring leaf surface, high stomatal conductance [1] and having a shallow root system [7]. For higher yield, an adequate water supply and relatively moist soils are required during the entire growing season. Low water availability prior to flowering of pepper reduced the number of flowers and retarded the occurrence of maximum flowering. The water deficit during the period between flowering and fruit development reduced final fruit production [9]. So, chili crop requires good and precise amount of water for higher yield and quality. In this direction, drip irrigation offers great opportunity for precise application of water and nutrients to the crop. The system has proved its superiority over other conventional method of irrigation, especially in fruits and vegetable crops owing to precise and direct application of water in the root zone [3, 13]. Sivanappan and Padmakumari [17] compared drip irrigation and furrow irrigation systems and found that 1/3rd to 1/5th of the normal quantity water was enough for the drip irrigated plots compared to normal quantity of water applied to plots under surface irrigation in vegetable crops.

Furthermore, there is good potential for adoption of drip irrigation and use of water soluble fertilizers with drip system, that is, fertigation technique for achieving better productivity and quality in different crops. The micro irrigation also enables use of fertilizers, pesticides and other soluble chemicals along with the irrigation water more economically and thus enhancing quality of produce and yield [15]. Micro-irrigation is a highly efficient method of water application to crops, which substantially saves water and fertilizer, increases yield besides improving quality of produce and reducing labor. In the recent years there has been a serious concern of global shortage of water. It is estimated that in India by 2025, 33% of India's population will live under severe scarcity conditions [5]. Low temperature and frost injury during winter season are the limiting factors for growing high value vegetables, like chili. Chilli (*Capsicum* *annuum* L.) is an important spice cum vegetable crop cultivated extensively in India. India contributes one fourth of world's production of chili with an average annual production of 1,289,000 tons in an area of 759,000 ha [2]. Considering all these factors, present experiment was conducted to find out minimum use of water, optimum spacing and use of nutrients for maximum yield and return through drip irrigation.

13.2 MATERIALS AND METHODS

Field trial was conducted, under farmers participatory research project, in the farmers field in the Bihta – district Patna of Bihar – India, on sandy loam soil having pH 7.3, E.C. 0.18 dsm^{-1}. The experiment was conducted in a FRBD design with two irrigation treatments (Drip and Flood irrigation method), three dripper/ plant Spacing (30, 45, 60 cm and row to row fixed at 60 cm spacing) and two nitrogen application methods, that is, through fertigation and as a top dressing. The variety 'California Wonder' was planted in first week of October during each year. Seedlings were grown in small bags (8 cm × 4 cm size). Seedlings of 25–30 days were transplanted in appropriate treatment in randomized plots. The crop was fertilized with recommended dose of FYM (2 kg/m^2), phosphate (200 kg/ha) given as SSP and potash (250 kg/ha) given as MOP was applied as basal dose in all treatments in both the crops at 15 days before planting and after 30 days of planting in split doses at every 25 days intervals during all the years. Insecticides and fungicides were used as per crop requirement. Considering all these factors, present experiment was conducted to find out minimum use of water, optimum spacing and compact use of nutrients for maximum yield and returns through drip Irrigation.

The drip system consists of filters (sand and screen), venture attachment for fertigation, pipeline (PVC main supply pipe, size 30 mm, sub main LLDPE laterals size 12 mm), and dripper size 0.6 PEE with the water discharge capacity of 2 l/h. The submain laterals were fixed at 60 cm apart and drippers were fixed at 30, 45 and 60 cm along the laterals. All submain laterals were controlled by gate valve system. Nitrogen was provided by venturi system of fertigation. The drip system was operated at alternate days or at two days interval for 10 min. Flood irrigation was provided by using plastic pipes (2 cm size) as per need or moisture content. The data were recorded and calculated in randomly selected 3–5 plants in each plot.

13.3 RESULTS AND DISCUSSION

13.3.1 EFFECT OF IRRIGATION

The results revealed that the drip irrigation method significantly increased yield (10.50 kg/m^2) and net income (60.30 Rs./m^2) of chili as compared to flood irrigation in all the years. The crop yield was improved by 60.30% in drip irrigated chili. Maximum water saving minimized weeds, diseases and total time of irrigation in drip irrigation. However, in flood irrigation resulted in no water saving, more occurrence of weeds, high disease incidence and total time. The results were in agreement with the past findings, that is, Refs. [10, 14, 15, 18].

TABLE 1 Effects of drip irrigation, dripper spacing and fertigation on the performance of chili.

Treatment	Yield (Kg/m^2)	Income (Rs/m^2)	Yield increased by drip irrigation against flood irrigation (%)	Disease incidence (%)	Weed incidence (%)	Saving of water (%)	Time of total irrigation (hr.)
Irrigation method							
Drip	10.50	67.00	60.30	05.00	32.40	40	10
Flood	6.55	11.70	—	20.00	100.00	—	40
Dripper spacing							
30 cm	10.40	65.60	58.77	08.00	35.60	30	10
45 cm	9.20	48.80	40.45	05.00	32.30	35	10
60 cm	8.22	35.08	25.49	04.00	22.70	40	10
Nitrogen							
Fertigation	10.20	62.80	55.72	04.50	16.40	35	10
Top dressing	7.70	27.80	17.55	15.50	31.50	30	10
CD (5%)							

Average selling price of Rs. 14/Kg; Total cost of cultivation of Rs. $80/m^2$.

Rs. = Indian rupee = US\$0.0167

13.3.2 EFFECT OF DRIPPER SPACING

The dripper spacing at 30 cm recorded significantly positive effect on yield and net returns as compared to 45 cm spacing. The yield was 58.77% greater in chili at 30 cm wider dipper spacing as compared to flood irrigation method. However, wider dripper spacing (60 cm) saved more water, total irrigation time, minimized the diseases and weeds incidence as compared to closer dripper spacing in each years (Table 1). This improvement can be due to the fact that closer spacing accommodates higher plant population, resulting more number of fruits, which increases total yield and net returns. These findings are in agreement with the other investigators [5, 11, 16].

13.3.3. EFFECT OF NITROGEN

The maximum yield in chili (10.20 kg/m^2), net income, weed incidence, minimal diseases and saved water and total irrigation time as compared to top dressing method during each year (Table 1). These benefits resulted due to fertigation. All the yield components were significantly influenced by nitrogen fertigation. The fertigation of nitrogen recorded 34.46% higher yield compared to top dressing method. The results are in agreement with those reported by Chauhan [5], Khan [10] and Jade [8]. Higher weed density and weed growth were observed at higher level of nitrogen. Similar results were reported by Narda and Lubana [12]. Increase in yield with higher level of nitrogen fertilizer might be due to higher amount of nitrogen availability for promotion of better carbohydrates utilization to form more protoplasm and cell and also due to readily available nitrogen in the vicinity of the root zone due to fertigation resulting in more efficient utilization of applied nitrogen than placement method. Similar results were reported by Veranna et al. [19].

13.4 CONCLUSIONS

Based on the results in this chapter, one can conclude that drip irrigation enhanced the net income and minimized the time, fruit yield, weeds and diseases of the crop. The 30 cm dripper spacing of improved net-income and higher yield, whereas wider spacing (60 cm) saved the maximum water, minimized weed and disease incidences. The application of irrigation at an alternate day was effective in vegetable crops. The drip irrigation is more effective to get more fruits and fruit weight/plant and yield of the vegetable crops compared with the traditional method of irrigation. This type of studies can also be carried out in other vegetable crops to arrive at some concrete decisions for making recommendations for use of drip irrigation in vegetable crops. Fertigation is very important activity to be undertaken with micro irrigation system to harvest to harvest quality produce at competitive price to boost up the export and promote hi-tech horticulture. The farmers should be trained to adopt these technologies as per scientific recommendations to produce quality product.

13.5 SUMMARY

A field experiment was conducted to investigate the effects of drip irrigation, dripper spacing and nitrogen fertigation on Chilli (Capsicum annuum L.) performance and crop yield. The results revealed that drip irrigation enhanced the fruit yield, net income and minimized the time, weeds and diseases of the crop. Closer spacing at 30 cm produced higher yield (58.77%) and net income as compared to 45 cm spacing. Fertigation resulted in maximum yield (10.20 Kg/m^2), minimal disease and saved water and total irrigation time as compared to top dressing. The drip irrigation had significantly increased yield (10.50 Kg/m^2) and net income (60.30%) as compared to flood irrigation.

KEYWORDS

- **Bihar India**
- **Chilli (Capsicum Annum)**
- **Crop yield**
- **Drip irrigation**
- **Dripper spacing**
- **Fertigation**
- **Fertigation practices**

- **India**
- **Nitrogen fertigation**
- **Row spacing**
- **Sustainable micro irrigation**
- **Top dressing**

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CHAPTER 14

IRRIGATION SCHEDULING FOR SWEET PEPPER

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CONTENTS

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14.1 INTRODUCTION

A study was conducted to evaluate the influence of agricultural lime ($CaCO_3$) on the movement and uptake of inorganic nitrogen for a sweet pepper crop (*Capsicum annuum*) grown on an Oxisol soil (Coto clay) in north-west Puerto Rico. The Coto clay soil, which contains the 1:1 kaolinite mineral, has a low pH (4 to 4.5). The 1:1 type clays are known to possess a net positive charge at low pH, resulting in the adsorption of negatively charged ions such as nitrate. From an environmental standpoint this characteristic of the 1:1 clay is favorable, since nitrate leaching, a major cause of groundwater pollution in many areas, is reduced relative to soils with net negative charge. However, agricultural plants, such as sweet peppers, favor a higher soil pH (approximately 6.5), which can be obtained by the application of agricultural lime. This, however, may have the negative effect of increasing the potential for nitrate leaching, as the net charge on the soil particles becomes negative with increasing pH.

This chapter describes the results of a nitrogen leaching analysis for two sweet pepper crop seasons. The analysis was based on multiplying the daily percolation flux through the soil profile by the measured concentration of nitrogen below the root zone. Irrigations were scheduled using the pan evaporation method for estimating crop water requirements. No significant difference in nitrogen leaching was observed for the lime and no-lime treatments. This was attributed to the low nitrate retention capacity of this soil, even at low pH. The average percent of nitrogen leached during the 1st and 2nd season, relative to the amounts applied, were 26% and 15%, respectively. Leaching events were associated with large rainstorms, suggesting that leaching of N would have occurred regardless of the irrigation scheduling method used.

14.2 TECHNICAL APPROACH

14.2.1. EXPERIMENTAL SITE

Sweet pepper crops were planted at the UPR Experiment Station at Isabela in northwest PR (Fig. 1) during March 2002, and January 2003. Harmsen et al. [1] provided a detailed description of the experimental layout of the field site. The soil at the Isabela Experiment Station belongs to the Coto series. It is a very fine kaolinitic, isohyperthermic Typic Eutrustox. These are very deep, well drained, moderately permeable soils formed in sediments weathered from limestone. The available water capacity is moderate, and the reaction is strongly acidic throughout the whole profile. Consistence is slightly sticky and slightly plastic in the Oxic horizons. A strong, stable granular structure provides these soils with a very rapid drainage, despite their high clay content [2]. Average values of hydraulic properties published for the Coto clay soil near the study area are as follows: air dry bulk density1.39 g/cm3, porosity 48%, field capacity 30%, wilting point 23%, available water holding capacity (AWHC) 9% [12]. The AWHC of this soil is low for clay. Typical values for clay are 15 to 20% [3]. A small value of AWHC means that there is a greater potential for leaching since the soil moisture content associated with the field capacity is more easily exceeded.

FIGURE 1 Location of field site at Isabela, PR.

The experimental site of 0.1 ha was divided into four blocks, each block divided into four plots, one for each treatment, for a total of 16 plots. The plots measure 67 m^2. The treatments included two lime levels (lime and no lime) and two fertigation frequencies (F1 and F2). Each plot had four beds covered with plastic (silver side exposed) with two rows of sweet pepper plants per bed. The transplanted sweet peppers were grown in rows 91 cm apart, 30 cm apart along rows, with beds 1.83 meter on center. This gave a plant population of approximately 37,000 plants per hectare. There was an initial granular application of triple super-phosphate of 224 Kg/ha and 80 Kg/ha of 10–10–10 fertilizer. Peppers were planted from March 11th through March 13th, 2002 and January 27 through January 31th, 2003. KNO3 and urea were injected through the drip irrigation system throughout the season at different frequencies (weekly [F1] or bi-weekly [F2]). The total nitrogen applied during the season was 225 Kg/ha. After transplanting, soil samples were taken bi-weekly at 20 cm increments, down to an 80 cm depth from each plot to be analyzed for moisture content and nitrogen concentration. Each date in which soil samples were collected, whole plants were harvested for growth data. Periodic pesticide applications were made to control weeds and insects affecting crop growth.

14.2.2 WATER BALANCE

A water balance approach [Eq. (1)] was used in this study to estimate percolation past the root zone.

$$PERC = R - RO + IRR - ET_c + \Delta S \qquad (1)$$

where: PERC is percolation below the root zone, R is rainfall, IRR is irrigation, RO is surface runoff, ET_c is crop evapotranspiration, and $\Delta S = S1 - S2$, where S1 and S2 are the water stored in the soil profile at times 1 and 2, respectively. The units of each term in Eq. (1) are in mm of water per day. Rainfall was obtained from a tipping bucket-type rain gauge located on the Isabela Experiment Station property. The rain gauge was located within a weather station complex located approximately 0.4 km from the study area. The weather station consisted of a 10 meter (high wind resistant) tower with lighting protection, data logger and radio communication system, and sensors to measure the following parameters: wind direction and speed, temperature, relative humidity, barometric pressure, cumulative rainfall, and solar radiation [4]. Irrigation (IRR) was applied through a drip irrigation system. The inline-type emitters produced a flow of 1.9 L per hour per emitter at a design pressure of 10 pounds per square inch (psi). Emitters were spaced every 30 cm. Irrigations (IRR) were scheduled based on the estimated evapotranspiration rate as determined with Eq. (2), where: ET_{pan} is the pan evaporation-derived evapotranspiration, K_c is the evapotranspiration crop coefficient for sweet peppers [5], which varied daily; K_p is the average annual value of the pan coefficient equal to 0.78 for Isabela, PR [6]. A cumulative water meter was used to control the gallons of irrigation water applied. The evapotranspiration term in Eq. (1) was estimated with Eq. (3), where: K_c is the crop coefficient (dimensionless) and ET_o (mm/day) is the reference evapotranspiration obtained using the Penman-Monteith method [5], as described in Eq. (4).

$$IRR = ET_{pan} = (K_c * K_p * Epan) \tag{2}$$

$$ETc = K_c * ET_o \tag{3}$$

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \left(\frac{900}{T + 273} \right) \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{4}$$

In Eq. (4): Δ is a slope of the vapor pressure curve [kPa°C^{-1}], R_n is net radiation [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], γ is psychrometric constant [kPa°C^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is the saturated vapor pressure and e_a is the actual vapor pressure [kPa]. Equation (4) applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1} and an albedo of 0.23.

Data required by Eq. (4) were obtained from the weather station located near the study area. Wind speeds obtained from the 10 m high tower were adjusted to the 2 m wind speed, required by the Penman-Monteith method, by means of an exponential relationship. Initial values of the crop coefficient were obtained from the literature for sweet pepper for the initial, mature and end crop stages (FAO Paper No. 56). Adjustments of K_c were made during the calibration of Eq. (1) as described later in this section. ET_o was estimated on a daily basis using a spreadsheet program. The calculation methodology is described by Allen, et al. [5]. The values of S in Eqs. (1) and (2) were obtained from Eq. (5).

$$S = \theta_v * Z \tag{5}$$

where: θ_v is the vertically averaged volumetric soil moisture content over the depth Z, obtained by multiplying the moisture content, mass-basis (θ_m), by the soil bulk density and dividing by the density of water. The soil bulk densities were obtained from undisturbed soil cores.

Between sampling dates when measured values of θ_v were not available, daily values were estimated using Eq. (1) along with information about the moisture holding capacity of the soil. In this method, if the water added to the profile by rainfall or irrigation exceeds the soil moisture holding capacity (or field capacity), then the excess water was assumed to be equal to PERC and the moisture content was set equal to the field capacity on that day. This approach has previously been used for irrigation scheduling [7], waste landfill leachate estimation [8] and estimation of aquifer recharge rates [9, 10]. In this study, the effective field capacity of the soil was determined in-situ by saturating the soil and obtaining the soil moisture content within 48 h.

Calibration of the water balance equation was accomplished by adjusting the ratio of runoff to rainfall (RO/R) within reasonable limits, until the measured and estimated soil moisture content were in reasonable agreement. [1 – (RO/R)] represents the fraction of rainfall that infiltrates into the soil bed. This contribution of water can occur in several ways for the plastic covered bed-type system used in this study. Rainfall may enter directly through the holes in the plastic made for the plants. Rainfall that runs off of the plastic into the furrow or that falls directly into the furrow may also be absorbed into the beds. Under flood conditions, which occurred on several occasions during the two crop seasons, water could have entered the beds under a positive water pressure. For nonflooding rainfall events, soil water may move from the furrows into the beds by means of unsaturated flow, which is controlled by the pore water pressure gradient between the furrow and the bed.

14.2.3 NITROGEN LEACHING

Nitrogen leaching (nitrate and ammonium) was estimated by multiplying the daily value of PERC by the concentration of nitrogen within the 60 to 80 cm depth of soil. This vertical interval was considered to be below the root zone, since plant roots were not observed within this interval any time throughout the two seasons. The following Eq. (6) was used to estimate nitrate and ammonium leaching, respectively:

$$LNO_3 = [0.01*(\rho_b)*(NO_3)*(PERC)]/\,[\theta_{vol}] \tag{6a}$$

$$LNH_4 = [0.01*(\rho_b)*(NO_4)*(PERC)]/\,[\theta_{vol}] \tag{6b}$$

where: LNO_3 and LNH_4 are the kg of nitrate and ammonium leached below the root zone per hectare, NO_3 and NH_4 are the nitrate and ammonium soil concentration in mg/kg in the 60 to 80 cm depth interval, PERC is the percolation rate in mm, ρ_b is the bulk density (gm/cm^3), and θ_{vol} is a volumetric moisture content (cm^3/cm^3) in the 60 to 80 cm depth interval. Equations (6a) and (6b) were used on a daily basis. Each measured value of soil concentration used in Eqs. (6a) and (6b) were based on the average of four replications. Values of NO_3 and NH_4 between sampling dates were linearly interpolated.

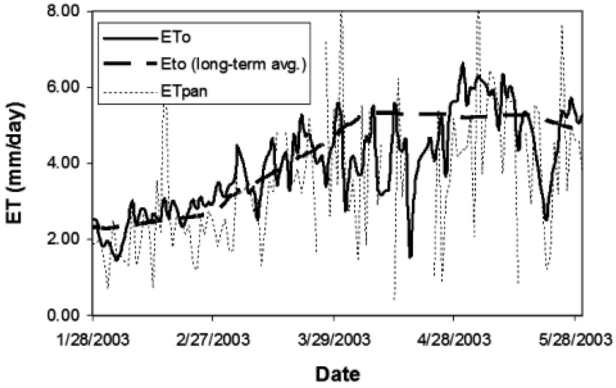

FIGURE 2 Daily values of evapotranspiration for a sweet pepper crop between January 27th to June 12th, 2003 at Isabela, PR. ET was derived from the pan evaporation and Penman-Monteith methods.

TABLE 1 Physical and hydraulic properties of Coto clay in the 0–20, 20–40, 40–60 and 60–80 cm depth intervals[1].

Depth	% Sand[1]	% Silt[1]	% Clay[1]	Soil Classification	Bulk Density	Porosity
0-20 cm	35.10	19.35	45.55	silty clay	1.36	0.49
20-40 cm	28.72	1.85	69.43	clay	1.36	0.49
40-60 cm	22.50	5.00	72.50	clay	1.31	0.51
60-80 cm	20.00	5.80	74.20	clay	1.29	0.51

Depth	Hydraulic Conductivity (cm/day)	In-Situ Field Capacity Year 1 Site	In-Situ Field Capacity Year 2 Site	Moisture Content at 0.33 bar Pressure	Moisture Content at 15 bar Pressure	Available Water Holding Capacity (AWHC)
0-20 cm	1210.06	0.33	0.44	0.44	0.39	0.05
20-40 cm	316.99	0.33	0.37	0.37	0.27	0.10
40-60 cm	70.10	0.37	0.36	0.36	0.31	0.05
60-80 cm	12.19	0.37	0.38	0.38	0.3	0.08

[1] Soil texture data for the 40–60 cm and 60–80 cm were obtained from Soil Conservation Service [12]. All other data were measured during the project.

14.3 RESULTS AND DISCUSSION

The Coto clay soil was analyzed for various physical and hydraulic properties (Table 1). The soil has a relatively high sand content and high hydraulic conductivity in the 0–20 cm interval, which accounts for it high water intake capacity. We observed on several occasions the rapid infiltration of water after large rainfall events. In fact, the value of hydraulic conductivity for the 0–20 cm interval is similar to sand, which averages 900 cm/day [11]. Bulk density, porosity, hydraulic conductivity, moisture content at 0.33 and 15 bars pressure, and AWHC were obtained from undisturbed cores in the laboratory.

Measured soil pH soil was between 4 and 5. Laboratory incubation tests were performed to determine the proper amount of lime needed to be applied to the soil to increase the pH to around 6.5 in the limed treatments; this amount was 7.4 tons lime/ha. The first year the pH did not respond as expected in the limed plots, and therefore, this may have contributed to there being no significant difference observed in the estimated nitrate losses by leaching between the lime and no-lime treatments. The second year the amount of lime applied to the limed treatments was doubled (14.8 tons lime/ha) and pH levels rose as expected.

Figure 2 shows a comparison of the evapotranspiration derived from pan and Penman-Monteith methods during Year 2. ET_{pan} was observed to have higher variability than ETc. For reference, Fig. 2 also shows the ETc based on long-term average climate data for Isabela, PR. The seasonal ET (mm per season) was 447 for the Epan methods, 402 for Penman-Monteith method based on weather station data and 511 for Penman-Monteith based on long-term data, respectively.

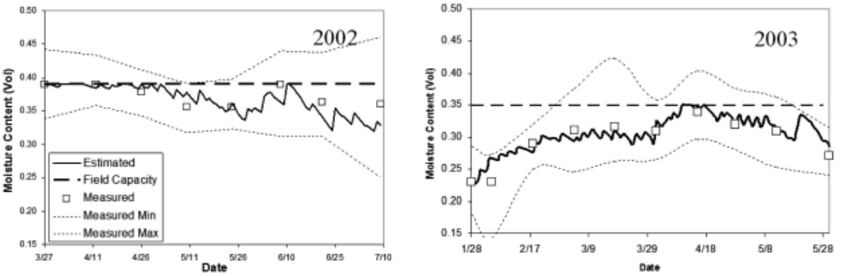

FIGURE 3 Estimated and measured volumetric soil moisture content between March 27th and July 9th 2002 and January 27th and June 12th, 2003.

The water balance equation (the Eq. (1)) was calibrated for the site conditions. Figure 3 shows the simulated and measured average soil moisture content for Year 1 and Year 2. The measured moisture contents shown in Fig. 3 represent the vertically averaged moisture content over all 16 plots. The minimum and maximum measured soil moisture content is also shown in Fig. 3. Vertically averaged values of the in-situ-measured field capacity equal to 0.39 and 0.35 were used in the Year 1 and Year 2 analyzes, respectively, (averages from Table 1). It was necessary to use a value of RO/R = 0.25, reasonable agreement between the estimated and measured soil moisture content. During Year 1, the beginning of the season was quite wet. On April 6, 2002, a 176 mm rainfall occurred, which caused severe flooding of the study area. During Year 2, a rainy period occurred during April 5th through April 18th with flooding observed in the field plots. The largest rainfall of the season occurred on April 10, 2003 equal to 97 mm.

According to the procedure described above, percolation occurred on those days when the estimated moisture content exceeded the field capacity moisture content (0.39 for Year 1 and 0.35 during Year 2). On those days, the water in excess of the field capacity was assigned to PERC and the moisture content set equal to the field capacity. This can be seen in Fig. 3 for those days in which the moisture content curve touched the dashed horizontal line associated with the field capacity moisture content. Figure 4 shows the estimated percolation during the Year 1 and Year 2. During the April 6, 2002 rainfall event of 175 mm, 43 mm were converted to percolation. During the April 10th, 2003 rainfall event of 97 mm, 31 mm were converted to percolation. Recall that only 25% of the rainfall was allowed to infiltrate, which was equal to 44 mm on April 6, 2002 and 24 mm on April 10, 2003. In the latter case 18 mm of irrigation was also applied, which together (24 mm + 18 mm) equaled 42 mm. In this case 31 mm was lost to percolation and 11 mm was stored in the root zone. Table 2 shows the Year 1 and Year 2 seasonal components of the water balance.

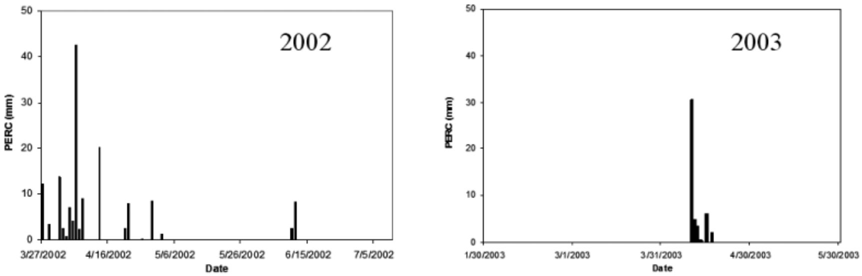

FIGURE 4 Estimated percolation past the root zone during the Year 1 and Year 2 seasons.

TABLE 2 Components of the seasonal water balance for Years 1 and 2.

	Year 1 (2002)	Year 2 (2003)
R-RO	175	136
IRR	350	411
ETc	416	441
ΔS	50	-52
PERC	159	54

TABLE 3 Nitrate, ammonium and nitrate plus ammonium (Total) leached during Year 1 and 2 for the four experimental treatments.

		2002				2003			
	Units	LF1	LF2	NLF1	NLF2	LF1	LF2	NLF1	NLF2
NO3	kg/ha	36	50	47	42	34	32	34	24
NH4	kg/ha	10	13	21	11	2	3	2	3
Total	kg/ha	46	63	67	54	36	35	36	27
Total	%	21	28	30	24	16	16	16	12

Table 3 compares the Year 1 and Year 2 results of the nitrogen leaching analysis. The leached nitrate and ammonium estimates were obtained from equations/5a/ and/5b/, respectively. Figure 5 shows the nitrate concentrations in the 60 – 80 cm depth interval during the Year 1 season. During Year 1 the range of estimated nitrogen leached was between 36 and 67 **kg**/ha. During Year 2, the range of estimated nitrogen leached was between 27 and 36 **kg**/ha. Interestingly, the amount of nitrate lost (average of all treatments) on April 6, 2002 and April 10, 2003 was 19.6 **kg**/ha and 20.1 **kg**/ha, respectively. For years 1 and 2 this represented 34% and 60% of the total N lost by leaching during the two seasons, respectively. Figure 6 shows the estimated percent of nitrogen (i.e., nitrate plus ammonium) leached relative to N applied (225 **kg**/ha) during the Year 1 and Year 2 seasons for the four experimental treatments.

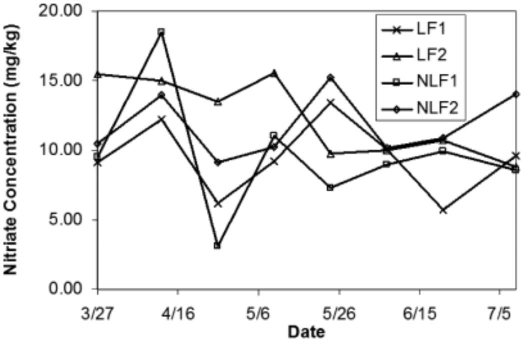

FIGURE 5 Year 1 Soil nitrate concentrations in the 60–80 cm depth interval. Values between the sampling dates were obtained by linear interpolation.

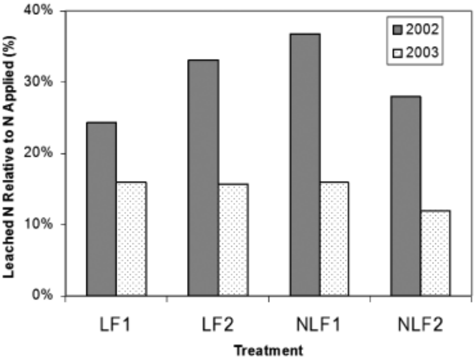

FIGURE 6 Estimated nitrogen leached during the Year 1 and year 2 season. LF1 is the Lime-Fertigation 1 treatment, LF2 is the Lime-Fertigation 2 treatment, NLF1 is the No-Lime-Fertigation 1 treatment, NFL2 is the No-Lime-Fertigation 2 treatment.

The smallest amount of nitrogen leaching occurred in the LF1 treatment in 2002 and the NLF2 treatment during the second year. There is no clear difference between either the lime or fertigation treatments. Ammonium leaching was typically much lower than nitrate leaching (Table 3) except in the case of treatment NLF1 in 2002, in which 21 **kg**/ha ammonium was leached as compared to 47 **kg**/ha nitrate. The fact that no clear difference was observed between nitrogen leaching for the two lime treatments is consistent with laboratory studies currently being conducted on the Coto clay soil at the University of Puerto Rico Mayaguez Campus, which indicates that the pH at which this soil will possess a net positive charge (<4) is below the native pH measured in the field (around 4.3).

14.4 METHOD LIMITATIONS

There are several sources of uncertainty in the estimates of nitrogen leaching, which include:

- Between sampling dates, soil nitrogen concentrations were derived by linear interpolation. Nitrogen concentrations were measured every two weeks. In some cases, the average nitrate concentration was observed to change as much as 15 mg/kg in the 60–80 cm depth interval. The estimated nitrogen leaching would be in error if these concentrations did not change linearly between sampling dates.
- The method of estimating percolation in this study does not account for the leaching that can potentially occur by unsaturated flow. All leaching was assumed to occur when the moisture content of the soil exceeded the soil field capacity. However, significant downward gradients can exist which would result in unsaturated flow. Although not presented in this paper, continuous soil pressure data obtained from vertically spaced tensiometers indicated downward hydraulic gradients throughout most of the season.

14.5 SUMMARY

This chapter described the results of a nitrogen leaching analysis for two sweet pepper crop seasons. The study was conducted on an Oxisol soil in NW Puerto Rico. The analysis was based on multiplying the daily percolation flux through the soil profile by the measured concentration of nitrogen below the root zone. Irrigations were scheduled using the pan evaporation method for estimating crop water requirements. Estimated percolation in 2002 was three times greater than occurred in 2003, whereas the nitrogen leached during 2002 was only slightly greater than two times the nitrogen leached during 2003.

No clear difference in nitrogen leaching was observed for the lime and no-lime treatments. This result is consistent with on-going studies of the Coto clay, which indicate that this soil has little to no capacity to retain nitrate. The average percent of nitrogen (nitrate plus ammonium) leached during the 1st and 2nd season, relative to the amounts applied, were 26% and 15%, respectively. Leaching events were associated with large rainstorms, suggesting that leaching of N would have occurred regardless of the irrigation scheduling method used. During the first and second seasons, respectively, 34% and 60% of the total N lost by leaching occurred during a single day (April 6 in 2002 and April 10 in 2003) when flooding was observed in the study areas.

KEYWORDS

- Agricultural lime
- Aquifer recharge
- Available water holding capacity
- Deep percolation
- Emitter
- Evaporation
- Evapotranspiration
- Fertigation
- Fertilization
- Field capacity
- Humid region
- Irrigation
- Irrigation scheduling
- Lime fertigation
- Linear interpretation
- Nitrogen leaching
- Oxisol
- Pan evaporation
- Penman-Monteith
- Percolation
- Puerto Rico
- Rainfall
- Runoff
- Soil moisture content
- Surface runoff
- Sweet pepper
- Vegetable crops
- Water balance
- Wilting percentage

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CHAPTER 15

MICRO IRRIGATION PRACTICES IN TOMATO

BALRAM PANIGRAHI

CONTENTS

15.1 INTRODUCTION

Land and water are the two vital natural resources for sustenance of agricultural production in any country. Out of these two resources, water is very important, because it plays a crucial role in maximizing production and productivity of any crop. Because of a limited water resource, its efficient utilization is basic to the survival of mankind. Though India is blessed with plenty of water resources, yet the utilizable water for irrigation is being exhausted due to various physiographic constraints, legal constraints and present method of utilization. Improper irrigation management practice not only waste scarce and expensive water resources but also decreases crop yield through salinization and alkalinization [9, 22]. It is necessary to economize the use of water for agriculture in order to bring more area under irrigation. It is therefore essential to formulate efficient and economically viable irrigation management strategies in order to irrigate more area with the existing water resources. This can be achieved by introducing advanced and sophisticated method of irrigation like drip/micro, sprinkler and improved water management practices. By the use of these advanced irrigation methods, a lot of costly irrigation water can be saved which will in other way help in expanding the irrigation potential, irrigation intensity as well as cropping intensity.

In drip irrigation, water in small quantity but in frequent times is applied to the root zone of the crop. The root zone application of water eliminates the chances of water losses due to surface runoff and deep percolation. This consequently enhances the water application efficiency. Use of the advanced methods of irrigation like micro and sprinkler is very limited in India. Although we have about 60.90 million ha land under irrigation (43% of net sown area) in India, yet only 5% of the irrigated areas are covered under sprinkler irrigation and only 3.1% are under micro irrigation. Even a developing country China has been able to bring less area under sprinkler and drip irrigation, although it has covered large area under other sources of irrigation including surface irrigation. Some developed countries like USA and United Kingdom have achieved about 50% and 95% of total irrigated areas under sprinkler irrigation, respectively. Israel has been able to bring about 73.6% of the total irrigated areas under micro irrigation. The spread of irrigation by different sources like sprinkler and micro irrigation/drip irrigation for some selected countries in the world is presented in Table 1 [11].

Presently in India, 7.49 million ha area is cultivated with vegetable crops with an annual production of 116.03 million tons. It is estimated that, by 2020 AD, the vegetable demand of the country will be around 135 million tons. To achieve this target, our attention must be focused on the vertical expansion instead of horizontal expansion just by increasing the crop area [16]. The working group on horticulture constituted by the Planning Commission had recommended deployment of hi-tech horticulture and precision farming for achieving vertical growth in horticulture. As proposed by National Committee on Plasticulture Applications in Horticulture (NCPAH) – Government of India, the hi-tech interventions in horticultural crops are drip irrigation and *in-situ* moisture conservation through plastic mulching [17].

TABLE 1 Coverage of areas under sprinkler and micro irrigation in some selected countries [11].

Country	Total irrigated area, (M ha)	Sprinkler irrigation		Micro-irrigation		Year
		Area, ha	% of total irrigated area	Area, ha	% of total irrigated area	of reporting
Australia	2.55	524,000	20.6	191,000	7.5	2000
Brazil	4.45	2,410,000	54.2	328,000	7.4	2006
Bulgaria	0.59	21,000	3.6	3000	0.5	2008
Canada	0.87	6,83,000	78.5	6030	0.7	2004
Chile	1.09	16,000	1.5	23,000	2.1	2006
China	59.30	2,930,000	4.9	1,670,000	2.8	2009
Chinese Taipei	0.38	18,900	5.0	8750	2.3	2009
Czech Rep.	0.15	11,000	7.2	5000	3.3	2007
Estonia	0.001	500	50.0	500	50.0	2010
France	2.90	1,380,000	47.6	103,000	3.6	2011
India	60.90	3,040,000	5.0	190,0000	3.1	2010
Iran	8.70	460,000	5.3	270,000	3.1	2009
Israel	0.23	60,000	26.0	170,000	73.6	2000
Italy	2.67	981,000	36.8	571,000	21.4	2010
Korea	1.01	200,000	19.8	400,000	39.6	2009
Malaysia	0.38	2000	0.5	5000	1.3	2009
Mexico	6.20	400,000	6.5	200,000	3.2	1999
Morocco	1.65	190,000	11.5	8250	0.5	2003
Philippines	1.52	7180	0.5	6640	0.4	2004
Poland	0.10	5000	5.0	8000	8.0	2008
Portugal	0.63	40,000	6.4	25,000	4.0	1999
Russia	4.50	3,500,000	77.8	20,000	0.4	2008
Saudi Arabia	1.62	716,000	44.2	198,000	12.2	2004
South Africa	1.67	920,000	55.1	365,000	21.9	2007
Spain	3.41	733,000	21.5	1,630,000	47.8	2010
Syria	1.28	93,000	7.3	62,000	4.8	2000
Turkey	5.34	110,000	2.1	26,000	0.5	2009
United Kingdom	0.11	10,5000	94.5	6000	5.5	2005
USA	24.70	12,300,000	50.0	1,640,000	6.6	2009

Furrow irrigation is the conventional methods widely used to irrigate most of the vegetable crops grown in India. However, this method uses more water compared to other high-tech water saving irrigation methods such as sprinkler, drip, etc. Many researchers have reported the higher application efficiency of drip irrigation system over the conventional furrow irrigation systems [5, 8, 22]. There was savings of 67 to 80% with drip irrigation more irrigation water than with surface irrigation methods [20]. Based on a study conducted at Rahuri – India [10], 60% higher yield of okra with water savings of 40% under drip irrigation as compared to furrow irrigation has been reported. The 100% irrigation requirement was met through drip irrigation and the highest yield of okra under black plastic mulch has been obtained (14.51 tons/ha) with 72% increase in yield compared to furrow irrigation [22]. Field experiments for two years on clay loam soil in the northern region of Allahabad – India were conducted to study the effects of 8 levels of pan evaporation replenishments (25, 50, 75, 100, 125, 150, 175 and 200%) on marketable yield, irrigation production efficiency and economic return of potato under drip irrigation [7]. The highest mean marketable yield (two years) of potato was 48.98 tons/ha at 150% pan evaporation replenishment with irrigation production efficiency being maximum with a value of 106.26 kg/m^3. Irrigation at the said level of pan replenishment gave highest economic return and benefit-cost ratio.

In Odisha – India, economic evaluation of drip irrigation in fruit crops (coconut, mango and sapota: chikoo in Hindi) has revealed that this system conserves considerable amount of water and results better returns despite higher initial investment [4]. The response of banana to drip irrigation in terms of yield improvement was found to be different in different agro-climatic and soil conditions in India [1, 6, 15, and 18]. Response of vegetable to drip irrigation in terms of increase in yield was also different in different agro-climatic and soil conditions in India. Use of soil cover and mulching is also beneficial chiefly due to the influence of soil moisture conservation, solarization and weed control. Beneficial response of plants to mulch includes early production, more yield and reduced insect and disease problems [3, 15]. Linear Low Density Poly Ethylene (LDPE) plastic films have been proved to be superior mulch because of its puncture resistance quality, thinness and lower cost [13].

In Odisha – India, although the average annual rainfall is 1500 mm, yet there is hardly any rainfall in winter season (only 11% of annual rainfall occurs in winter). Hence there is scarcity of water in rest periods of the year for growing crops in up and medium lands. Drip irrigation has created interest among farmers because of less water requirement, possible increased production and better quality produce. The Government of India is also offering financial assistance to the farmers who use this technique for growing preferably vegetables and fruits. Among the different vegetables cultivated in the Odisha state, tomato is an important vegetable and is grown in all agro-climatic conditions. Due to lack of information of proper irrigation management technique, the crop yield is very low.

Therefore, a field experiment was conducted in the West Central Table Land Zone of Odisha – India to study the effects of drip irrigation and furrow irrigation on yield and water use efficiency of tomato grown under the mulching and nonmulching conditions. This chapter discusses these research results.

15.2 MATERIALS AND METHODS

During the two-year period (2006 and 2007), field experiments were conducted at the Regional Research and Technology Transfer Station in Chiplima, which comes under the West Central Table Land Zone of Odisha – India. The latitude, longitude and altitude for the site are 20^0 21'N, 80^0 55' E and 178.8 m above the mean sea level, respectively. The area falls under the subhumid climatic condition in the eastern part of India. The total rainfall in the study area during the crop growing season (8th Jan to 3rd April) was 32.0 mm for 2006 and 29.0 mm for 2007, respectively. The mean daily air temperature during the crop growing period ranged from 15.4 °C to 31.3 °C during 2006 and 16.8 °C to 29.97 °C during 2007, respectively. The mean daily relative humidity ranged from 45.5% to 689.7% in 2006 and 47.2% to 70.5% in 2007, respectively.

The soil texture of the study area is sandy loam with sand, silt and clay percentage of 78.8, 10.8 and 10.4, respectively. Average values of bulk density, volumetric moisture content at field capacity and permanent welting point are 1.55 gm/cc, 26% and 10%, respectively. Average pH, EC and organic carbon were 6.3, 0.09 dS/m and 0.51%, respectively.

Tomato variety Arjun was planted in the plots with 75 cm spacing from row to row and 60 cm from plant to plant. Plantations (25 days seedlings) were transplanted on 8th Jan of each of the two years and harvested on 3rd April for both the years. Applications of N, P and K fertilizers were 150, 100 and 100 kg/ha, respectively. Nitrogen was applied 50% as preplating and rest 50% as top-dressing one month after planting. Phosphate and potash fertilizers were applied 100% as preplanting each. All preplanting fertilizers were applied in pits whereas top dressing fertilizers were applied as ring placement in all the plots. Other cultural practices of the crop were followed as per recommendations by Indian Council of Agricultural Research – New Delhi [21].

The LDPE (low density poly ethylene) film of 50-micron thickness was used for mulching around the plant. The lateral lines of 12 mm diameter LDPE pipes were laid along the crop rows and each lateral served one row of crop. The laterals were provided with on-line emitters of 4 L/hr. discharge capacity. LDPE pipes of 75 mm diameter were used for main and 63 mm diameter was used for submain. The main line was directly connected to a 1.5 HP submersible pump installed to lift water from an open sump. The manifold unit was connected with a screen filter, a pressure gauge and control valve. The duration of delivery of water to each treatment was controlled with the help of gate valve provided at the inlet end of each lateral. In case of furrow irrigation, irrigation was scheduled at weekly interval.

The experiment was laid out in randomized block design having eight treatments and replicated thrice with a plot size of 6 m × 3 m. Each treatment was spaced 0.5 m apart to avoid overlapping of treatments (Fig. 1). The treatments were:

T1 = 100% irrigation requirement (IR) through drip irrigation (VD);
T2 = 80% IR through drip irrigation (0.8 VD);
T3 =60% IR through drip irrigation (0.6 VD);
T4 = 100% IR by furrow irrigation (V);
T5 = 100% IR through drip irrigation with black LDPE mulch (VD+M);
T6 = 80% IR through drip irrigation with black LDPE mulch (0.8 VD+M);

T_7 = 60% IR through drip irrigation with black LDPE mulch (0.6 VD+M); and
T8 = 100% IR by furrow irrigation with black LDPE mulch (V+M).

In furrow treatment, irrigation was applied to each furrow. Furrows were laid at 0.25% bed slope. The furrows had dyes at the downstream end to prevent runoff. Polythene sheets were inserted to a depth of 60 cm in the inner side of the dykes of each plot to prevent lateral seepage. In case of drip irrigation, there were two crop rows per each lateral and one dripper per plant. Figures 2 and 3 show the actual layout of drip in tomato crop in the field.

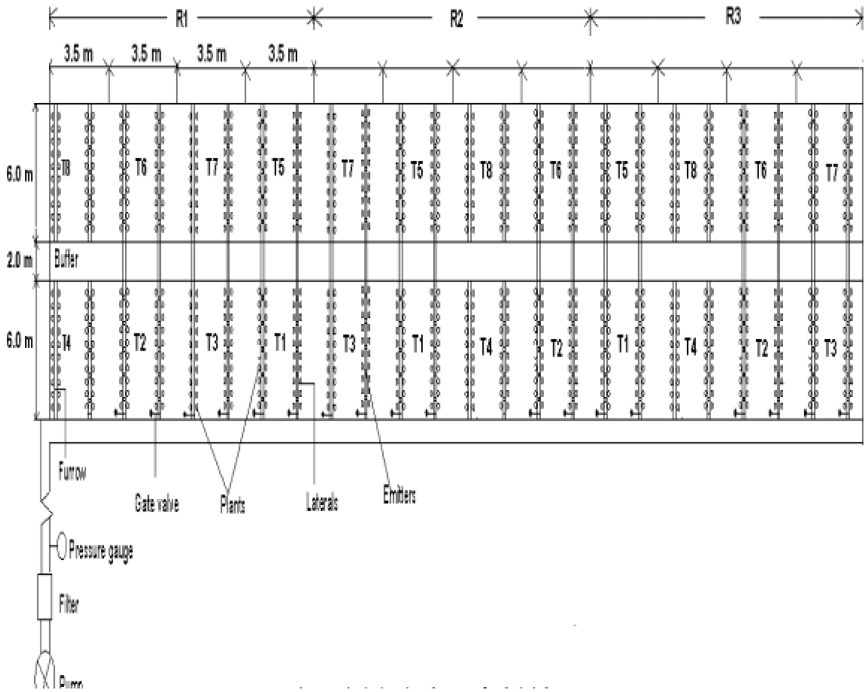

FIGURE 1 Schematic layout of the field experiment for the tomato crop.

FIGURE 2 Layout of laterals and drippers in the experimental field.

FIGURE 3 Tomato crop under drip irrigation.

15.3 ESTIMATION OF DAILY CROP WATER REQUIREMENT

The daily crop water requirement was computed by using Eq. (1) [19].

$$V = E_p.K_p.K_c.S_p.S_r.W_p \quad (1)$$

where: V = Volume of water required (liter/day/plant); E_p = Pan evaporation as measured by Class-A pan evaporimeter (mm/day); K_c = Crop coefficient which depends on crop growth stage; K_p = Pan coefficient, 0.8 [12]; S_p = plant-to-plant spacing (m); S_r = row-to-row spacing (m); and W_p = Fractional wetted area that varies with crop growth stage.

Based on the field experiment, the value of K_c of tomato was for 0.45 crop establishment, 0.75 for crop development, 1.10 for mid-season, and 0.65 for maturity stages, respectively. The values of W_p was assumed as 0.5 during crop establishment stage and 0.75 during other stages [2].

Water requirement of tomato was estimated on daily basis for all months of a particular year by drip method. Daily operating time for drip irrigation system was worked out taking the application rate per plant. Drip system was scheduled to operate on alternate days, therefore total quantity of water delivered was cumulative water requirement of two days. Operating time of the drip irrigation for each treatment was computed using Eq. (2).

$$\text{Operating time} = [V]/[(\text{Number of emitters per plant}) \times (\text{emitter discharge rate})] \quad (2)$$

where: V is volume of water required (liter/day/plant), and operating time is in hours. Volume of irrigation water and hence the operating time of each treatment was different depending on evaporation rate, crop growth stage as well as treatment irrigation scheduling. Observations on water requirement and yield of tomato were recorded and analyzed statistically following the standard procedures [14]. The water use efficiency (WUE) of the crop was determined by dividing the yield with crop water requirement. Biometric observations were recorded for plant height, number of branches per plant, number of leaves and average yield attributing characters such as days taken to first harvest, number of fruits per plant and the yield of tomato.

15.4 RESULTS AND DISCUSSION

15.4.1 YIELD AND YIELD ATTRIBUTING PARAMETERS

Data for 2006 and 2007 included yield attributing characters: Plant height, number of branches per plant, days taken to first harvest, number of fruits per plant and the yield of tomato; and are presented in Tables 2 and 3 including the statistical data. The mean data of different yield attributing parameters and yield of tomato are also presented in Table 4 along with the statistical test data.

TABLE 2 Yield and yield attributing parameters of tomato as affected by different treatments for the year 2006.

Treatments	Plant height, cm	No. of branches per plant	Days taken to first harvest	No. of fruits per plant	Yield t/ha
T_1	58.0	23.6	70	39.4	16.5
T_2	56.8	22.0	71	37.8	15.0
T_3	57.0	21.6	72	35.7	13.5
T_4	55.0	20.1	74	30.2	12.0
T_5	60.8	28.5	66	45.4	18.8
T_6	60.3	27.1	67	43.2	16.8
T_7	58.1	25.3	69	40.5	14.7
T_8	57.2	21.3	75	34.7	12.5
SE (m)	0.955	0.698	0.771	0.490	0.43
CD (0.05)	2.898	2.117	2.340	1.486	1.29

TABLE 3 Yield and yield attributing parameters of tomato as affected by different treatments for the year 2007.

Treatments	Plant height, cm	No. of branches/ plant	Days taken to first harvest	No. of fruits per plant	Yield t/ha
T_1	59.2	24.6	69	40.1	17.5
T_2	57.8	23.0	70	38.3	16.6
T_3	57.0	21.9	70	36.7	14.1
T_4	56.2	20.8	72	31.0	12.8
T_5	60.5	29.5	67	46.0	19.2

TABLE 3 *(Continued)*

Treatments	Plant height, cm	No. of branches/ plant	Days taken to first harvest	No. of fruits per plant	Yield t/ha
T_6	59.7	28.1	68	44.2	17.4
T_7	58.6	26.8	69	42.5	15.3
T_8	57.2	22.3	74	35.3	13.0
SE (m)	0.965	0.798	0.756	0.530	0.456
CD (0.05)	2.798	2.317	2.542	1.566	1.312

TABLE 4 Mean yield and yield attributing parameters of tomato as affected by different treatments.

Treatments	Plant height, cm	No. of branches/ plant	Days taken to first harvest	No. of fruits/ plant	Yield t/ha
T_1	58.6	24.1	69.5	39.8	17.0
T_2	57.3	22.5	70.5	38.1	15.5
T_3	57.0	21.8	71.0	36.2	13.8
T_4	55.6	21.5	73.0	30.6	12.4
T_5	61.7	28.8	66.5	45.7	19.0
T_6	60.0	27.6	67.5	43.7	17.1
T_7	58.4	26.1	69.0	41.5	15.0
T_8	57.2	21.7	75.0	35.0	12.8
SE (m)	0.951	0.761	0.745	0.523	0.448
CD (0.05)	2.722	2.392	2.523	1.511	1.304

The results in Tables 2 to 4 show that yield and yield attributing parameters are significantly superior in the treatment T_5 as compared to the rest of the treatments. The treatment T_5 recorded the lowest days to harvest the first fruit, that is, 66 days in 2006 and 67 days in 2007, respectively, with a mean value of 66.5 days. Compared to the furrow irrigation without any mulch (treatment, T4), these values were 72 in 2006 and 74 in 2007, respectively, with mean value of 73 days. The mean value represents that it takes 6.5 days less for the first fruit to be harvested in treatment T5 as compared to treatment T4.

Mulching treatment for various irrigation scheduling rates represents that imposition black plastic mulch (LDPE) decrease the days for harvesting the fruits. This fact is true for both the years of data and also for the mean value (Tables 2 to 4). Number of fruits per plant in treatment T_5 (100% irrigation requirement through drip irrigation with LDPE mulch) was recorded highest (45.4 for 2006 and 46.0 for 2007 with a mean value of 45.7), which is 15.2, 14.7 and 14.9% higher compared to the values in treatment T1 (100% irrigation requirement through drip irrigation without LDPE mulch) for the corresponding years in sequence. As regards to number of branches per plant, maximum value of the mean of two years data was recorded in T_5 (28.8) followed by T_6 (27.6) and lowest value in T_4 (20.5).

The results also show that the influence of mulch on growth of the plants in terms of number of branches per plant, which is also high. The reader can observe in Table 3 that the number of branches per plant for treatment T1 is 24.1 compared to 28.8 for treatment T5. This trend is true for all other treatments with mulch and nonmulch conditions. The highest increase in yielding attributing parameters in treatment T_5 might be due to availability of soil moisture as well as optimum temperature as compared to all other treatments. The lowest value of the yield attributing parameters in treatment T4 may be due to unfavorable moisture regime (moisture stress or excess moisture) in the soil through surface irrigation and competition of weeds for nutrients. All the yield-attributing characters are significantly higher in treatment T_5 compared to other treatments. Mulch has significant effect on yield attributing characters than nonmulch treatments.

The crop yield was 18.8 t/ha in 2006 and 19.2 t/ha in 2007, respectively, with a mean value of 19.0 t/ha. The corresponding values were 16.5, 17.5 and 17.0 t/ha for treatment T1; 12.0, 12.8 and 12.4 t/ha for treatment T4; and 12.5, 13.0 and 12.8 t/ha for treatment T8, respectively. Therefore, this study reveals that mulching has a great effect on the crop yield. The data represents that imposition of mulch in the crop enhances the crop yield by increasing 11.8% yield for the treatment T5 and for furrow irrigation method (surface irrigation), the yield increase was 3.2% for the treatment T8 over the treatment T4 (See Table 4).

Irrigation scheduling also had a great influence on the crop yield. Irrigation with 100%, 80% and 60% irrigation requirements with mulch and nonmulch conditions, recorded lower crop yield in sequence. For example, the mean crop yield in treatment T1 was 9.7% higher than treatment T2 and 23.2% higher than the treatment T3 (Table 4). Similarly, with the incorporation of mulch, the mean crop yield of treatment T5 was 11.7% higher than treatment T6 and 26.7% higher than the treatment T7. When we compare the mean yield data, it is observed that the drip irrigation has a significant effect on augmenting the yield over the conventional furrow irrigation. For example, the mean yield of tomato with 100% irrigation requirement without mulch has 37.1% increase than the furrow-irrigated treatment without any mulch.

The low yield recorded under surface irrigation method may be due to water stress during critical growth period, coupled with aeration problem in first few days immediately after irrigation. Also due to heavy application of irrigation water, the availability of nutrients for crop growth was less due to leaching and also due to heavy weed infestation between the crops. On the other hand in drip irrigation system, water is applied at a low rate for a longer period at frequent intervals near the plant root zone through low-pressure delivery system. It increased the availability of nutrients near the root zone with a reduction in leaching losses. More nutrient availability, especially near the root zone might have increased the translocation of photosynthesis to storage organs of tomato resulting in an increased growth and hence increasing the yield. With introduction of the LDPE sheet, the crop yield with 100% irrigation requirement is found to be 48.4% higher than the furrow irrigated crop with mulching. This fact is true for all other treatments with mulch and nonmulch conditions. Thus, the study represents that irrigation schedules, methods of irrigation and mulching have significant effect on increasing the crop yield.

15.4.2 CROP WATER REQUIREMENTS

Crop water requirements for various treatments for both 2006 and 2007 are presented in Tables 5 and 6, respectively. The mean data is presented in Table 7.

TABLE 5 Yield, water requirement and water-use-efficiency of tomato for different treatments in 2006.

Treatments	Yield, t/ha	Water requirement, cm	Water-use-efficiency, t/ha/cm
T_1	16.5	25.5	0.647
T_2	15.0	24.2	0.620
T_3	13.5	23.3	0.579
T_4	12.0	29.3	0.410
T_5	18.8	24.1	0.780
T_6	16.8	23.6	0.711
T_7	14.7	22.1	0.665
T_8	12.5	27.2	0.460
SE (m)	0.426	0.11	0.231
CD (0.05)	1.293	0.31	0.431

TABLE 6 Yield, water requirement and water-use-efficiency of tomato for different treatments in 2007.

Treatments	Yield, t/ha	Water requirement, cm	Water-use-efficiency, t/ha/cm
T_1	17.5	26.2	0.668
T_2	16.6	25.3	0.656
T_3	14.1	24.1	0.585

TABLE 6 *(Continued)*

Treatments	Yield, t/ha	Water requirement, cm	Water-use-efficiency, t/ha/cm
T_4	12.8	30.0	0.430
T_5	19.2	25.0	0.768
T_6	17.4	24.2	0.719
T_7	15.3	23.2	0.659
T_8	13.0	28.0	0.464
SE (m)	0.456	0.13	0.243
CD (0.05)	1.312	0.38	0.441

Crop water requirement is less in treatment T3 compared to T1 for both the years. The crop water requirement for T3 was 23.3 T3 in 2006 and 24.1 in 2007, respectively, with a mean value of 23.7 cm. The mean water requirement in T3 was 8.5% more than T1 and 4.4% more than T2. The reason of low water requirement in T3 may be due to higher application of irrigation since we have to supply 100% irrigation in T1 and 80% irrigation requirement in T2, and in treatment T3 we are applying only 60% irrigation requirement at each irrigation. Comparing the water requirement of drip and furrow irrigation, it is observed that the furrow irrigation required higher amount of water than the drip system for both the years. In treatment T4 which is furrow irrigated treatment without mulch, the mean water requirement of the crop was 29.7 cm, which is 14.7, 19.8 and 25.3% higher as compared to treatments T1, T2 and T3, respectively. The reasons of obtaining higher water requirement in furrow irrigation may be due to higher application rate than the actual crop requirement resulting deep percolation and runoff. However, because of some limitations, deep percolation study in various treatments could not be carried out.

TABLE 7 Mean yield, water requirement and water-use-efficiency of tomato for different treatments.

Treatments	Yield, t/ha	Water requirement, cm	Water-use-efficiency, t/ha/cm
T_1	17.0	25.9	0.656
T_2	15.5	24.8	0.625
T_3	13.8	23.7	0.582
T_4	12.4	29.7	0.418
T_5	19.0	24.9	0.763
T_6	17.1	23.9	0.715

TABLE 7 *(Continued)*

Treatments	Yield, t/ha	Water requirement, cm	Water-use-efficiency, t/ha/cm
T_7	15.0	22.7	0.661
T_8	12.8	27.6	0.464
SE (m)	0.448	0.439	0.253
CD (0.05)	1.304	1.312	0.453

Incorporation of mulch in some treatments reveals that it has significant effect on reducing the crop water requirement. The mean water requirement of treatment T1 was 25.9 cm and when we used mulch the same treatment (now it is designated as treatment T5) gave water requirement of 24.6 cm (Table 7). Thus there is a reduction of 5.01% water requirement because of mulching. Similarly, the mean water requirement of furrow method of irrigation without mulch (Treatment T4) is 29.7 cm but it is reduced by 7.07% for mulching. The reason that mulching reduces water requirement may be due to the fact that evaporation from the crop root zone is reduced because of LDPE cover in the soil and thereby reducing the crop evapotranspiration. This causes less amount of water to be applied to the crop, consequently decreasing the water requirement. Thus, the study reveals that irrigation scheduling, methods of irrigation as well as mulching has significant effect on water requirement of the crops and thus, play great role in saving of irrigation water. From the study, it is suggested that the crop should be irrigated with drip methods rather than furrow and inclusion of mulch will save a lot of costly irrigation water.

15.4.3 WATER USE EFFICIENCY

Yield, water requirement and water-use-efficiency (WUE) of the crop for 2006 and 2007 are presented in Tables 5 and 6, respectively. The mean values of the above mentioned parameters are presented in Table 7. The data in Tables 5 to 7 indicate that the values of WUE of the crop are highest for treatment T5 with values of 0.780 t/ha/cm and 0.768 t/ha/cm in 2006 and 2007, respectively, with a mean value of 0.763 t/ha/cm. This value of WUE in treatment T4 is computed to be the lowest with value of 0.410 t/ha/cm in 2006 and 0.430 t/ha/cm in 2007 with a mean value of 0.418 t/ha/cm (Table 7). Thus there is 82.5% more WUE of the crop in treatment T5 as compared to treatment T4. The furrow treatments resulted in reduced WUE than the drip irrigated treatments. The reason may be due to low yield of the crop in furrow treatments with high water requirement. The drip treatments gave higher yield and at the same time required less water, and therefore the value of WUE was less. Among the different irrigation scheduling methods used in drip treatments, treatment T1 gave mean WUE value of 0.656 t/ha/cm whereas T2 and T3 gave 0.625 and 0.582 t/ha/cm, respectively. Treatment T1 resulted in obtaining 5.0% more WUE than T2 and 12.71% more in treatment T3. The reason of getting more WUE for treatment T1 may be due to the fact that in treatment T1, more water is applied to the crop in the effective root zone resulting a favorable soil moisture regime that enhances the growth and yield of the crop; consequently giving high value of WUE.

The study further indicated that mulching had significant influence in increasing the WUE of the crop. When mulching was done, drip irrigation with 100% irrigation requirement enhanced the mean WUE by 16.3% as compared to drip irrigation with 100% irrigation but with no mulch. Similar trend was noticed for other treatments with and without mulch. Thus, the study suggests that irrigation to tomato may be done by drip irrigation to meet the 100% irrigation requirement along with inclusion of black plastic mulch.

15.5 SUMMARY

Field experiments were conducted at the Regional Research and Technology Transfer Station in Chiplima – Odisha – India for two years (2006 and 2007) to study the effects of drip and furrow irrigation on yield and water use efficiency of tomato grown under the mulching and nonmulching condition. The experiment was laid out in randomized block design having eight treatments and three replications each. Out of the eight treatments, six comprises of 100, 80 and 60% irrigation requirement of the crop with mulching and nonmulching conditions irrigated by drip system and two with furrow irrigation at 100% irrigation requirement with mulching and nonmulching condition.

The study revealed that treatment with 100% irrigation requirement along with mulching (Treatment T5) gave the highest yield and yielding attributing data among all other treatments. The same treatment also gave significantly highest of tomato (19.0 t/ha, mean of two years) compared to other treatments with highest water -use-efficiency of 0.763 t/ha/cm (mean of two years). Yield and water-use-efficiency of the crop for drip-irrigated system are found to be more than conventional furrow irrigation. Amongst the drip irrigated crops, the yield of the crop was found to be maximum when the crop was irrigated to meet 100% irrigation requirement. The study also indicated that mulching played a significant role in enhancing yield, decreasing water requirement and hence augmenting the water-use-efficiency of tomato. When the crop is irrigated by drip system to meet 100% irrigation requirement along with mulching, water-use-efficiency increases by 82.5% than when the crop is irrigated by furrow system without any mulch, which is the conventional irrigation system for tomato in the region.

KEYWORDS

- **Drip Irrigation**
- **Furrow Irrigation**
- **India**
- **Irrigation requirement**
- **Micro-irrigation**
- **Mulching**
- **Orissa University of Agriculture and Technology**

- **Plastic mulch**
- **Sprinkler Irrigation**
- **Tomato**
- **Water use efficiency**
- **Yield**

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CHAPTER 16

TENSIOMETER BASED AUTOMATED IRRIGATION FOR TOMATO UNDER PLASTICULTURE

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CONTENTS

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16.1 INTRODUCTION

More than 65% of U.S. total vegetable acreage is irrigated [14]. Although used on approximately 7% of the total irrigated acreage in the U.S., drip irrigation is widely used on high-value crops [15]. Improvements in drip irrigation and increases in plasticulture production have prompted significant increases (> 500%) in its use over the previous 20–30 years, [14]. Drip irrigation, if properly managed, can achieve up to 95% application efficiencies [25].

Due to increases in yield and quality, growers often over irrigate, viewing it as a cheap insurance policy for growing fruits and vegetables. However, just 5 h after the initiation of drip irrigation, the wetting front under an emitter may reach 45 cm from the soil surface, effectively below the root zone of many vegetables [9]. Water can migrate upward into the root zone through capillary action on fine textured soils; however, movement decreases as texture becomes coarser. Additionally, small scale variability in soil textures may affect water movement [18, 40]. If water reaches a clay subsoil, upward movement into a coarser loam topsoil can be limited. Fertilizers and pesticides may also leach below the root zone of plants grown in coarse soils when excessive water is applied [36]. Methods for improved scheduling and management of irrigation may increase water use efficiency as well as potentially reduce the leaching of agricultural chemicals.

Irrigation scheduling has traditionally been weather or soil based; although several plant-based scheduling methods have been proposed [10, 16]. In weather-based scheduling, the decision to irrigate relies on the soil water balance. The water balance technique involves determining changes in soil moisture over time based on estimating evapotranspiration (Et) adjusted with a crop coefficient [23]. This method takes environmental variables into account along with crop coefficients that are adjusted for growth stage and canopy coverage [12]. However, irrigating based on crop Et values may be subject to inaccuracies due to variations in local conditions and production practices [1, 5]. Furthermore, some growers do not have access to appropriate local weather data and the programs necessary to properly schedule irrigation.

Often soil moisture-based methods are used to schedule irrigation. Perhaps the simplest and most common technique is the "feel method," where irrigation is initiated when the soil "feels" dry [1]. More sophisticated methods involve using a tensiometer or granular matrix type sensor [20, 24, 30, 34]. These methods require routine monitoring of sensor(s), with irrigation decisions made when soil moisture thresholds have been reached. This requires the development of threshold values for various crops and soil types. Soil water potential (Ψ_s) thresholds for vegetable crops such as tomato (*Lycopersicon esculentum*) and pepper (*Capsicum spp.*) have been developed [13, 30, 32, 35]. In threshold studies, Ψ_s levels are maintained at a near constant level using automated systems [30]; or the soil is wetted for a period of time then allowed to dry out [35]. In sandy soils, high-frequency, short-duration (pulsed) irrigation events can reduce water use while maintaining yields of tomato when compared to a traditionally scheduled high-volume, infrequent irrigation [20]. Pulsed irrigation results in a shallower wetting front shortly after the irrigation event, increasing application efficiencies [2, 43, 44]. Although data for pulsed irrigation is available for sandy soils, comparisons of the effects of irrigation duration and frequency at different thresholds for vegetables on fine textured soils are largely unavailable.

The purpose of this research was to use a tensiometer-controlled, automated irrigation system to compare pulsed irrigation to longer-duration, high-volume irrigations at different soil water potential (Ψ_s) levels for tomato grown using a plasticulture production system in a silt loam soil.

16.2 MATERIALS AND METHODS

This study was conducted during 2009 and 2010 at the University of Kentucky Horticulture Research Farm in Lexington, KY (lat. 38°3'N, long. 84°30'W). 'Mountain Fresh' tomato seeds (Seedway, Elizabethtown, PA) were planted into 72 cell greenhouse trays filled with soil-less media (Pro-Mix BX; Premier Tech, Riviere-du-Loup, QC, Canada) on 15 April 2009 and 4 May 2010. Seedlings were grown in the greenhouse with temperature set points of 25/20 °C (day/night). Plants were watered daily as needed and fertilized weekly with a 150 $mg \cdot L^{-1}$ nitrogen (N) solution (20N–4.4P–16.6K; Scotts, Marysville, OH). Tomato plants were greenhouse grown using recommended practices for transplant production in Kentucky [6]. Tomato seedlings were transplanted using a water-wheel planter on 29 May 2009 and 14 June 2010. Plants were set into 4–5-inch tall raised beds covered with 1-mil embossed black plastic mulch with a single line of drip irrigation tubing (12-inch emitter spacing, 0.45 gal/min per 100 ft., Aqua-Traxx; Toro, El Cajon, CA) placed approximately 1 inch below the soil surface in the center of each bed. Plants were set approximately 4 inches to the side of drip irrigation lines. Beds were approximately 30-inches across and spaced on approximately 6.5-ft centers. Transplants were placed in single rows on each bed with 18-inch in-row spacing.

The soil was a Maury silt loam series, mesic Typic Paleudalfs. Soil samples were collected after bed formation and transplanting. Five samples were taken from each plot to a depth of 100 cm, in 20-cm segments. The pipette method was used for particle size analysis [29]. Soil texture was found to be either silt loam or silty clay loam. Sand and silt content varied from 6.5% to11.0% and 49.6% to73.2%, respectively. Clay content ranged from 19.3% to 39.3%. Bulk densities of soil under natural conditions were determined using a core of known volume [11]. A core sampler was pushed into the soil at depths of 5–15 cm and 25–35 cm. Soil extracted from the sampler was oven dried and weighed. Bulk density varied from 1.33–1.74 $g \cdot cm^{-3}$.

Preplant fertility (19N–8.3P–15.8K; Southern States Cooperative, Richmond, VA) was applied under the plastic mulch at a rate of 75 lb/acre N. Supplemental fertility was initiated two weeks after transplanting and was supplied through five fertigation events alternating between calcium nitrate and ammonium nitrate, applied at a rate of 15 lb/acre N per week. Preventative spray schedules for diseases were followed with weekly sprays made according to recommendations for fresh market tomato grown in Kentucky [6]. One application of spiromesifen (Oberon 2SC; Bayer Crop Science, Research Triangle Park, NC) was made in August 2009 to control two-spotted spider mite (*Tetranchyus urticae*).

Automated irrigation was managed using paired or single-switching tensiometers (model RA 12-inch; Irrometer, Riverside, CA). In paired treatments, one tensiometer functioned to turn on irrigation while the other turned it off. In the single-tensiometer treatment, irrigation solenoids were turned on and off by one switch. A single-tensiometer treatment was chosen to determine if a simpler automated system with one measurement point could be comparable to a two-tensiometer setup. Tensiometers were placed approximately 8 inches from the tomato plants and 4-inches from the edge of the raised beds, at a depth of 8-inches from the upper surface of the bed. On/off set points for the four, two-tensiometer treatments were as follows: on/off −30/–10, −30/–25, −45/–10, −45/–40 kPa. The single-tensiometer treatment was set at −35 kPa in 2009 and −40 kPa in 2010. These set points were based on previously reported thresholds [8, 39]. Irrigation treatments were implemented on 17 June 2009 and 27 June 2010 after plants were established. The frequency and duration of the automated and manual irrigation events were recorded with data loggers (Hobo U9 State Data Logger; Onset, Cape Cod, MA). Water usage for the season was calculated by multiplying the frequency and duration of irrigation events by the flow rate of drip irrigation tubing at a constant pressure (10 psi). There were four replications of irrigation treatments. Treatment plots consisted of 20 plants (measurements were taken on 16 plants in the center of each plot) arranged in a completely randomized design for a total of 20 experimental plots. Previous research indicated that growing conditions in the plots used for this trial were uniform and a blocking design was not required.

In the 2009 growing season, two soil moisture probes (EC-5; Decagon Devices, Pullman, WA) per plot were placed at 6 and 12-inch depths into the raised beds in the same relative location to the tomato plants as tensiometers. Data loggers were unavailable for soil moisture data collection in 2010. On 3 July 2009, an access hole adjacent to the plant bed was dug and probes were inserted into undisturbed soils in the plant bed under the plastic. Probes were inserted in a parallel orientation with the soil surface at depths of 6 and 12 inches. Probes were connected to data loggers (Em 50; Decagon Devices) and soil volumetric water content (VWC) recorded hourly throughout the season.

Tomatoes were harvested five times each year. In 2009 harvests were conducted from 4 Aug. to 8 Sept. In 2010 fruit were harvested from 16 Aug. to 13 Sept. Plants were harvested approximately weekly. Fruit were graded according to U.S. Department of Agriculture standards for fresh market tomatoes [37].

Predawn and midday leaf water potential (Ψ_L) and leaf relative water content (RWC) measurements were initiated on 7 and 14 July 2009 and 2010, respectively. Measurements of leaf RWC and Ψ_L were conducted during the same time period on the same days throughout the study. Measurements were taken biweekly in 2009 and weekly in 2010. Plant Ψ_L was measured using a pressure chamber (Model 615; PMS Instrument Company, Albany, OR) using two recently matured, fully expanded leaves from plants near the center of each plot [27]. Leaf RWC, was conducted according to the method of Barrs and Weatherley [3], was determined on samples of five, recently matured, fully expanded leaves obtained from plants near the center of each plot. Upon removal from plants, leaves for Ψ_L and RWC were immediately placed in sealed polyethylene bags, packed in a cooler with ice and measured within 30 min of sampling.

Weather data were obtained from an on-farm weather station that recorded environmental variables every minute and provided hourly averages (Kentucky Mesonet, Fayette County Station, Lexington, KY [37]). The studies were terminated on 8 and 13 Sept. 2009 and 2010, respectively.

Statistical analyzes were conducted using the GLM, repeated measures, and Fishers least significant difference of SAS statistical software when appropriate (Version 9.1; SAS Institute, Cary, NC).

16.3 RESULTS AND DISCUSSION

The growing season in 2010 was drier and warmer than in 2009. Daily average air temperatures were 71.3 and 72.6°F in July and Aug. of 2009, respectively; but were 77.5 and 77.4°F in July and Aug. 2010, respectively. Rainfall was greater in 2009 compared to 2010. In 2009 the research site experienced 15.47 inches of rain during the study, while 10.19 inches were received in 2010. Irrigation events and water use are summarized in Table 1. In 2010, less water was applied than in 2009, despite being a hotter and drier growing season. Although it may be expected that greater irrigation would have been required in 2010, the results are supported by field observations. High temperatures observed in 2010 were supra optimal for tomato plant growth and plants were smaller in 2010 than in 2009 [17]. Typically soil moisture sensor-based irrigation systems will distribute water in a manner that is reflective of canopy and root growth [22, 42]. Therefore, it is not unexpected that plants with less leaf area would require less water.

TABLE 1 Mean number of irrigation events, irrigation time per event, and irrigation volume for the season 'Mountain Fresh' tomato grown under five automated irrigation regimes in 2009 and 2010 in Lexington, KY.

Irrigation Treatment on/off	2009			2010		
	Irrigations	Mean irrigation time	Mean irrigation volume	Irrigations	Mean irrigation time	Mean irrigation volume
kPa[z]	(no.)	(min/event)	(gal/acre[z,y])	(no.)	(min/event)	(gal/acre)
–30/–10	39	110	138,996	28	144	130,637
–30/–25	59	91	173,956	22	140	99,792
–45/–10	21	221	150,368	22	167	119,037
–45/–40	76	40	98,496	18	146	85,147
–35 or −40[x]	52	93	156,686	44	84	119,750

[z] 1 kPa = 1.0 cbar, 1 gal/acre = 9.3540 L·ha^{-1}.

[y] Assuming 7200 row feet (2194.6 m) per acre with drip irrigation emitter rate of 0.45 gal/min per 100 ft. (0.0559 L·min^{-1}·m^{-1}).

[x] Single tensiometer treatment set at −35 kPa (–35.0 cbar) in 2009 and −40 kPa (–40.0 cbar) in 2010.

Average water applied ranged from 98,500 to 173,960 gal/acre in 2009 and 85,150 to 130,640 gal/acre in 2010. In 2009, the −30/–10 or −45/–10 kPa treatments irrigated less frequently, but for longer periods of time than the −30/–25 and −45/–40 kPa treatments (Table 1). The −45/–10 treatment irrigated the fewest number of times, but represented the longest average irrigation duration of the given treatments in 2009. The −45/–40 kPa treatment reflected a pulsed irrigation regime with 76 irrigation events with an average duration of 40 min in 2009. This treatment also used the least water in the study, with 98,500 and 85,150 gal/acre in 2009 and 2010, respectively, (Table 1). The single-tensiometer treatment, which was set at −35 kPa in 2009, irrigated 52 times with an average length of 91 min and was most similar to the −30/–25 kPa treatment. This suggests that a single-tensiometer system can simulate pulsed irrigation, simplifying installation of an automated-irrigation system.

There were smaller differences among the pulsed and nonpulsed irrigation treatments in 2010 compared to 2009. In 2010, the number of irrigations ranged from 18 in the −45/–40 kPa treatment to 28 in the −30/–25 kPa treatment, and 44 in the −40 kPa treatment. In 2010, smaller plants demanding less water may have allowed sufficient time for greater movement of water in the plant bed through capillary action during the day [18], resulting in less frequent irrigations. In 2010, the pattern of irrigation duration and frequency for the single-tensiometer treatment was similar to 2009, but the other treatments were less reflective of the 2009 treatments. Although the frequency of irrigation in 2010 did not reflect the pulsed treatment settings as closely as in 2009, the amount of water applied was more representative of what would be expected in a pulsed system [42].

Soil VWC data was recorded hourly at depths of 6 and 12 inches in 2009 and generally was representative of the irrigation treatments (Fig. 1A–E).

There were significant differences in soil VWC between the different treatments at the depths measured (Table 2). In addition, there was a significant depth by treatment interaction for soil VWC (Fig. 1A–E). With the exception of a period of high rainfall in late July and early Aug., treatments had a consistent level of soil VWC in 2009 (Fig. 1A–E). In all treatments, soil VWC was greatest at a depth of 12 inches. Excavation of a representative sample of tomato plants and intact roots after harvest indicated that maximum rooting depth of plants ranged from 12 to 15 inches, with 80% of roots residing in the top 6 -inches of soil (data not shown). Average soil VWC at 6 inches ranged from 19.6% to 22.5% (Table 2). At a depth of 12 inches, soil VWC was significantly different in all treatments, ranging from 24.5% to 33.4%. The soil VWC measured at a depth of 6 inches more closely represented the applied irrigation treatments and water applied than when measured at 12 inches. Rooting depth and soil VWC results suggest that 6 inches may be an appropriate depth to monitor soil moisture in plasticulture grown tomato.

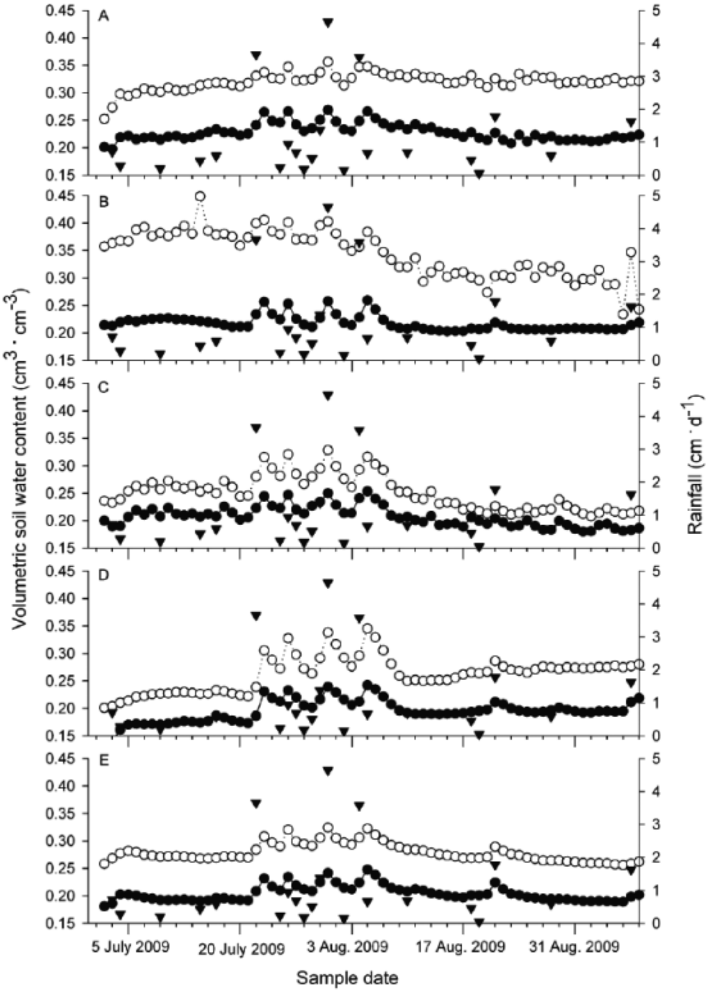

FIGURE 1 (A-E) Average daily soil volumetric water content (cm·cm^{-3}) measured at depths of 6 inches (●) and 12 inches (○) as well as daily rainfall (▼) (cm·day^{-1}) during the 2009 growing season for five automated, tensiometer-controlled irrigation regimes: on/off −30/–10 kPa (A), −30/–25 kPa (B), −45/–10 kPa (C), −45/–40 kPa (D), −35 kPa (E) for 'Mountain Fresh' tomato grown in Lexington, KY; 1 kPa = 1.0 cbar, 1 cm = 0.3937 inch, 1 cm^3 = 0.0610 inch^3.

TABLE 2 Mean volumetric water content (VWC) and differences between VWC measured at depths of 6 and 12 inches (15.2 and 30.5 cm) for 'Mountain Fresh' tomato grown in under five automated irrigation regimes in 2009 in Lexington, KY.

Irrigation Treatment on/off	**VWC at 6 inches^z**		**VWC at 12 inches**		**Difference (12 inch – 6 inch)**	
kPa^z	(%)					
–30/–10	22.5	a^y	31.8	b	9.3	b
–30/–25	21.7	b	33.4	a	11.7	a
–45/–10	20.3	c	24.5	e	4.2	d
–45/–40	19.6	d	26.4	d	6.8	c
–35	20.3	c	27.6	c	7.3	c

^{z}1 in = 2.54 cm, 1 kPa = 1.0 cbar.

^{y} Values in the same co lumn followed by the same letter are not significantly different at P≤0.05 according to Fisher's least significant difference test.

TABLE 3 Mean yields of medium, large, extra large, and total marketable fruit, average fruit weight and percentage of cull fruit for tomato 'Mountain Fresh' grown with five automated irrigation regimes in 2009 and 2010 in Lexington, KY. Fruit were graded according to USDA standards for fresh market tomatoes.

Irrigation Treatment on/off	**Total marketable yield**		**Medium fruit**	**Large fruit**		**Extra large fruit**	**Average fruit weight^z**	**Cull fruit**
kPa^y	**(kg·ha^{-1})^y**						**(g·fruit^{-1})^y**	**(%)**
2009								
–30/–10	46,250		15,410	13,610^x	a	17,230	296	25.8
–30/–25	46,050		16,100	13,980	a	15,960	287	27.8
–45/–10	44,880		15,040	14,510	a	15,330	297	26.5
–45/–40	48,210		21,060	13,230	a	13,920	278	25.3
–35	38,500		16,150	9,530	b	12,820	278	32.8
Treatment^w	NS		NS	*		NS	NS	NS
–30/–10	19,730	a	10,510	5,240	3,980	ab	104	50.2
–30/–25	15,460	b	9,860	3,700	1,900	c	103	55.8
–45/–10	18,300	ab	9,130	4,260	4,910	a	108	50.3
–45/–40	16,590	ab	9,230	3,890	3,480	b	106	57.8
–40	17,460	ab	10,130	4,330	3,000	bc	106	53.3
Treatment	*		NS	NS	*		NS	NS
Year x Treatment	NS		NS	NS	NS		NS	NS

^{z} Average weight of marketable fruit

^{y}1 kg·ha^{-1} = 0.8922 lb/acre, 1 g = 0.353 oz, 1 kPa = 1.0 cbar

^{x} Values in the same column and year followed by the same letter are not significantly different at P≤0.05 according to Fisher's least significant difference test

^{w} NS, *= not significant and significant at *P*≤0.05, respectively.

The difference between soil VWC at 6 and 12 inches was greatest in the −30/–25 kPa and smallest in the −45/–10 kPa treatment (Table 2). Much of this difference was due to an increase in the soil VWC at the 12-inch depth. Interestingly, for a given threshold (–30 kPa or −45 kPa) in the paired tensiometer treatments, the pulsed treatments had a larger difference in soil VWC between the 6 and 12-inch depths.

These results indicate that the automated irrigation management system used in this trial provided the desired soil moisture regimes, similar to previously suggested thresholds [20, 39]. In addition, the utility of using an automated system for conducting irrigation research in a field setting has been demonstrated. Total marketable yields were not affected by irrigation treatment in 2009, but were significantly affected in 2010 (Table 3). However, these were not significant year by treatment interactions for yield parameters measured.

In 2009, total marketable fruit yields averaged 44,780 kg·ha^{-1}. Yields of medium fruit averaged 16,750 kg·ha^{-1}, with large and extra large fruit contributing 12,970 and 15,050 kg·ha^{-1}, respectively. In 2009, the −35 kPa treatment had significantly less large fruit than the other treatments. However, this did not result in different total marketable yields. Average fruit weight was 287 g/fruit in 2009 and was not affected by irrigation treatment. Cull fruit averaged 27.6% in 2009 and were not significantly different among treatments.

In 2010 total marketable fruit yields were significantly affected by irrigation treatment. Yields of medium and large fruit were unaffected, averaging 9750 and 4280 kg·ha^{-1}, respectively. However, yields of extra large fruit were affected by irrigation regime (Table 3).

Yields of extra large fruit were lowest in the −30/–25 kPa treatment and highest in the −45/–10 and −30/–10 kPa treatments. When comparing the longer-duration irrigation regimes (–30/–10 and −45/–10 kPa) to the pulsed (–30/–25 and −45/–40 kPa) programs, the extended-duration regimes had higher yields of extra large fruit at a given setpoint. The −30/–10 kPa program yielded significantly more extra large fruit than the −30/–25 kPa regime. Similarly, the −45/–10 treatment yielded significantly more extra large fruit than the −45/–40 treatment. The pulsed, −40-kPa treatment had yields of extra large fruit that were significantly different from the −45/–10 kPa treatment, but no others. The −45/–40 kPa treatment used the least amount of water while producing yields that were no different from the highest yielding treatments in both years of the trial. Average fruit weight was 105 g/fruit and was not affected by irrigation regime in 2010. The average percentage of cull fruit was unaffected by treatment in 2010 and was 53.5%. In 2010, the cull rate was significantly greater than in 2009. The high percentage of cull fruit was the result of large numbers of small fruit in 2010.

Yields for all grades of fruit and total marketable fruit were significantly greater in 2009 than in 2010. Total marketable fruit yields ranged from 38,500 – 48,210 kg·ha^{-1} in 2009 and 15,460–19,730 kg·ha^{-1} in 2010. Yields were appropriate for fresh market tomato grown in Kentucky in 2009, which typically average 45,500 kg·ha^{-1}, but were considered low in 2010 [41]. The growing season in 2010 was warmer than 2009, resulting in smaller plants with significantly lower yields. Yields of medium fruit, which were not significantly affected by irrigation treatment in either year, were lower in 2010 than 2009 (Table 3). Medium fruit yield averaged

16,750 kg·ha^{-1} in 2009 and 9750 kg·ha^{-1} in 2010; a reduction of approximately 41%. However, yields of large and extra large fruit were reduced by 67% and 77%, respectively, in 2010. This reduction in yield of large and extra large fruit was reflected in average fruit weight, which was reduced from an average of 287 g/fruit in 2009 to 105 g/fruit in 2010. Air temperatures during the summer of 2010 were supra optimal for field tomato production in Kentucky [16]. The higher than normal temperatures in July and Aug. 2010 resulted in yield losses for many fruiting vegetables in Kentucky [28, 33].

In both years of this trial the −45/–40 kPa treatment used the least water. The most typical irrigation practice for fresh market tomato growers in Kentucky would be reflected in the −30/–10 and −40/–10 kPa treatments where plants may be watered for three or four hours, once or twice per week. Trials conducted with sandy soils reported similar water savings through pulsed irrigations, without significant differences in yield compared to typical grower practices [20, 42]. This suggests that irrigation practices may be altered in Kentucky to achieve additional water savings.

Predawn and midday plant Ψ_L and leaf RWC were analyzed to determine if physiologic stresses were imposed. Predawn and midday Ψ_L were not affected by irrigation in 2009 and 2010 (Fig. 2A–D). In both years, midday Ψ_L was significantly greater than predawn Ψ_L. The increase in Ψ_L from predawn to midday varied according to sampling date. On 6 Aug. 2009 Ψ_L increased from 0.6 MPa predawn to 7.7 MPa midday, but on 1 Sept. 2010 Ψ_L increased from 4.2 to 7.6 MPa at predawn and midday, respectively. In 2009 a decrease in predawn Ψ_L was observed on 6 and 18 Aug. (Fig. 2C), which occurred after a rain event (Figs. 1A to 1E). In 2010 predawn Ψ_L increased significantly on 28 July and 11 Aug. (Fig. 2D), which did not correspond with a particular rain event, but did correspond with a period of daily high air temperatures greater than 90°F. Another study [21] reported similar fluctuations throughout the growing season when measuring Ψ_L bell pepper.

Predawn water potential was significantly greater in 2010 than in 2009. Average predawn Ψ_L for the 2010season was 4.2 MPa compared to 2.2 MPa in 2009 (Figs. 2C and 2D). This may be due to the higher temperatures observed in the 2010 growing season. Positive correlations between Ψ_L and air temperature were reported [7, 26]. Although environment affected Ψ_L in 2009 and 2010, irrigation regime was not shown to significantly affect Ψ_L.

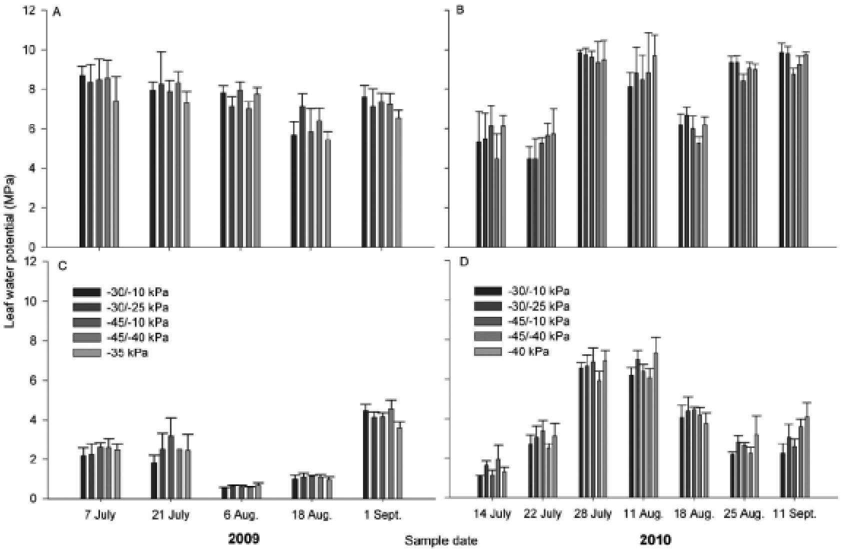

FIGURE 2 (A–D) Leaf water potential for five automated, tensiometer-controlled irrigation regimes: on/off −30/–10, −30/–25, −45/–10, −45/–40 kPa, and −35 or −40 kPa for 'Mt. Fresh' tomato grown in Lexington, KY in 2009 and 2010. Midday water potential in 2009 (A) and 2010 (B), and predawn leaf water potential in 2009 (C) and 2010 (D); 1 kPa = 1.0 cbar, 1 MPa = 10.0 bar.

Predawn and midday leaf RWC, were measured. Generally leaf RWC remains stable during initial increases in Ψ_L and then decreases with further increases in Ψ_L [3, 31]. Predawn leaf RWC was significantly higher than midday leaf RWC in 2009 and 2010 (Fig. 3A–D). Predawn and midday leaf RWC was significantly affected by sampling date in both years, fluctuating in response to the environment. Typically on those dates when Ψ_L increased, leaf RWC decreased. This was particularly evident on 28 July and 11 Aug. 2010. In 2010 midday leaf RWC was significantly affected by treatment (Fig. 3B). In 2010 midday leaf RWC was significantly greater in the −40 kPa treatment than the other treatments. The season average midday leaf RWC of the −40 kPa treatment was 89.5%, while the other treatments averaged 87.2% (Fig. 3B). This indicates that the −40 kPa treatment experienced slightly less water stress during midday sampling in 2010. The −40 kPa treatment irrigated at a much greater frequency (44 events) than all others in 2010 (Table 1). Leaf RWC, which measures water in leaves relative to a state of full turgor, may remain stable despite changes in Ψ_L, as plants compensate for changes in soil moisture or the environment [3, 4, 31]. Frequent irrigation events could have allowed for water to be readily available to the plant during midday stress.

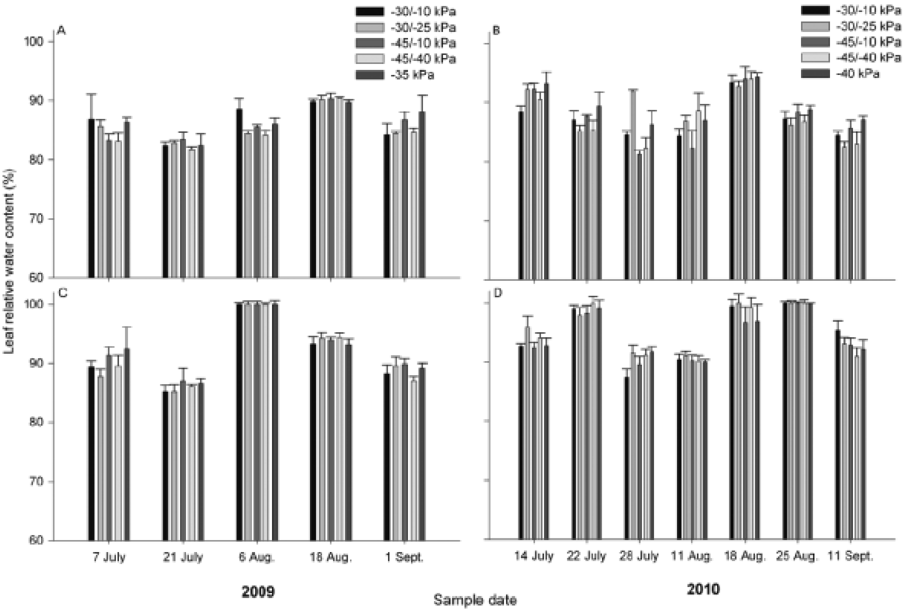

FIGURE 3 (A–D) Leaf relative water content for five automated, tensiometer-controlled irrigation regimes: on/off −30/–10, −30/–25, −45/–10, −45/–40 kPa, and −35 or −40 kPa for ‘Mountain Fresh’ tomato grown in Lexington, KY in 2009 and 2010. Midday leaf relative water content in 2009 (A) and 2010 (B), and predawn leaf relative water content in 2009 (C) and 2010 (D); 1 kPa = 1.0 cbar.

With the exception of midday leaf RWC in the −40 kPa treatment in 2010, no other irrigation treatment exhibited significant differences in Ψ_L or leaf RWC. This suggests that although there were differences in frequency, duration, and amount of irrigation applied, no particular treatment resulted in documented plant stress.

16.4 CONCLUSIONS

Pulsed irrigation regimes have been developed through the use of soil moisture sensors and irrigation controllers. The utility of these systems has been demonstrated on sandy soils, where water use is reduced without sacrificing yields [20]. The results of this two-year trial suggest that pulsed irrigation, when controlled by soil moisture sensors, can reduce water use if maintained at an appropriate threshold. The single tensiometer and −30/–25 irrigation systems were effective at applying water in pulses. However, the −45/–40 kPa irrigation regime used the least amount of water in both years while maintaining yields. This suggests that a pulsed irrigation system may be appropriate for plasticulture tomato production on a silt loam soil when thresholds are determined. Our data as well as others [39] suggest that using a paired tensiometer system with set points of −45/–40 kPa can be effective, though additional research should be conducted at lower soil moisture tensions to determine the limit for set points for tomato grown in a plasticulture system on a silt loam soil.

16.6 SUMMARY

Soil moisture-based, high-frequency, low-volume (pulsed) irrigation management strategies have saved water while maintaining yields of vegetables grown in coarse textured soils. However, little is known regarding the efficacy of soil moisture-based pulsed irrigation on finer textured soils. Therefore, five, tensiometer-based, automated irrigation treatments were tested for tomato (*Lycopersicon esculentum* syn. *Solanum lycopersicum*) grown in a Maury silt loam soil in 2009 and 2010 in Lexington, KY. Irrigation treatments consisted of paired-tensiometer systems with on/off setpoints of −30/–10, −30/–25, −45/–10, −45/40 kPa in 2009 and 2010 and a single-tensiometer system with setpoints of −35 and −40 kPa, in 2009 and 2010, respectively. In 2009, the pulsed systems (–30/–25, −45/–40, and −35 kPa) irrigated more frequently, but for a shorter duration than nonpulsed systems (–30/–10 and −45/–10 kPa). Soil moisture measurements in 2009suggested that probes set at a depth of 6 inches were more closely matched to irrigation setpoints than those at 12 inches. In both years, the −45/–40 kPa setpoint treatment used the least amount of water while maintaining total marketable yields that were not significantly different than other treatments. Yields were significantly higher in 2009 than 2010, though atypical air temperatures in 2010 may have been the cause. Leaf water potential and relative water content were measured predawn and midday throughout the growing season in 2009 and 2010. Leaf water potential was not significantly affected by the treatments in either year, though leaf relative water content was affected in 2010. In this trial an automated, soil moisture-based irrigation system maintained yields and saved water when compared to a nonpulsed irrigation system using similar irrigation set points for tomato grown in a silt loam soil.

KEYWORDS

- **Automated irrigation**
- **Drip irrigation**
- **Leaf water potential**
- **Lycopersicon esculentum**
- **Plasticulture**
- **Pulsed irrigation**
- **Relative water content**
- **Sensor irrigation**
- **Soil water content**
- **Soil water potential**
- **Tensiometer**
- **Tomato**

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CHAPTER 17

MICRO IRRIGATION PRACTICES IN STRAWBERRY (*FRAGARIA X ANANASSA*)

AJIT K. PANDEY, A. K. SINGH, S. K. SINGH, and AJAY KUMAR

CONTENTS

17.1 INTRODUCTION

The Micro or drip or trickle irrigation system has proved its superiority over other conventional methods of irrigation, especially for horticultural crops (fruit crops) due to precise and direct application of water in the root zone. A considerable savings in water and fertilizer use, increased growth/development/yield of vegetable crops under drip irrigation have been reported in the past [2, 3]. The use of black polythene mulch in fruit and vegetable crops has been reported to control the weed incidence, reduce nutrient losses and improves the hydro-thermal regime of soil [1, 5]. Strawberry, being a shallow rooted plant requires more frequent but less amount of water in each irrigation, which can be accomplished more efficiently through drip system. The consequences of drip irrigation in this crop have not yet been completely established.

The present studies were therefore, undertaken to evaluate the effects of drip irrigation alone and in conjunction with polythene mulch compared to surface irrigation on water use efficiency, yield and quality of Strawberry.

The use of black polythene mulch in strawberry has been reported to control the weed incidence, reduce nutrient losses and improves the hydro-thermal regime of soil [4]. Strawberry, being a shallow rooted plant requires more frequent but less amount of water in each irrigation, which can be accomplished more efficiently through drip system. Considering the additional cost of inputs and the selling price of the quality produce, the polythene mulch with drip irrigation may be recommended to the more progressive farmers for cultivation of strawberry in Bihar. However, grass mulch can also be used to make technology more resource crunched farmer friendly intervention for cultivation of strawberry especially under Bihar socioeconomic condition.

The strawberry is the most profitable fruit crop in the shortest possible time as compared to other fruits.

By spending Rs. 1000,000/ha, one can get a receipt of Rs. 2,000,000/ha in strawberry. It can be grown on any type of soil, poor sand to heavy clay provided proper moisture organic matter and drainage is present.

It is a short day plant (about 10 days of less than 8 h sunshine for initiation of flowering).

In winter, the plants do not make any growth and remain dormant. In the spring with longer days and warm weather, the plants resume growth and begin flowering.

17.2 MATERIALS AND METHODS

A Field trial was conducted, under farmer's participatory research project, in the farmers' field in the Bhojpur district of Bihar – India, on clay loam soil. Soil characteristics were: pH 6.43, E.C. 0.13 dSm^{-1}, organic carbon 0.86%, The available N, P and K were 203.06; 551.6 and 14.73 kg/ha, respectively, with objectives to improve strawberry (*Fragaria x ananassa*) productivity and quality through drip irrigation and polythene mulch and to enhance water productivity through pressurized irrigation coupled with use of black polythene mulch along with surface irrigation. Treatments comprised of two irrigation schedules (drip and surface irrigation) and three mulches viz., black polythene (25 micron), paddy straw (4.0 t ha^{-1}) and nonmulched conditions. These treatments were tested on 2 m × 2 m raised bed plots (each plot consisted of 10 beds) arranged in randomized block design (RBD) with six replications:

T1 = Surface irrigation (SI) + nonmulch;
T2 = SI + paddy straw;
T3 = SI + BP mulch;
T4 = Drip irrigation (DI) + nonmulch;
T5 = DI + paddy straw; and
T6 = DI + BP mulch.

TABLE 1 Effects of irrigation and mulch treatments on fruit and dry matter yield and quality characteristics of strawberry fruits.

Treatments	**Fruit yield ($q\ ha^{-1}$)**	**Runner production/ plant**	**Berry weight (g)**	**Total Soluble Solids (%)**	**Acidity (%)**	**TSS/ Acid ratio**
T1	40.15	11.3	5.6	7.17	0.82	8.79
T2	41.54	07.7	6.8	6.74	0.71	9.28
T3	43.64	7.75	6.3	6.99	0.78	9.01
T4	42.07	16.6	6.1	7.06	0.80	8.78
T5	45.90	11.5	8.4	6.66	0.70	9.50
T6	50.10	12.3	7.0	6.86	0.71	9.37
CD ± (5%)	56.00	1.2	0.3	0.27	0.08	0.87

One quintal (q) = 100 kg in India.

17.3 RESULTS AND DISCUSSION

17.3.1 CROP YIELD

The data on Strawberry fruit (Table 1) indicate that the drip irrigation without mulch increased the fruit yield by about 21.0 and 9.0% over surface irrigation. The corresponding values with paddy straw mulch were 15 and 10%. Maximum fruit yield was observed in drip irrigation with black polyethylene (BP) mulch and increase in yield of 22%, over the surface irrigation plus BP mulch. These results are in accordance with the findings by Rolbiecki et al. [6] who observed higher Strawberry yield under drip compared to surface irrigation. Both the mulches were found to be effective in increasing the yield over un-mulch treatment. Surface irrigation with paddy straw and BP increased the yield by about 18 and 37% respectively, over the un-mulch plots (Table 1). The higher yields observed under different mulches may be explained in the light of results reported by Raina [5]. They observed that the paddy straw and polythene mulches are effective in altering the soil hydrothermal regimes, thus providing a favorable soil environment for enhanced root/shoot growth & the nutrient uptake by Strawberry. Higher yield under mulch treatments may be ascribed to its favorable effects on weed control.

Drip irrigation with polythene mulch gave significantly highest yield (5010 kg ha^{-1}) as compared to surface irrigation in an nonmulched condition (4015 kg ha^{-1} = 5.01 t ha^{-1}), however, the yield under paddy straw (4590 kg ha^{-1}) and nonmulched (4207 kg ha^{-1}) was next in order to drip with polythene mulch but were significantly at par among themselves. When calculated the percentage increase the drip with polythene mulch gave 25% higher yield than surface with nonmulched condition. The use of black polythene mulch in strawberry has been reported to control the weed incidence, reduce nutrient losses and improves the hydro-thermal regime of soil. Strawberry, being a shallow rooted plant requires more frequent but less amount of water for each irrigation, which can be accomplished more efficiently through drip system. Polythene especially black polythene mulch contributed significantly to control leaf spot disease. Higher yield under mulch treatments may be ascribed to its favorable effects on weed control. Quality fruits were harvested due to infestation free crop. Result shows that there was 85% weed control was achieved under black polythene mulch as compare to weedy check plot. Mulching could save precious laborer as it requires frequent weeding @ 15 days interval during the growing season. Considering the additional cost of inputs and the selling price of the quality produce, the polythene mulch with drip irrigation may be recommended to the more progressive farmers for cultivation of strawberry in Bihar. However, grass mulch can also be used to make technology more resource crunched farmer friendly intervention for cultivation of strawberry especially under Bihar socioeconomic condition. The corresponding values for water savings and increase in yield for Strawberry were 51 and 19%, respectively.

- The results further document that irrigation requirement of Strawberry can be met effectively by operating the drip system having discharge rate of 4 L/hr. biweekly during the growing season.

17.3.2 STRAWBERRY RUNNER PRODUCTION

Drip irrigation without mulch and with paddy straw mulch significantly increased the runner production. However, with drip plus BP mulch it was reduced significantly compared with surface irrigation (Table 1). Since the black polythene could not provide an anchor for the roots of the new runners, this impeded their production. It is therefore, suggested that after crop harvest, black polythene be removed to provide favorable soil environment for higher runner production.

17.3.3 QUALITY CHARACTERISTICS

Maximum fruit weight (8.39 g/fruit) was recorded under drip plus paddy straw treatment. It may be attributed to the fact that under paddy straw treatment, number of flowers and fruits was less than those under BP mulch [5]. Drip plus paddy straw produced fruit with higher TSS/acidity ratio. In Strawberry, drip irrigation without mulch increased the fruit weight by about 6% over surface irrigation and when coupled with paddy straw and BP, the corresponding increase was 32 and 16%, respectively, (Table 1).

17.3.4 WATER USE EFFICIENCY (WUE)

The WUE values for drip plus paddy straw and surface irrigation plus paddy straw were 6.8 and 4.7 kg.ha^{-1} mm^{-1} and these values for drip plus polythene mulch and polythene mulch plus surface irrigation were 7.7 and 5.1 kg.ha^{-1} mm^{-1}, respectively. Highest water use efficiency of 7.7 kg ha^{-1} mm^{-1} was observed under drip plus black polythene mulch (Table 2). Drip system delivers water directly into the root zone without wetting the entire area. The probably resulted in higher water use efficiency compared to surface irrigation. Drip irrigation, both with and without polythene mulch registered higher water use efficiency (WUE) as compared to surface irrigation. Averaged overall level of irrigation, drip irrigation, without mulch gave water use efficiency of 5.5 (kg ha^{-1} mm^{-1}) against 3.7 (kg ha^{-1} mm^{-1}) under surface irrigation (Table 2).

TABLE 2 Quality of water applied and water use efficiency (WUE) of strawberry under various treatments.

Treatments	Water Use Efficiency (kg ha^{-1} mm^{-1})		
	1st year	2nd year	Pooled
T1	3.8	3.6	3.7
T2	4.9	4.6	4.7
T3	6.3	5.9	6.1
T4	6.2	6.7	6.5
T5	7.7	7.9	7.8
T6	10.5	10.3	10.4
CD ± (5%)	1.2	1.7	1.5

17.4 CONCLUSIONS

Drip system is very effective and efficient method of irrigation for raising Strawberry crop, especially on light texture soils & in water scarce areas. The corresponding figures for water savings & increase in yield for Strawberry were 51 and 19%, respectively. The results further document that irrigation requirement of Strawberry can be met effectively by operating the drip system having discharge rate of 4 L per hour biweekly during the growing season.

17.5 SUMMARY

Field trial was conducted under research project in the farmers' field in the Bhojpur district of Bihar – India on clay loam soil to improve strawberry (*Fragaria x ananassa)* productivity and quality through drip irrigation and polythene mulch and to enhance water productivity through pressurized irrigation coupled with use of black polythene mulch along with surface irrigation. Drip irrigation with polythene mulch gave significantly highest yield (5010 kg.ha^{-1}) as compared to surface irrigation in an

nonmulched condition (4015 kg.ha^{-1}), however, the yield under paddy straw (4590 kg. ha^{-1}) and nonmulched (4207 kg.ha^{-1}) was next in order to drip with polythene mulch but were significantly at par among themselves. When calculated the percentage increase the drip with polythene mulch gave 25% higher yield than surface with nonmulched condition. Similarly, the water use efficiency (WUE) was highest in drip irrigation with polythene mulch (7.7 kg ha^{-1} mm^{-1}) as compared to surface irrigation (5.1 kg ha^{-1} mm^{-1}). The fruit yield of strawberry under drip irrigation was found to be 4607 kg.ha^{-1} compared to 4015 kg.ha^{-1} under surface irrigation. Moreover, polythene mulch plus drip irrigation further raised the yields. Fruit weight increased significantly while other analyzed quality characteristics did not differ significantly among treatments. Drip irrigation besides giving a saving of 50–55% irrigation water resulted in 20–40% higher yield of crops studied.

KEYWORDS

- **Bihar – India**
- **Black polythene**
- **Drip irrigation**
- **Home garden**
- **India**
- **Mulch**
- **Paddy straw**
- **Polythene mulch**
- **Rs = Indian rupees = US$0.0167**
- **Strawberry**
- **Tomato**
- **Water use efficiency**

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CHAPTER 18

WATER USE EFFICIENCY OF MICRO-IRRIGATED CITRUS (*CITRUS RETICULATA* VAR. BLANCO) TREE

P. PANIGRAHI, A. K. SRIVASTAVA, and A. D. HUCHCHE

CONTENTS

18.1 INTRODUCTION

Citrus is the third important fruit crop in India after banana and mango. The mandarin (*Citrus reticulata*) occupies the top position in terms of area and production among citrus cultivars in India. Nagpur mandarin (*Citrus reticulata* Blanco), a well-known commercial citrus cultivar is extensively grown in around of 185,000 hectares area of central India as an irrigated crop [11]. The acreage under the crop is increasing exponentially each year due to its high production economics, as well as the cultivar suitability in this region. The crop is basically irrigated by bore well or dug well through conventional basin or furrow irrigation method**.** For the last few years, the water level in present bore wells and dug wells is declined alarmingly creating water shortage in summer for sustaining the crop. So every year thousand hectares of area under the crop is permanently wilted due to water shortage, which is a great economical loss to the orchard growers of this region. Hence, proper irrigation water management by optimum use of available water resource is quite necessary in this crop condition.

With the advent of drip irrigation, the use of it is gradually gaining popularity among the citrus growers. The positive response of drip-irrigation on plant growth and yield along with water economy is well studied in different citrus species in various citrus growing regions of the world [1, 3, 4, 9]. Moreover, mulching by plastic polythene has proved its effectiveness in conserving the soil moisture and increasing the growth, yield and quality of fruits in different citrus cultivars [6, 10]. However, the information regarding water use, plant growth and yield parameters in response to various drip irrigation regimes with plastic mulch versus conventional basin irrigation method is not reported in case of Nagpur mandarin grown in central India. Thus, a study was undertaken to evaluate the performance of drip irrigation in conjunction with plastic mulch versus basin irrigation method in Nagpur mandarin grown in hot subhumid tropical climate of central India.

18.2 MATERIALS AND METHODS

The field experiment was conducted at experimental farm of National Research Center for Citrus, Nagpur (21° 08'45" N, 79° 02' 15" E and 340 m above mean sea level) during 2006–2009 with 4-year-old Nagpur mandarin (C*itrus reticulata* Blanco) plants budded on rough lemon (*Citrus Jambhiri* Lush) root stock with spacing of 6x 6 m. The experimental soil was clay loam (31.65% sand, 23.6% silt and 44.8% clay) with field capacity (–0.33 bar) and permanent wilting point (–15.00 bar) of 29.26% (v/v) and 18.5% (v/v), respectively, with bulk density of 1.18 g cm^{-3}. The mean daily USWB Class-A pan evaporation rate varied from 1.8 mm in month of December to as high as 13.5 mm in May at the experimental site.

The treatments imposed to irrigate the plants were drip irrigation scheduled at 40, 60, 80 and 100% of cumulative class-A pan evaporation rate on alternate day (Ecp) through two on-line 4 l/h pressure compensated dripper per plant, placed at 0.4 m away from trunk and basin (circular ring of 0.75 m diameter) irrigation at 50% depletion of available soil moisture at 0–0.3 m soil profile. The experiment was laid out in randomized block design (RBD) with four replications and three adjacent trees in a row per replication. Irrigation quantity for different drip irrigation treatments was calculated using the Eq. (1) [4].

$$V = [S \times Kp \times K_C \times (Ecp - ER)]/[r] \tag{1}$$

where: V = Irrigation volume (l/tree), S = Tree canopy area (m^2), Kp= Pan factor (0.7), Kc = Crop factor (0.6), Ecp= Cumulative class-A pan evaporation for two consecutive days (mm), ER = Cumulative effective rainfall for corresponding two days (mm), and r = Water application efficiency of irrigation system (» 90%). Water quantity applied in basin irrigation method was computed using Eq. (2).

$$V = (F.C. - R.S.M.) \times d \times A \tag{2}$$

where: V = Volume of irrigation water (m^3), F.C. = Field capacity (v/v,%), R.S.M. = Required soil moisture (at 50% depletion of available soil moisture » 23.9% v/v) to start irrigation, d = Depth of effective root zone (0.3 m), A = Mean canopy area of the plants.

The black linear low-density polyethylene sheet of 400-gauge thickness with 1.0 m ′ 1.0 m size was used in mulching on each plant basin keeping the plant at the center.

The soil moisture content at 0.45 m distance from tree trunk was monitored twice in a week at 0.30 m and 0.60 m depths through neutron moisture meter (Troxler model–4300, USA). Leaf samples (2nd – 4th leaf from tip of branches) surrounding the trees at a height of 1.5 m to 1.8 m from the ground were collected at the end of irrigation seasons and nutrient (N, P, K, Fe, Mn, Cu, and Zn) analysis was done as per the standard procedure followed by Srivastava et al. [12]. The plant height, stem height, canopy width, and stem (stock and scion) girth were measured for all plants and their polled annual incremental magnitudes were compared. The canopy volume was calculated using Eq. (3) [7].

$$\text{Canopy volume} = 0.5233\, H\, W^2 \tag{3}$$

where: H = (plant height – stem height), and W = the canopy width [7]. The fruit samples (10 number/ tree) were collected to evaluate the yield and quality (juice, acidity and TSS) parameters in different treatments. The All the data generated were subjected to analysis of variance (ANOVA) and the Least Significant Difference (LSD) at 5% probability level was obtained according to the method described by Gomez and Gomez [5].

18.3 RESULTS AND DISCUSSION

18.3.1 IRRIGATION WATER

The monthly irrigation water applied was highest in May and lowest in December irrespective of irrigation method and regime due to highest and lowest atmospheric demand in respective months (Fig. 1). In whole, the annual mean depth of irrigation water applied was 272, 408, 544 and 680 mm through drip irrigation scheduled at 40, 60, 80 and 100% of pan evaporation with plastic mulch, respectively, compared to 635 mm under basin irrigation method. The reduction of water consumption through drip at optimum irrigation level with plastic mulch over conventional basin irrigation method was also studied in Kinnow mandarin [6].

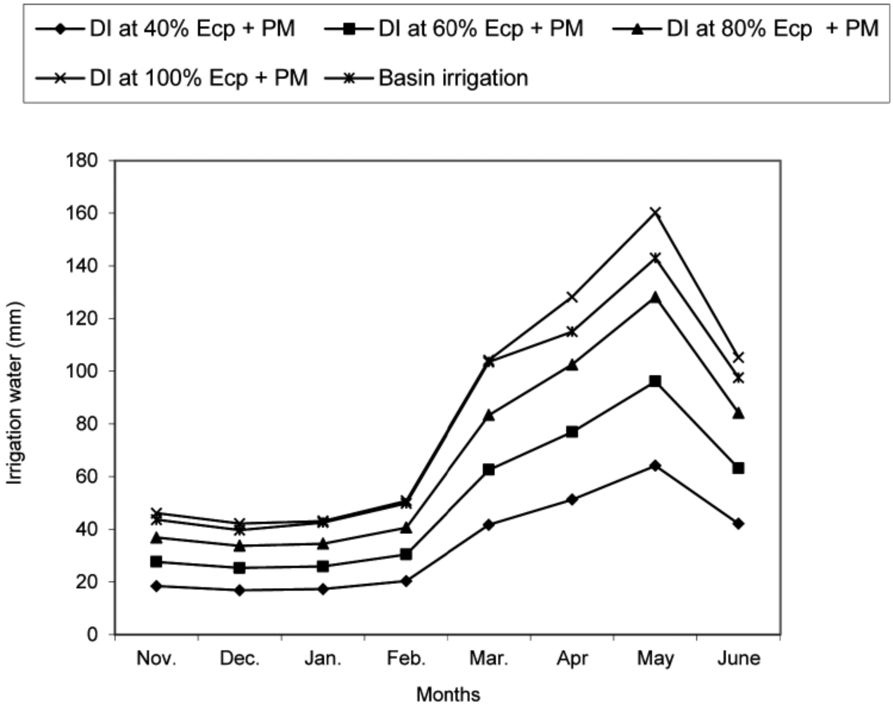

FIGURE 1 Irrigation water applied in different treatments in various months during 2005–08.

18.3.2 SOIL MOISTURE VARIATION

The mean monthly soil moisture variation observed at 0.3 m and 0.6 m depths indicated that drip irrigation at 100% Ecp with plastic mulch showed the highest moisture content among the treatments, which is very near to field capacity of soil throughout the irrigation seasons (Table 1). It was observed that the soil moisture fluctuation between two measurements in a week under basin irrigation was wider than any of the drip irrigation treatment. It was due to higher rate of evaporation from larger wetted surface area under basin-irrigated soil coupled with higher transpiration rate of the plants caused by abundant soil moisture available within the tree rhizosphere just after irrigation under basin method, as reported by Cohen [3]. Among different drip irrigation treatments, the range of soil water depletion at 0.3 m depth was progressively increased with increasing irrigation level, indicating the higher rate of evapotranspiration (ET) of the plants under higher level of irrigation, even with low volume irrigation system. However, the soil moisture depletion under different drip irrigation regimes was almost nil at 0.6 m depth, whereas some incremental was found under basin method, confirming the percolation of irrigation water from 0–0.3 m soil profile under basin irrigation. This fluctuation was somewhat lower during November to March than April to June, supporting the higher rate percolation under higher rate of irrigation water application in summer (Apr.–Jun.).

TABLE 1 Soil moisture content (%, v/v) in various months at 0.3 m and 0.6 m depths under different irrigation treatments (Mean data during 2006–2009).

Treatment	At 0.3 m depth							
	Months							
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.
*DI at 40% Ecp + PM	25.7	25.9	25.3	25.1	24.9	24.4	23.7	23.1
DI at 60% Ecp+ PM	26.1	26.3	25.8	25.6	25.2	24.7	23.8	23.3
DI at 80% Ecp + PM	27.4	27.4	26.9	25.8	25.6	25.1	24.2	23.8
DI at 100% Ecp + PM	28.2	28.4	27.8	26.4	26.2	25.6	24.9	24.3
Basin irrigation	25.2	25.8	24.6	22.9	24.8	25.2	24.8	25.6
#LSD $_{0.05}$	0.13	0.17	0.04	0.08	0.11	0.03	0.06	0.04

At 0.6 m depth								
Treatment	Nov.	Dec.	Jan.	Feb.	Mar.	Apr	May	June
*DI at 40% Ecp + PM	28.3	28.2	27.7	27.6	27.4	27.0	26.8	26.6
DI at 60% Ecp+ PM	28.5	28.2	27.8	27.4	27.3	27.0	26.4	26.8
DI at 80% Ecp + PM	28.6	28.9	28.7	27.8	27.3	27.2	27.0	27.1
DI at 100% Ecp + PM	28.9	28.8	28.7	27.4	27.1	27.0	27.2	27.0
Basin irrigation	27.4	27.8	27.3	27.1	27.0	26.8	27.0	26.8
#LSD $_{0.05}$	NS	NS	NS	NS	NS	NS	NS	NS

* DI = Drip Irrigation; PM = Plastic mulch.

LSD$_{0.05}$ = Least significant difference at 5% probability level,
NS: Not significant.

18.3.3 LEAF NUTRIENTS COMPOSITION

The imposed irrigation treatments showed a differential response on leaf nutrient status of mandarin plants (Table 2). The higher leaf N was registered under drip irrigation at 60% Ecp with plastic mulch compared with leaf N under basin irrigation method. The leaf K uptake was highest under drip irrigation at 60% Ecp with plastic mulch, which was at par with other drip irrigation treatments, probably due to high available K in soil. But, it was significantly lower under basin irrigation method. The lower level of leaf N and K with basin-irrigated plants might be caused by leaching of the NO_3-N and K^+ in soil within the effective root zone due to flooding in this treatment. Though, the highest leaf P content was registered under drip irrigation at 80% Ecp with plastic mulch, but overall it was not affected significantly within the treatments. The treatments imposed had no significant effect on the fluctuation in leaf micronutrient contents, except Fe statistically ($P < 0.05$). Highest leaf Fe was registered under drip irrigation at 100% Ecp with plastic mulch, followed by drip irrigation at 80% Ecp with plastic mulch as compared with lowest in basin irrigation. Highest plant uptake of Fe in drip irrigation at 100% Ecp with plastic mulch is attributed to increased solubility of reduced form of iron (Fe^{2+}) due to lack of oxygen in the rhizosphere under increased waterlogged condition in this treatment [8]. The leaf-Fe content under drip irrigation 60% Ecp with plastic mulch was at optimum level as per the standard foliar diagnosis chart for Nagpur mandarin developed by Srivastava et al. [13].

TABLE 2 Leaf nutrients composition of 'Nagpur' mandarin' under various irrigation treatments with plastic mulch (Mean data during 2006–2009).

Treatment	Macronutrients (%)			Micronutrient (ppm)			
	N	P	K	Fe	Mn	Cu	Zn
*DI at 40% Ecp + PM	1.98	0.063	1.47	97.5	46.6	7.4	7.8
DI at 60% Ecp + PM	2.56	0.072	1.88	112.6	49.3	8.5	18.8
DI at 80% Ecp + PM	2.08	0.125	1.65	120.8	54.6	12.4	11.7
DI at 100% Ecp + PM	2.07	0.118	1.54	130.7	57.2	11.3	9.3
Basin irrigation	1.43	0.087	1.07	97.3	47.6	7.8	11.8
#$LSD_{0.05}$	0.5	NS	0.32	5.5	NS	NS	NS

* DI = Drip Irrigation; PM = Plastic mulch.

\# $LSD_{0.05}$ = Least significant difference at 5% probability level.

NS: Not significant.

18.3.4 VEGETATIVE GROWTH RESPONSE

The annual increase in plant height responded significantly to different drip irrigation levels with the maximum value at 60% Ecp with plastic mulch over plant height (0.45 m) under basin irrigation method (Table 3). The treatments had no significant influence on stock girth, whereas, a significant increase in the scion girth (41–52 mm) and canopy volume (0.531–0.991 m^3) was observed in response to drip irrigation treatments with plastic mulch in comparison to basin irrigation (39 mm, scion girth; 0.473 m^3, canopy volume). The maximum scion girth diameter and plant canopy volume were recorded under drip irrigation at 60% Ecp with plastic mulch followed by drip irrigation at 80% Ecp with plastic mulch. The better plant growth even with 36% less water supply under drip irrigation at 60% Ecp with plastic mulch over basin irrigation might be due better availability and uptake of nutrients facilitated by optimum root zone soil moisture in this treatment.

The higher annual vegetative growth under drip irrigation with plastic mulch was also reported in acid lime [10].

TABLE 3 Annual incremental vegetative growth parameters of 'Nagpur' mandarin' under various irrigation treatments with plastic mulch (Mean data during 2006–2009).

Treatment	Tree height (m)	Stock girth (mm)	Scion girth (mm)	Canopy volume (m^3)
*DI at 40% Ecp + PM	0.50	45	43	0.593
DI at 60% Ecp + PM	0.64	55	52	0.991
DI at 80% Ecp + PM	0.55	51	48	0.723
DI at 100% Ecp+ PM	0.47	43	41	0.531
Basin irrigation	0.45	39	39	0.473
#LSD $_{0.05}$	0.08	NS	4.1	0.04

* DI = Drip Irrigation; PM = Plastic mulch.

$LSD_{0.05}$ = Least significant difference at 5% probability level.

NS: Not significant.

18.3.5 FRUIT YIELD, QUALITY AND WATER USE EFFICIENCY (WUE)

The number of fruits and average fruit weight in drip irrigation treatments with plastic mulch were observed to be significantly higher over fruit number and average fruit weight in basin irrigation (Table 4). In consequence, a significantly higher total fruit yield was estimated under drip irrigation treatments with plastic mulch in comparable with total fruit yield in basin irrigation (9.0 kg/plant). The highest total fruit yield was recorded in drip irrigation at 60% Ecp with plastic mulch followed by drip irrigation at 80% Ecp with plastic mulch. The higher yield in case of drip irrigation with plastic mulch was probably due to optimum evapotranspiration demand met at critical growth stages under this system, a prerequisite for dry matter accumulation and its partitioning within the plant. Increase in yield under drip at optimum irrigation level with plastic mulch has been well advocated by Lal et al. [6] in Kinnow mandarin.

TABLE 4 Fruit yield, quality and water use efficiency (WUE) affected under various irrigation treatments in Nagpur mandarin (Mean data during 2006–2009).

Treatment	Yield parameters			Water applied (mm)	Water use efficiency (kg/ plant/ mm)	Quality parameters		
	No. of fruits/ plant	Average fruit weight (g)	Total yield (kg/ plant)			Juice (%)	Acidity (%)	T.S.S (^{0}Brix)
*DI at 40% Ecp + PM	65	142.7	9.2	272	0.033	36.56	0.83	9.75
DI at 60% Ecp + PM	98	153.3	15.0	408	0.036	39.83	0.78	10.50
DI at 80% Ecp + PM	74	149.6	11.0	544	0.020	37.68	0.84	10.00
DI at 100% Ecp + PM	59	143.9	10.5	680	0.015	36.89	0.86	9.70
Basin irrigation	63	142.5	9.0	635	0.014	36.47	0.85	9.88
#LSD $_{0.05}$	3.2	12.4	0.12	—		0.51	NS	NS

* **DI** = Drip Irrigation; PM = Plastic mulch.

\# **LSD$_{0.05}$** = Least significant difference at 5% probability level; NS: Not significant

The estimation of water use efficiency (WUE) under different irrigation treatments indicates that all the drip irrigation regimes with plastic mulch had significantly higher WUE (0.015–0.036 kg/plant/mm) with maximum magnitude in drip at 60% Ecp with plastic mulch, over basin irrigation method (0.014 kg/plant/mm). The higher WUE under drip with plastic mulch was attributed to higher increase in fruit yield with comparatively less increase in irrigation water consumption over other treatments. Quality assessment of fruits showed that a significantly higher juice content (39.83%) was recorded in drip irrigation at 60% Ecp with plastic mulch over juice content in basin irrigation (36.47%).

18.4 CONCLUSIONS

The drip irrigation with plastic mulch is found to be an effective water saving technique over conventional basin irrigation method in Nagpur mandarin orchards. The higher leaf nutrients uptake, improved plant growth, fruit yield and quality under drip at optimum irrigation regime (60% Ecp) with black polythene mulch, using 36% less water over basin irrigation method warrants the adoption of drip irrigation with black polythene mulch in mandarin orchards of central India. It could enhance the longevity and productivity of the citrus orchards in sustainable basis and support the further expansion of area under the crop.

18.5 SUMMARY

As an evergreen fruit crop, citrus require adequate water for its annual life cycle. In water scarce area, irrigation becomes a major constraint for citrus production. In these regions, use of drip irrigation and plastic mulch may be a good option for commercial citrus production. Keeping this in view, a field experiment was conducted during 2006–2009 to assess the response of various drip irrigation regimes, viz 40,60, 80 and 100% of cumulative pan evaporation on alternate day (Ecp) with black polyethylene mulch versus basin irrigation method in 4 year old Nagpur mandarin (*Citrus reticulata*) plants budded on rough lemon (*Citrus jambhiri*) root stock. All the drip irrigation regimes with plastic mulch produced a significantly higher annual increase in tree height (0.47–0.64 m), canopy volume (0.53–0.99 m^3), fruit yield (9.2–15.0 kg $plant^{-1}$) and water use efficiency (0.015–0.036 kg $plant^{-1}$ mm^{-1}) over basin irrigation. However, drip irrigation at 60% Ecp with plastic mulch produced the highest magnitude of plant growth parameters, fruit yield and water use efficiency. Among different fruit quality parameters (juice percentage, TSS and acidity), significantly higher juice content (39.8%) was observed in drip irrigation at 60% Ecp with plastic mulch over control (36.5%). Analysis of leaf nutrients (N, P, K, Fe, Mn, Cu, and Zn) indicated that the drip irrigation at 60% Ecp with plastic mulch produced a significantly higher leaf N (2.56%), K (1.88%), and Fe (112.6 ppm) over basin irrigation. The study overall concludes that the use of optimum drip irrigation with plastic mulch is a viable option for citriculture in water scarce regions.

KEYWORDS

- **Citrus**
- **Water scarcity**
- **Yield**
- **Water use efficiency**
- **Fruit quality**

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CHAPTER 19

REGULATED DEFICIT IRRIGATION FOR MICRO-IRRIGATED CITRUS (*CITRUS RETICULATA* VAR. BLANCO) TREE

P. PANIGRAHI and R. K. SHARMA

CONTENTS

19.1 INTRODUCTION

Scarcity of water is one of the major factors responsible for suboptimal productivity and decline of citrus orchards in world. Deficit irrigation (DI) is recently proposed water saving techniques in different irrigated crops. Reducing irrigation water quantity to optimal level of crop water requirement in particular growth stages of the crop which is less sensitive to water deficit improves water use efficiency and quality of produces, without affecting the yield significantly [18]. Therefore, the correct application of DI requires the thorough understanding of the yield response of crops to irrigation [8].

As an evergreen perennial fruit crop, citrus require adequate soil water in root zone. Irrigation water is a key input to successful cultivation of citrus especially tropical and subtropical regions of the world [20, 26]. In recent years, several research contributions have documented the advantages of using DI in citrus. The 'Clementina de Nules' citrus tree performance was evaluated under DI at 25% or 50% ETc during flowering and fruit set, initial fruit enlargement phase, and final fruit growth and maturation phases [12]. It was reported that water stress during flowering and fruit set period significantly reduced the fruit yield up to 62% over full irrigation. It was observed that water stress at initial fruit growth period and final fruit growth period of 'Lane late' orange reduced the yield significantly [23]. DI scheduled with 40 and 60% reduction in irrigation water quantity at initial fruit enlargement stage of 'Navalina' sweet orange in Spain did not affect the yield and fruit quality [10]. Drip irrigation at 80% crop water requirement enhanced the yield and water use efficiency significantly in 'Nagpur' mandarin in clay soil [21]. Overall, the studies indicate that the level and time of water stress along with its duration are the main factors responsible for success of DI in citrus. Moreover, pedo-climatic characteristics of the orchard, crop characteristics play a greater role in success of DI [29].

The cultivation of 'Kinnow' mandarin, a hybrid of 'King' mandarin and 'Willow leaf' mandarin, is mainly confined to semiarid and arid environments of northern India, where more than 90% of annual rainfall (600 mm) is concentrated in 3 to 4 months (June–October) of a year. Irrigation is a common practice during January–June to improve the productivity of citrus orchards in this region. Ground water is the common source of irrigation for the crop. For last few years, the shortage of irrigation water caused by over exploitation of ground water becomes a major threat to citrus production. Farmers are more concerned with the sustained production of 'Kinnow' mandarin using less water. Optimal DI scheduling under drip irrigation is one of the option for sustaining 'Kinnow' mandarin production in this region.

In absence of the information on the crop response to DI in early fruit growth period (EFGP, April–June), the orchardists adopt faulty irrigation strategy, which affects the yield drastically with inferior quality fruits. Moreover, the information on the responses of mandarin cultivars of citrus to water stress in summer months, which coincides with EFEP are very limited worldwide. This chapter discusses the research results to optimize the DI scheduling in EFGP in relation to yield, fruit quality and water use efficiency of 'Kinnow' mandarin in a semiarid subtropical climate of North India.

19.2 MATERIAL AND METHODS

The field experiment was conducted in Indian Agricultural Research Institute, New Delhi, India. The citrus plant used in the study was 'Kinnow' mandarin (*Citrus reticulata* var. Blanco) budded on rough lemon (*Citrus jambhiri* Lush) rootstock. The experiment was conducted in 2010 and 2011 with 10 year-old drip-irrigated plants. The plant-to-plant spacing in a row and within the row was 4 m and 5 m, respectively.

The texture of experimental soil was sandy loam with bulk density 1.54 g cm^{-3}. The field capacity (–0.033 MPa) and permanent wilting point (–1.50 MPa) of the soil were 24.0% and 8.5% on volume basis, respectively. The soil had almost neutral pH (7.2) with mild EC (0.15 dS m^{-1}). The water level in the groundwater wells, situated at 100 m distance from the experimental plot, was around 17.0 m deep. The climate of the experimental site is characterized as semiarid subtropical, with hot and dry summers. The mean annual rainfall is 600 mm, out of which around 85% is received during monsoon (June–September). The mean daily class-A pan evaporation rate varied from 1.6 mm in January to as high as 10.7 mm in June.

Two DI regimes: no irrigation (RDI_0) and 50% crop evapotranspiration (RDI_{50}) were applied at EFEP and their impact on crop performance was compared with that under full irrigation (FI, 100% crop evapotranspiration). The duration of EFEP was taken from mid-April to mid-June, as suggested [7] for 'Kinnow' mandarin in the study region. Irrigation was applied through drip system from mid-January to June and from October to December. Water supply was stopped during monsoon season (July–September) due to adequate rainfall fulfilling the crop water need during this period. The experimental design was randomized complete block. Twelve trees in three adjacent rows were taken as a replicated unit and two central trees of each plot were considered as experimental plants. All the measurements were taken from these experimental trees.

Irrigation was imposed every other day through six on-line 8 $l.h^{-1}$ pressure compensated drip emitters per tree, fitted on two 16 mm diameter lateral pipes (3 emitters per lateral). The emitters were placed at 1.0 m away from tree stem. The water quantity applied under full irrigation (FI, 100% ETc) was estimated based on 100% class-A pan evaporation rate for 'Kinnow' mandarin plants grown in Delhi condition [13], using Eq. (1).

$$ETc = Kp \times Kc \times Ep \qquad (1)$$

where: ETc = Crop-evapotranspiration (mm/day); Kp = Pan coefficient (0.8), Kc = Crop-coefficient (0.60–0.85) for bearing 'Kinnow' plant [13] and Ep = 2-days cumulative pan evaporation (mm). The volume of water applied under FI was computed with Eq. (2).

$$V_{id} = [\pi (D^2/4)\ '\ (ET_c - R_e)]/E_i \qquad (2)$$

where: V_{id} = Irrigation volume applied in each irrigation (liter $tree^{-1}$), D = Mean tree canopy spread diameter measured in N-S and E-W directions (m), ETc = Crop-evapotranspiration (mm), R_e = Effective rainfall depth (mm), and E_i = Irrigation efficiency of drip system (90%). As per FAO-25, the effective rainfall was estimated as the summation of soil water content enhancement in root zone of the trees (mm) due to rainfall and potential evapotranspiration (mm) for the rainfall day [5].

The mean monthly water applied under different treatments in various months differed in two years of observation. This was attributed to change in evaporation rate, rainfall and canopy diameter of the plants. Under different treatments, same quantity of irrigation water was applied at different growth stages of the crop except EFEP. Irrigation at 50% ETc was supplied at PFP to create desirable water stress for flowering in citrus. The water supply in each irrigation treatment was regulated by adjusting the operating hours with the help of lateral valves provided at the inlet end of lateral pipes.

The fertilizer (354 g N as both urea and urea-phosphate, 160 g P_2O_5 as urea-phosphate and 345 g K_2O as muriate of potash per plant) was applied 4 times (January, March, June and October) in a year through drip irrigation system, as recommended for bearing 'Kinnow' plants in Delhi region [13]. Ground floor of the experimental orchard was kept weed free, and uniform plant protection measures against insect pests and diseases were adopted for all plants in the experimental block.

Soil sampling was done at 30 cm, 60 cm, 90 cm, 120 cm, and 150 cm distances from plant stem along and in between the drip emitters and at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm depths once in January and subjected to analysis for available nutrients (N, P, K, Fe, Mn, Cu and Zn). One plant basin from each replicated plot (7 experimental plants per treatment) was taken for soil sampling. Available nutrients were determined by following the standard procedures [28]. The depth wise mean values of available nutrients in different treatments were calculated and averaged for entire root zone depth (0–100 cm).

Three- to five- months old leaf samples (3rd and 4th leaf from tip of nonfruiting branches) at a height of 1.5 m from ground surface surrounding the plant canopy were collected at end of October and analyzed for macronutrients (N, P, K) and micronutrients (Fe, Mn, Cu, and Zn) following the standard methods [28].

Stem water potential measured at 12:00–13:00 PM (mid-day stem water potential, MSP) was determined fortnightly on a cloudless day using a Pressure chamber (PMS instrument, Oregon, USA). Two leaves per plant near the trunk or a main scaffold branch were covered by both aluminum sheet and black polythene sheet before 2 h of measurement and their water potential represented the MSP [23]. Moreover, the mid-day water stress integral (S_ψ) for each treatment was calculated using the midday stem water potential data, according to the Eq. (3) by Gonzaalez-Altozano [12].

$$S\Psi = Absolute\ value\ of \sum_{i=0}^{i=1} \left\{ \left(\psi i, i+1 \right) - C \right\} n \tag{3}$$

where: S_ψ is water stress integral (MPa day), $\psi_{i,\,i+1}$ is average midday leaf/stem water potential for any interval i and i+1 (MPa), c is maximum leaf/stem water potential measured during the study and n is number of days in the interval.

The net photosynthesis rate (P_n), stomatal conductance (g_s), and transpiration rate (T_r) of leaves were recorded fortnightly, in one hour interval from 9 am to 3pm on a clear-sky day by portable infrared gas-analyzer (LI-COR–6400, Lincoln, Nebraska, USA) during the irrigation seasons. Four mature leaves per plant (3rd or 4th leaf from tip of shoot) from exterior canopy position (one leaf in each North, South, East and

West direction), and two plants per treatment were taken for these measurements. Leaf water use efficiency (LWUE) was calculated as the ratio of P_n to T_r of leaves.

The plant height (distance from ground surface to top of plant crown), stem height (distance from ground surface to base of first branch on stem), canopy diameter (mean of canopy spread diameter measured in N-S and E-W directions), and stem girth diameter (stem diameter measured at 0.1 m above bud union) were recorded annually by using a metric tape. Plant canopy volume was estimated using the following formula [17]:

$$V_{pc} = 0.5238\, H\, (D)^2 \tag{4}$$

where: V_{pc} is the plant canopy volume (m^3), H the plant canopy height (difference between plant height and stem height) in meter and D the mean plant canopy spread diameter (North-South and East-West) in meter.

The number and weight of entire fruits harvested for each plant under consideration in the experiment were recorded, and the mean yield per plant under various treatments was worked out. Irrigation water use efficiency (IWUE) was worked out as the fruit yield per unit quantity of irrigation water applied. Five fruits per plant were taken randomly for determination of fruit quality parameters: size, juice percent, acidity, total soluble solids (TSS), Vitamin-C, Sugars (total and reducing). All the quality parameters were determined following the standard methodology [24].

Benefit Cost Ratio (BCR) is estimated to analyze the usefulness of any project in view of farmers prospective. In this study, BCR was calculated to analyze the return of the production system of Kinnow fruits under different drip irrigation strategies. Following assumptions were made for estimating the components of BCR which include capital cost of the trickle irrigation system and gross and net return under different irrigation treatments:

- Area of field is one ha
- Land is flat and
- Water source is located at the corner of the field.

The analysis was carried out to study the effect of production of Kinnow crop and irrigation system on through the BCR parameter.

The annual fixed cost (AFC) and annual operating cost (AOC) of the drip irrigation system were calculated. Energy cost includes the electrical cost, which was taken as Rs. 5 per kwh which are existing energy charges. The energy consumed is calculated based on the operating hours of the irrigation system. The cost of cultivation of Kinnow includes intercultivation, weeding, application of manure, fertilizer and plant protection and harvesting, etc. Operating cost is changing according to irrigation system running hours. Total annual cost of the system includes both the annual fixed cost and annual operating cost.

The gross income from the production system includes market return from the Kinnow crop. The prevailing market price of Kinnow crop was taken for the estimation of gross return. The wholesale price of Kinnow for Delhi region is taken as Rs. 23.10 per kg and Rs. 14.58 per kg in January, 2011 and January 2012, respectively [16]. The data generated were subjected to analysis of variance (ANOVA) and separation of means was obtained using Duncan multiple range test (DMRT), according to the methods described by Gomez and Gomez [11].

19.3 RESULTS AND DISCUSSION

19.3.1. SOIL WATER VARIATION

The mean fortnightly volumetric water contents (θv) observed at different soil depths (0.2, 0.4, 0.6 and 1.0 m) in early fruit growth period (EFGP) during 2010 and 2011 are presented in Figs. 1a and 1b. The θv decreased progressively from the day after onset of stress (DAOS) to end of stress period (60 DAOS) in both the years of experiment, except at 0.2 m depth at 30 DAOS in 2010 and at 0.2 m and 0.4 m depths at 45 DAOS in 2011. The increase in θv at 30 DAOS in 2010 and 45 DAOS in 2011 attributed to rain (8.8 mm and 33 mm in respective years) during EFGP. The fortnightly estimated soil water depletion (SWD) was found maximum with RDI_0 (4.4–12.4% in 2010 and 3.4–9.0% in 2011), followed by RDI_{50} (2.0–3.7% in 2010 and 1.0–2.4% in 2011) at different soil depths. The higher SWD was estimated in 2010 than 2011, in spite of higher rainfall in 2011 at EFGP. This was due to higher evaporative demand of the plants in 2010 (mean daily pan evaporation, 10.01 mm) compared to that in 2011 (mean daily pan evaporation, 6.95 mm) in this period. However, the SWD at top 0.4 m soil between 2 observations in a week was observed to be higher with FI than that with other treatments, reflecting the higher evapotranspiration of the trees under increased soil water regime in this treatment (Figs. 1a and 1b).

19.3.2 VARIATION IN AVAILABLE SOIL NUTRIENTS

The θv value increased with depth under each treatment. However, the maximum SWD was found at 0.4 m soil depth, followed by 0.2 m depth, indicating the existence of the most active roots of mandarin trees at 0.2–0.4 m depth. The earlier findings showed a shallow active root zone of 0.15 m for drip-irrigated 'Nagpur' mandarin budded on Rangpur lime grown in vertisol of central India [2, 19]. This difference in rooting is due to the variation of citrus cultivars and root stock used in varied pedo-climatic conditions.

However, the active root depth observed in 'Kinnow' mandarin in our research is strongly supported by the earlier observation of Bhambota et al. [3], which showed that the active root zone of Jatti Khatti, the citrus cultivar used as a rootstock for Kinnow mandarin, exists within the top 0.4 m soil. The SWD value at 0.6 m depth under RDI_0 was significantly increased compared with that under RDI_{50} and FI. This happened due to the higher root activity, which was probably caused due to extension of roots in 0.6 m soil under water stress condition in RDI_0 treatment.

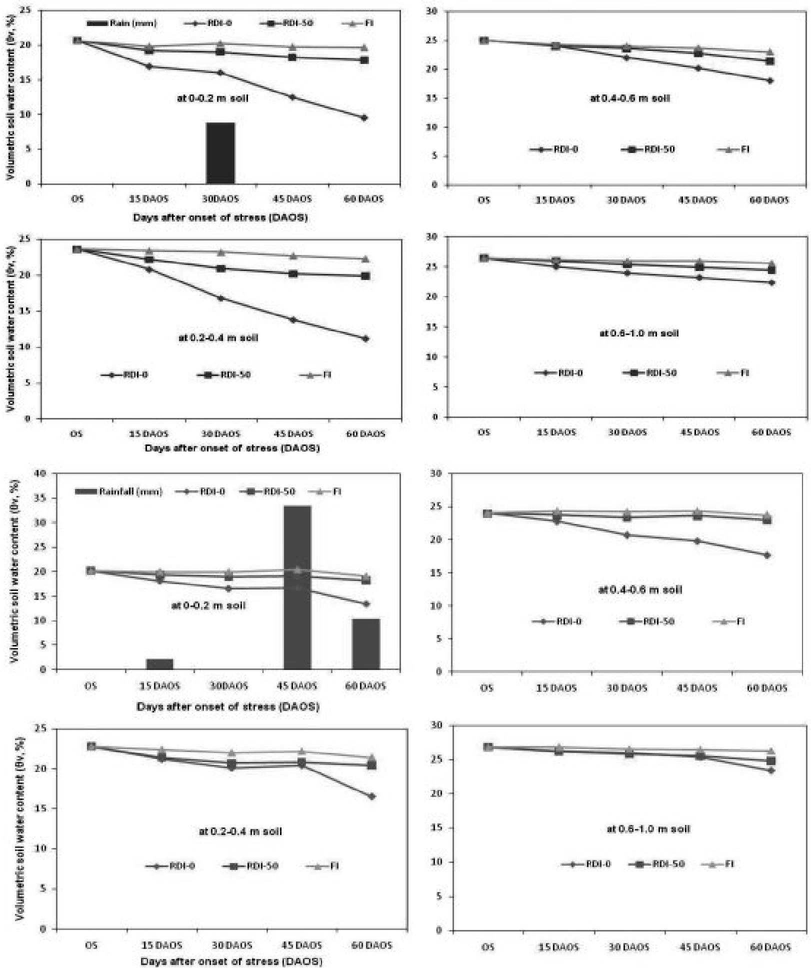

FIGURE 1 Soil water content variations at different depths at early fruit growth period (EFGP) of 'Kinnow' mandarin: **(a)** in 2010 and **(b)** in 2011.

TABLE 1 Changes in available macronutrients (N, P and K) and micronutrients (Fe, Mn, Cu and Zn) concentration in soil under different irrigation treatments in 'Kinnow' mandarin during 2010 and 2011.

Treatments	Macronutrients (mg kg^{-1} soil)								
	2010			2011			Mean		
	N	P	K	N	P	K	N	P	K
RDI$_0$	+2.94^{c}	+0.85^{a}	+3.85^{c}	+0.7 °C	+0.35^{a}	+1.48^{c}	+1.82^{c}	+0.60^{a}	+2.67^{c}
RDI$_{50}$	+3.45^{b}	+0.87^{a}	+4.21^{b}	+1.10^{b}	+0.48^{a}	+1.71^{b}	+2.28^{b}	+0.67^{a}	+2.96^{b}

TABLE 1 *(Continued)*

Treatments	Macronutrients (mg kg^{-1} soil)								
	2010			2011			Mean		
	N	P	K	N	P	K	N	P	K
FI	$+4.29^{a}$	$+0.93^{a}$	$+4.65^{a}$	$+1.78^{a}$	$+0.51^{a}$	$+1.93^{a}$	$+3.03^{a}$	$+0.72^{a}$	$+3.29^{a}$

	2010				2011				Mean			
	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn
RDI$_0$	-0.72^{b}	-0.53^{b}	-0.21^{a}	-0.12^{b}	-0.78^{b}	-0.60^{b}	-0.24^{a}	-0.14^{b}	-0.75^{b}	-0.56^{b}	-0.23^{a}	-0.13^{b}

	2010				2011				Mean			
	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn
RDI$_{50}$	-0.97^{a}	-0.89^{a}	-0.26^{a}	-0.18^{a}	-0.99^{a}	-0.92^{a}	-0.28^{a}	-0.21^{a}	-0.98^{a}	-0.90^{a}	-0.27^{a}	-0.20^{a}
FI	-1.19^{a}	-1.06^{a}	-0.27^{a}	-0.23^{a}	-1.24^{a}	-1.11^{a}	-0.31^{a}	-0.27^{a}	-1.22^{a}	-1.08^{a}	-0.29^{a}	-0.25^{a}

'+' sign indicates the increase and '–ve' sign indicates decrease in the magnitude of the variables.

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test

The changes in available macronutrients (N, P and K) in root zone of the plants under various irrigation treatments show that the nutritional status of the soil improved in both the years of experiment (Table 1). This happened due to the application of NPK-based fertilizers to the plants during irrigation seasons. The maximum increase in the soil available N, P and K was observed with FI, followed by RDI$_{50}$. However, the effect of irrigation on available-P was statistically insignificant, due to low solubility and slow movement of P in soil water continuum [1]. The increase in available nutrient amount was higher in 2010 than 2011, indicating higher nutrients uptake by plants in the latter year.

The magnitudes of available micronutrients (Fe, Cu, Zn, Mn and Cu) in the soil decreased, irrespective of irrigation treatments (Table 1). The maximum decrease in concentration of available micronutrients was observed under FI and the minimum was with RDI$_0$. The higher loss of micronutrients in soil under FI might be caused due to higher plant uptake of these nutrients under increased soil water content in this treatment. However, the effect of irrigation on available Cu was insignificant. The consistent amount of Cu maintained in soil under different treatments was due to the application of Cu-based fungicides, which is a common recommendation against *Phytopthora* disease in the crop. The consistent reduction of micronutrients (except Cu) in soil suggests a need for application of appropriate quantity of micronutrients-based fertilizers to mandarin plants to improve the efficiency and longevity of the orchards.

19.3.3 CHANGES IN LEAF NUTRIENTS COMPOSITION

The macronutrients (N, P and K) concentration in leaves showed a differential response to irrigation treatments (Table 2). FI treatment produced the higher concentrations of N, P and K in leaves compared with N, P and K in leaves in DI treatments. The higher N, P and K content in leaves of fully irrigated trees was caused by increased availability of such nutrients in soil under FI. The concentration of nutrients in leaves decreased with decrease in irrigation regime. However, the amount of N, P and K in leaves was adequate with both FI and RDI_{50}, when compared to the foliar diagnostic chart (2.50–2.93% N, 0.17–0.28% P and 1.63–1.89% K) developed for optimum 'Kinnow' mandarin productivity in North India condition [27]. The suboptimum leaf nutrient concentration with RDI_0 indicates that withholding irrigation in EFGP is not suitable for balanced nutrition of 'Kinnow' mandarin plants, which is a prerequisite for higher productive life of the orchards [14, 27]. The trend of leaf nutrients observed in this study was reflective of the observations made by [22] in 'Nagpur' mandarin, which stated that the leaf nutrient composition is affected by water stress in citrus. In contrast, [25] observed that mineral (N, P, and K) nutrition of 'Clemenules' mandarin budded on 'Cleopatra' mandarin in Spain was not affected by water stress which was imposed by stopping irrigation in both initial fruit growth period and final fruit growth period. This variation was attributed to the higher nutrients concentration in soil, better soil water availability due to intermittent rainfall, and higher capability of the rootstock plant ('Cleopatra' mandarin) for mineral uptake due to its superior root morphology (higher specific root length and higher root fineness) in the study site as compared with 'Kinnow' mandarin in the present study.

TABLE 2 Macronutrients (N, P and K) and micronutrients (Fe, Mn, Cu and Zn) content in leaves of 'Kinnow' mandarin as affected by various regulated deficit irrigation (RDI) and full irrigation (FI) during 2010 and 2011.

Treatments	Macronutrients (mg kg^{-1} soil)								
	2010		2011				Mean		
	N	P	N	N	N	K	N	P	K
RDI_0	2.34^{c}	2.38^{c}	2.36^{c}	2.36^{c}	2.36^{c}	+1.48^{c}	+1.82^{c}	+0.60^{a}	+2.67^{c}
RDI_{50}	2.52^{b}	2.57^{b}	2.54^{b}	2.54^{b}	2.54^{b}	+1.71^{b}	+2.28^{b}	+0.67^{a}	+2.96^{b}
FI	2.69^{a}	2.71^{a}	2.70^{a}	2.70^{a}	2.70^{a}	+1.93^{a}	+3.03^{a}	+0.72^{a}	+3.29^{a}

	2010				2011				Mean			
	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn
RDI_0	55.6^{b}	46.2^{b}	7.2^{a}	24.2^{b}	54.4^{b}	46.0^{b}	7.0^{a}	24.0^{b}	55.0^{b}	46.1^{b}	7.1^{a}	24.1^{b}
RDI_{50}	59.7^{a}	55.6^{a}	7.6^{a}	26.3^{a}	58.8^{a}	54.2^{a}	7.3^{a}	26.0^{a}	59.3^{a}	54.9^{a}	7.5^{a}	26.2^{a}
FI	62.6^{a}	61.5^{a}	8.2^{a}	27.1^{a}	61.3^{a}	61.0^{a}	8.0^{a}	26.9^{a}	61.9^{a}	61.3^{a}	8.1^{a}	27.0^{a}

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

RDI_0 = No irrigation at early fruit growth period (EFGP); RDI_{50} = Irrigation at 50% crop evapotranspiration at EFGP.

The micronutrient (Fe, Mn, Cu and Zn) concentration in leaves except Cu followed the same trend of N and K under different irrigation treatments (Table 2). Overall, in all irrigation treatments except RDI$_0$, the leaf micronutrients (Fe, Mn and Zn) content was higher than their threshold values (57.8–69.4 ppm Fe, 52.7–76.3 ppm Mn and 25.9–28.5 ppm Zn) required for optimum productivity of 'Kinnow' mandarin [27]. Similar trend of micronutrient concentration in leaves was observed 'Nagpur' mandarin [19] under DI. However, [25] concluded that water stress has no significant affect on Fe, Mn, Cu and Zn concentration of leaves in citrus. This difference from the present observation might be due to higher micronutrients concentration in their soil that supported the availability of the nutrients to plants even under water stress condition, as compared to the soil in the present study. Moreover, the concentration of micronutrients in leaves decreased from 2010 to 2011 due to their reduced availability in soil over time.

19.3.4 LEAF WATER CONTENT AND STEM WATER POTENTIAL

The mean RLWC and LWC in EFGP were significantly affected under various irrigation treatments (Table 3). The maximum values for RLWC and LWC were observed with FI, whereas the minimum values were observed with RDI$_0$.

Irrigation treatments affected y and S$_y$ of the plants significantly (Table 4). The mean values for ψat EFGP were from −0.8 to −1.4 MPa and −0.7 to −1.1 MPa in 2010 and 2011, respectively. The higher values of y with lower S$_\psi$in 2011 than that in 2010 was caused by higher amount of rainfall (82.2 mm), and lower temperature (mean, 31 °C) in conjunction with lower evaporation rate (6.95 mm/day) during EFGP in 2011 compared with rainfall (8.8 mm), mean temperature (33 °C) and evaporation rate (10.01 mm/day) in 2010. The trees with FI exhibited the highest y with lowest S$_y$, whereas the trees with RDI$_0$ exhibited the lowest values.

TABLE 3 Relative leaf water content (RLWC), leaf water concentration (LWC), mid-day stem water potential (Ψ) and water stress integral (SΨ) of 'Kinnow' mandarin under regulated deficit irrigation (RDI) and full irrigation (FI) during 2010 and 2011.

Treatments	Leaf water relation factors											
	2010				2011				Mean			
	RLWC (%)	LWC (%)	Ø (MPa)	SØ (MPa day)	RLWC (%)	LWC (%	Ø (MPa)	SØ (MPa day)	RLWC (%)	LWC (%)	Ø (MPa)	SØ (MPa day)
RDI$_0$	75.6^c	66.8^c	–1.4^c	45.8^a	78.2^c	68.2^c	–1.1^c	39.2^a	76.9^c	67.5^c	1.25^c	42.5^a
RDI$_{50}$	83.5^b	70.6^b	–1.2^b	29.3^b	84.6^b	73.7^b	–0.8^b	24.1^b	84.0^b	72.1^b	1.00^b	26.7^b
FI	93.7^a	78.4^a	–0.8^a	18.9^c	94.2^a	79.6^a	–0.7^a	16.2^c	93.9^a	79.0^a	0.75^a	17.6^c

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

RDI$_0$ = No irrigation at early fruit growth period (EFGP); RDI$_{50}$ = Irrigation at 50% crop evapotranspiration at EFGP.

TABLE 4 Photosynthesis rate (P_n, μmol m^{-2} s^{-1}), stomatal conductance (g_s, mmol m^{-2} s^{-1}), transpiration rate (T_r, mmol m^{-2} s^{-1}), and leaf water use efficiency (LWUE) of 'Kinnow' mandarin under regulated deficit irrigation (RDI) and full irrigation (FI) during 2010 and 2011.

Treatments	Leaf physiological parameters											
	2010				2011				Mean			
	P_n	g_s	T_r	LWUE	P_n	g_s	T_r	LWUE	P_n	g_s	T_r	LWUE
RDI_0	3.03^c	29.13^c	1.73^c	1.75^c	3.61^c	28.48^c	1.51^c	2.39^c	3.32^c	28.8 °C	1.62^c	2.05^c
RDI_{50}	3.59^b	31.01^b	1.82^b	1.97^a	4.16^b	30.47^b	1.57^b	2.64^a	3.88^b	30.74^b	1.70^b	2.28^a
FI	3.88^a	37.78^a	2.08^a	1.86^b	4.37^a	37.37^a	1.74^a	2.51^b	4.13^a	37.60^a	1.91^a	2.16^b

Data in one column followed by different letter are significantly different at $P <0.05$, as per separation by Duncan's multiple range test.

RDI_0 = No irrigation at early fruit growth period (EFGP); RDI_{50} = Irrigation at 50% crop evapotranspiration at EFGP.

19.3.5 LEAF PHYSIOLOGICAL PARAMETERS

The P_n, g_s and T_r of leaves during EFGP was significantly influenced by irrigation treatments (Table 4). The values for P_n, g_s and T_r varied in the range 3.03–3.88 μmol m^{-2} s^{-1}, 29.13–37.78 mmol m^{-2} s^{-1} and 1.75–1.86 mmol m^{-2} s^{-1}, respectively, in 2010, whereas in 2011, these values were 3.61–4.37 μmol m^{-2} s^{-1}, 28.48–37.37 μmol m^{-2} s^{-1} and 2.39–2.51 μmol m^{-2} s^{-1}. The higher values of P_n in 2011 were probably due to lower temperature in this period, which favored the better photosynthesis rate of mandarin plants in comparison to that in 2010 [4]. However, the P_n started to decrease when air temperature became more than 35 °C, probably due to the partial damage of photosynthetic system with high temperature in this cultivar, as found in other citrus cultivars [23, 30].

The higher values of P_n with fully irrigated trees indicated the negative effect of soil water deficit on P_n of citrus trees. The greatest reduction in P_n value was between RDI_{50} and RDI_0 (14.5%) than that in between FI and RDI_{50} (6.0%). The higher reduction of P_n in between RDI_{50} and no irrigation treatments indicated the existence of threshold limit of irrigation applied at 50% ET_c, resulting in optimum P_n of mandarin plants under this treatment. In other way, it can be expressed that the mandarin plants could sustain their photosynthesis rate with 50% reduction of water supply, which is called as the photosynthetic acclimatization nature of citrus [31]. The g_s and T_r values followed the same trend of P_n in different irrigation treatments. However, the highest reduction percentage in g_s (18.2%) and T_r (11.0%) was observed between FI and RDI_{50} comparison with that between irrigation at RDI_{50} and RDI_0 (g_s, 6.3%; T_r, 4.7%), reflecting the existence of critical soil water regime in relation to transpirational water loss with irrigation at 50% ETc. The maximum reduction in g_s and T_r at higher irrigation level (50% ETc) compared to P_n (at no irrigation) reflects the less sensitivity of the trees to soil water deficit in irrigation at 50% ETc to produce higher water use efficiency in leaf level. Moreover, the reduction of g_s was higher than that of T_r under RDI compared to FI. The lower reduction of T_r could be probably due to the contribution of residual or mesophyll conductance (movement of water through intercellular spaces and mesophyll cells of leaves) to transpiration of leaves [6]. Leaf transpiration depends on total conductance (stomatal conductance + mesophyll conductance) of leaf. As water stress occurs, the stomatal closure restricts the entry of both CO_2 and water fluxes from surrounding atmosphere to leaf, but mesophyll conductance remains same and transpiration reduces disproportionately to stomatal conductance. The magnitude of LWUE (µmol CO_2 fixed per mmol H_2O transpired) increased from RDI_0 to RDI_{50} and then decreased at FI. The higher LWUE was with RDI_{50} treatment, due to the marginal decrease in P_n value associated with the higher decrease in T_r value under this treatment over other treatments.

19.3.6 PLANT VEGETATIVE GROWTH

The irrigation treatments significantly influenced the different growth parameters (PH, STGD, SGD and CV) of plants (Table 5). The minimum incremental of PH, STGD, SGD and CV was observed with rain-fed plants, whereas the maximum values were with fully irrigated plants. The higher vegetative growth under higher irrigation regime was probably due to better leaf photosynthesis rate and higher metabolic activities of fully irrigated plants under favorable soil water condition in the root-zone in this treatment. However, the increase in growth was more in 2011 than 2010, probably due to larger rainfall amounts and other weather parameters, which favored better plant growth in former year than the latter year. Earlier study by García-Tejero et al. [9] showed the similar findings of decrease in vegetative growth of deficit-irrigated 'Salustiano' orange plants in Spain.

TABLE 5 Annual increment of plant growth parameters of 'Kinnow' mandarin under various irrigation treatments in 2010 and 2011.

Treatments	Annual increment of plant growth parameters											
	2010				2011				Mean			
	PH* (m)	STGD** (mm)	SGD^{+} (mm)	CV^{++} (m^3)	PH* (m)	STGD** (mm)	SGD^{+} (mm)	CV^{++} (m^3)	PH* (m)	STGD** (mm)	SGD^{+} (mm)	CV^{++} (m^3)
RDI_0	28.31^{a}	17.14^{a}	24.64^{a}	0.66^{a}	22.16^{a}	15.21^{a}	21.75^{a}	0.57^{a}	25.23^{a}	16.17^{a}	23.20^{a}	0.62^{a}
RDI_{50}	37.90^{b}	20.81^{a}	29.91^{b}	0.79^{b}	30.72^{b}	19.90^{a}	25.22^{b}	0.69^{b}	34.31^{b}	20.36^{a}	27.57^{b}	0.74^{b}
FI	40.72^{c}	26.22^{a}	48.74^{c}	0.86^{c}	36.05^{c}	25.64^{a}	32.35^{c}	0.78^{c}	38.39^{c}	25.93^{a}	40.54^{c}	0.82^{c}

*PH: Plant height; **STGD: Stock girth diameter; $^{+}$SGD: scion girth diameter; $^{++}$CV: canopy volume.

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

RDI_0 = No irrigation at early fruit growth period (EFGP); RDI_{50} = Irrigation at 50% crop evapotranspiration at EFGP.

19.3.7 FRUIT YIELD AND WATER USE EFFICIENCY

Table 6 presents the fruit harvested (number of fruits tree^{-1}, average fruit weight and total fruit yield) and irrigation water use efficiency under different irrigation treatments. The number of fruits harvested and total fruit yield increased with increase in irrigation regime from no irrigation to FI. Conversely, the highest fruit weight was recorded with RDI_{50} followed by FI. The lower fruit weight in FI treatment over RDI_{50} treatment might be due to the higher fruit number under the former treatment over later one. However, the fruit yield recorded with fully irrigated plants was statistically ($P <$ 0.05) at par with that under RDI$_{50}$.

TABLE 6 Number of fruits harvested, average fruit weight, fruit yield and irrigation water use efficiency (IWUE) of 'Kinnow' mandarin under regulated deficit irrigation (RDI) and full irrigation (FI) during 2010 and 2011.

Treatments	Fruit yield parameters and irrigation water use efficiency											
	2010				2011				Mean			
	No. fruits tree^{-1}	Fruit weight (g fruit^{-1})	Fruit yield (t ha^{-1})	IWUE (t ha^{-1} mm^{-1})	No. fruits tree^{-1}	Fruit weight (g fruit^{-1})	Fruit yield (t ha^{-1})	IWUE (t ha^{-1} mm^{-1})	No. fruits tree^{-1}	Fruit weight (g fruit^{-1})	Fruit yield (t ha^{-1})	IWUE (t ha^{-1} mm^{-1})
RDI$_{0}$	487.3^{c}	125.7^{b}	30.6^{b}	0.07 °C	502.1^{c}	129.4^{b}	32.5^{b}	0.101^{c}	494.7^{c}	127.6^{b}	31.6^{b}	0.086^{c}
RDI$_{50}$	703.4^{b}	169.5^{a}	59.6^{a}	0.092^{a}	726.5^{b}	171.7^{a}	62.4^{a}	0.135^{a}	715.0^{b}	170.6^{a}	61.0^{a}	0.114^{a}
FI	763.7^{a}	162.3^{a}	62.0^{a}	0.073^{b}	776.1^{a}	162.8^{a}	63.2^{a}	0.105^{b}	769.9^{a}	162.6^{a}	62.6^{a}	0.089^{b}

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

RDI$_{0}$ = No irrigation at early fruit growth period (EFGP); RDI$_{50}$ = Irrigation at 50% crop evapotranspiration at EFGP.

The IWUE decreased with increase in irrigation regime from RDI$_{50}$ to FI and the values were comparatively higher than that with RDI$_{0}$. The higher IWUE under RDI$_{50}$ was attributed to higher increase in fruit yield with comparatively less water supply in this treatment over other treatments. However, the possible reasons for higher fruit yield per unit quantity of water applied under RDI$_{50}$ treatment may be due to suppressed vegetative growth without bringing much effect on leaf photosynthesis rate under this treatment. An improvement in IWUE in response to optimum RDI over FI was also reported earlier in citrus [9, 23].

19.3.8 FRUIT QUALITY

The effect of irrigation on fruit quality parameters (juice content, TSS, TA, ascorbic acid) is presented in Table 7. Juice percent increased with increase in irrigation level from no irrigation to FI in EFGP. However, juice percent under irrigation at 50% ETc and FI did not differ significantly, indicating the excess dehydration of juice sacs of fruits with no irrigation, which could not be fulfilled by osmotic adjustment to maintain sufficient turgidity of fruits in this treatment.

TABLE 7 Fruit quality parameters (juice content; Total soluble solids, TSS; Titrable acidity, TA and ascorbic acid) of 'Kinnow' mandarin under different irrigation treatments during 2010 and 2011.

Treatments	Fruit quality parameters											
	2010				2011				Mean			
	Juice content (%)	TSS (^{0}Brix)	TA (%)	Ascorbic acid (mg/l)	Juice content (%)	TSS (^{0}Brix)	TA (%)	Ascorbic acid (mg/l)	Juice content (%)	TSS (^{0}Brix)	TA (%)	Ascorbic acid (mg/l)
RDI_0	42.5^b	9.7^c	1.04^a	101.3^c	43.8^b	10.2^c	1.02^a	103.6^c	43.2^b	10.°C	1.03^a	102.5^c
RDI_{50}	47.3^a	10.8^a	0.76^c	116.8^a	48.6^a	10.9^a	0.74^c	119.1^a	48.0^a	10.9^a	0.75^c	118.0^a
FI	49.6^a	10.2^b	0.81^b	105.3^b	50.8^a	10.4^b	0.79^b	106.9^b	50.2^a	10.3^b	0.80^b	106.1^b

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

RDI_0 = No irrigation at early fruit growth period (EFGP); RDI_{50} = Irrigation at 50% crop evapotranspiration at EFGP.

The TSS in juice increased from RDI_0 to RDI_{50} and then decreased at FI. The higher juice content is one of the reasons for dilution of soluble solids concentrations in fruits with FI. Moreover, the TA percentage in juice was recorded maximum with RDI_0. The higher TA and lower TSS with the fruits in RDI_0 treatment compared to that in RDI_{50} was probably caused by enhanced transformation of acids to sugars in dehydrated juice sacs which is required to maintain the osmotic pressure of fruit cells under mild water deficit condition prevailed under RDI_{50}. Earlier studies also demonstrated the higher TSS in citrus fruits under soil water deficit condition in root zone of plants [15]. However, the TSS and TA did not show any significant difference at RDI_{50} and FI. The ascorbic acid concentration in juice, which is a vital vitamin of citrus fruits, increased from RDI_0 to FI. However, the RDI_{50} and FI were statistically at par ($P < 0.05$) in relation to ascorbic acid content.

19.3.9 ECONOMICS

The net income (NI), which is the subtraction of total annual cost from annual gross return was observed to be highest under FI, followed by RDI_{50} (Table 8). The net income under FI was higher (INR 30000) than RDI_{50}.However, the maximum return per unit investment, otherwise called benefit-cost ratio (B: C) was estimated to be highest under RDI_{50} (13.0). Also, RDI_{50} produced the highest economic water productivity (INR 1720 per mm water used) among the treatments.

TABLE 8 Economics of Kinnow production under drip irrigation with RDI and PRD treatments in 2010–2011.

Treatments	**Yield (tons ha^{-1})**	**Gross income (INR* ha^{-1})**	**Fixed cost (INR ha^{-1})**	**Operating cost (INR ha^{-1})**	**Total cost (INR ha^{-1})**	**Net income (INR ha^{-1})**	**B/ C**	**Economic water productivity [INR (mm irrigation water used)$^{-1}$]**
RDI$_0$	30.6^{c}	707,00 °C	$12{,}600^{a}$	$120{,}000^{a}$	$132{,}000^{a}$	575,00 °C	5.3^{ab}	$1{,}100^{ab}$
RDI$_{50}$	59.6^{a}	$1{,}380{,}000^{a}$	$12{,}600^{a}$	$93{,}000^{d}$	106,00 °C	$1{,}270{,}000^{a}$	13.0^{b}	1,72 °C
FI	61.9^{a}	$1{,}430{,}000^{a}$	$12{,}600^{a}$	$122{,}000^{a}$	$132{,}000^{a}$	$1{,}300{,}000^{a}$	10.8^{d}	$1{,}370^{d}$

Wholesale price of Kinnow = Rs. 2,310 per 100 kg; * Land charge is not considered assuming the land belongs to the grower. Electric power cost is assumed at Rs. 5 per kwh; B/C = Benefit-cost ratio. INR = Indian rupees, Rs.

19.4 CONCLUSIONS

The vegetative growth and fruit yield of the ‘Kinnow’ mandarin plants need for higher irrigation water quantity. However, deficit irrigation scheduled at 50% ETc at early fruit enlargement period improved irrigation water use efficiency substantially, due to higher water saving with a minor decrease in yield over FI. Moreover, better quality citrus fruits were harvested from the deficit-irrigated trees. The higher leaf nutrient concentration under FI was associated with higher availability of such nutrients in soil under this treatment. However, the consistent reduction of micronutrients in soil advocates for the application of appropriate quantity of the nutrients to the plants. Based on these results, it can be inferred that application of irrigation water at 50% ETc at early fruit enlargement period could be better option for ‘Kinnow’ mandarin cultivation in water scarce northern India.

19.5 SUMMARY

The shortage of irrigation water is emerging as the major *abiotic* constraint limiting the productivity of citrus in arid and semiarid regions. Regulated deficit irrigation (RDI) is the recently proposed water saving technique in irrigated agriculture. However, the information on response of citrus to RDI is very limited worldwide. Keeping this in view, the present study was conducted to explore the feasibility of RDI in drip-irrigated ‘Kinnow’ mandarin (*Citrus reticulata* Blanco) plants in a semi arid climate of northern India. Two RDI treatments: no irrigation (RDI$_0$) and irrigation at 50% crop-evapotranspiration (RDI$_{50}$) in early fruit growth period (EFGP) were compared with full irrigation (FI: irrigation at 100% crop-evapotranspiration) in the crop. RDI$_{50}$ proved superior, producing the fruit yield at par with FI, with better quality fruits. Moreover, RDI$_{50}$ resulted in 35% improvement in irrigation water use efficiency (IWUE) and generated higher net return and benefit–cost ratio compared with FI. The significant variation in soil water content at 0–40 cm depth indicated the confinement of effective root zone of the plants in top 40 cm soil. The maximum rate of net-photosynthesis, stomatal conductance and transpiration of leaves was recorded with FI. However, the plants under RDI_{50} exhibited the highest leaf water use efficiency. Overall, the study concludes that adoption of RDI_{50} with drip-irrigation could be the viable water saving technique in commercial 'Kinnow' mandarin cultivation in northern India and elsewhere having similar agro-climate of the study region.

KEYWORDS

- **Citrus**
- **Deficit irrigation**
- **Yield**
- **Fruit quality**
- **Water productivity**
- **Production Economics**

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CHAPTER 20

PERFORMANCE OF GRAPEVINES UNDER IRRIGATION SYSTEMS

HANI A. A. MANSOUR

CONTENTS

In this chapter, one feddan (Arabic: faddān, non-SI units of area in Egypt) = 4200 m2 = 1.038 acres = 0.42 hectare, ha = 10000 m2. It is used in Egypt, Sudan, and Syria. The feddan in Arabic means 'a yoke of oxen': implying the area of ground that can be tilled by an animal in a certain time.

The Egyptian pound (E£ or EGP, Arabic, *Genēh Maṣri)* is the currency of Egypt. The ISO 4217 code is EGP. Locally, the abbreviation LE or L.E. (stands for *livre égyptienne*: French for Egyptian pound) is frequently used. E£ and **£E** are rarely used. In this chapter, one LE = 0.1437 $US or one $US = 6.94 LE.

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20.1 INTRODUCTION

According to the limited water resources of 55.5 billion-m^3/year in Egypt from the River Nile, the required demand for reclamation more land, to facilitate the fast growing population climate, must use more efficient irrigation systems and technique than that of the traditional surface one.

Nowadays, all concerned with irrigation must plan to use more modified irrigation methods. Hence increasing water use efficiency through decreasing water losses, plant selection and fertilization is one of the important factors in irrigation policy. In addition, increasing fertilizers use efficiency through fertigation may increase both plant yield and water use efficiency.

Most of the agricultural land in the Valley (Wadi and Delta) of the River Nile in Egypt are mainly irrigated by using surface irrigation method, with an irrigation efficiency of less than 40%. Therefore, one will save irrigation water and fertilizer using the more developed irrigation methods and systems to replace the surface irrigation

Grape is the second major fruit crops in Egypt and it is the fourth crop of high potentiality for export. World production is 64.4 million tons and the total area is 7.6 million-hectare (8.5 tons/ha). The total grape production in Egypt is 1.196 million tons. The grape area in the Wadi valley occupies 50% of total area. In 2004 it reached about 155,743 Feddans.

This chapter discusses the response of grapevines (var. Thomposon seedless) and attributed changes in some soil physical and chemical properties under localized irrigation systems, maximizing water and fertilizers use efficiencies, and improving the quality of grape fruits.

20.1.1 IRRIGATION SYSTEMS

20.1.1.1 DRIP IRRIGATION

In Egypt, the first drip irrigation system was installed and tested in 1975, however, it was operated at a very low pressure of about 40 cm head [23]. Tsipori and Shimshi [78] described the drip irrigation as a discharge of a low flow of water from small diameter orifices connected to, or a part of distribution tubing's situated on above or immediately below the soil surface. Nakayama and Bucks [64] defined trickle irrigation as a slow application of water on above or beneath the soil by surface drip, subsurface drip, bubbler spray, mechanical-move, or pulse systems. Water is applied as discrete or continuous drops, tiny screams, or miniature spray through emitters or applicators placed along a water delivery line near the plant. Larry [53] described the drip irrigation system as the frequent slow application of water onto the land surface or into the root-zone of crop. He stated also that drip irrigation encompasses several methods of irrigation, including drip, surface, and spray and bubbler irrigation system.

Hillel [39] mentioned that several problems have been encountered in the mechanics of applying water with drip equipment for some soils, water qualities, and environmental conditions. Some of the more important possible disadvantages of drip irrigation compared with other irrigation methods include: 1) emitter clogging, 2) rodent or other animal damage, 3) salt accumulation near plant, 4) inadequate soil water movement and plant-root development, and 5) high initial cost and sophisticated technical know-how. James [44] indicated several problems associated with drip irrigation, such as, emitter clogging which can cause poor uniformity of water application. He added that a special equipment was needed to control clogging; and the size of pipes, emitters type, valves type, etc., in drip system often contributes to high cost per ha cost compared to solid-set sprinkler system).

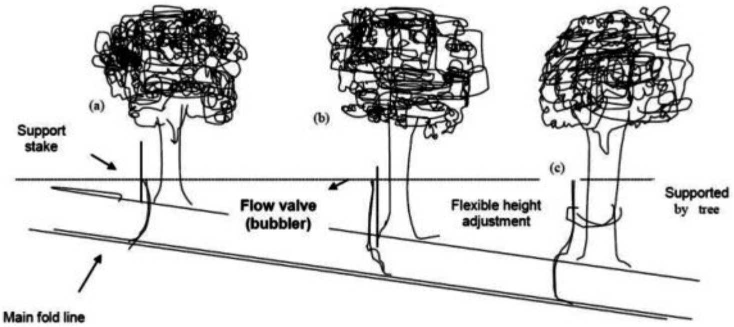


FIGURE 1 Typical diagram of low-head bubbler irrigation system [33].

20.1.1.2 LOW-HEAD BUBBLER IRRIGATION

Behoteguy and Thornton [12] defined the bubbler system as a type of drip irrigation that typically delivers flow rates of 2 to 4 L per minute through a small diameter of polyethylene (P.E) delivery tube attached to a large diameter of corrugated (P.E) pipe (buried lateral). Uniform irrigation is achieved by filling small basins or channels with equal quantities of water, as shown in Fig. 1. The bubbler irrigation system operates at low pressure (0.3 to 1 meter of water head) and by using 38.1 to 120 mm diameter of (P.E) lateral pipe. Conveying water down the lateral to the point is transferred to each tree basin by means of a 9.4 to 16 mm diameter (P.E) tube. They indicated several advantages of the bubbler irrigation system, such as: low maintenance of irrigation equipment, higher water application uniformity than furrow or flood irrigation, reduced tail water, the ability to more precisely apply nutrients to the tree, and lower water application rate. The bubbler irrigation system has also the advantage of being adaptable to existing pipeline delivery system.

Hull [41] stated that the advantages of bubbler irrigation system are: 1) higher flow rate and larger diameter pipe used, result in fewer blockages compared with drip systems, 2) elaborate-filtration equipment is unnecessary and the associated head loss resulting in increased pumping costs is therefore eliminated, 3) quality of the water is not critical, 4) operates at low heads associated with surface irrigation systems and 5) relatively low overall cost compared with other solid-set sprinkler irrigation. According to Hull, the disadvantages of the bubbler irrigation system are: 1) restricted use for slight slopes (1–3%), 2) usually greater water consumption than trickle system, 3) limited to orchard and plantation type crops because of costs, 4) possibly more leaching and evaporation losses than with trickle irrigation system and 5) not feasible in soils with faster infiltration rate. And also, bubbler irrigation is very sensitive to changes in pressure head and a constant head-source is essential for a commercial orchard or plantation. A change in pressure head at the inlet results in nonuniformity of application at each outlet. He found also that pressure head of one meter is very small and small changes in head can thus have a marked effect on the flow rate, which is fixed once the system is installed and is not easily changed.

Larry [53] showed that in bubbler-irrigation system water is applied to the land surface as a small stream. Habib and El-Awady [33] stated that the discharge uniformity of bubbler irrigation system can be controlled by varying the tube diameter and/or length and/or using a valve for each bubbler in a long lateral line. Yitayew et al. [86] showed that the name of that low-head bubbler system is derived from the fountain of water streaming out from the hoses, and from the bubbling noise made as air escapes from the pipeline when the system is turned on. Yitayew and Reynolds [87] compared the low head gravity flow bubbler irrigation system that is commonly used for tree crops. The bubbler system has a definite advantage in cost savings in addition to reduced water usage and equal or better water distribution uniformity.

20.1.1.3 MODIFIED SURFACE IRRIGATION WITH GATED PIPES

Layei et al. [54] studied the effect of irrigation methods and levels on yield and quality of hybrid tomato seeds and found that seed yield obtained from furrow irrigation was significantly lower than those of bucket watering and drip irrigation. Furrow irrigation also resulted in higher proportion of fruits that shown a symptom of blossom and rot. In clay soil, bucket watering and drip irrigation gave a significantly higher fruit weight and seed yield than furrow.

Charles [20] reported that furrow spacing was easy to adjust when furrows are used to irrigate permanent crops such as trees or vines, and the number of furrows/row can be varied. The same effect can be achieved by irrigation every other furrow on row crops when it is desired to apply a small depth of water during one irrigation.

El-Sayed [27] studied the different orifice discharge rates ranging from 0.1 L/sec (ls^{-1}) to 0.6 ls^{-1}. From the view point of the allowed discharge in irrigation furrow, he found that a discharge of 2 ls^{-1} is recommended for each-one meter of furrow width. And the proposed system can be used to irrigate long line and long strips with lengths between 100 to 180 m, ii) pressure head needed to operate the system (ranged between 15 cm to 100 cm), and the required head to operate the system in the field was 50 cm or less, therefore pumping unit is not a must. His results indicated that there is an agreement between the theoretical predicted hydraulic parameters and the actual ones.

20.1.2 EFFECTS OF IRRIGATION SYSTEMS ON GRAPE YIELD AND WATER USE EFFICIENCY

Grape is the second major fruit crop in Egypt. However, the grape area in the Wadi and valley Delta occupied about 50% of total area in 2004 (about 155,743 feddans). The total grape production was 1.196 million tons [60]. Matthews [58] suggested that optimum growth, grape yield and grape quality was possible with controlled irrigation during certain phenological stages of vine growth. Rakhlmanina et al. [69] indicated that the grape yield under drip irrigation were 4.50, 10.13 and 18.50 tons/ha in 1985, 1987 and 1988, respectively; compared to 1.50, 4.38 and 4.25 tons/ha under furrow irrigation and, respectively.

Kramer and Boyer [52] stated that the leaf photosynthetic production was decreased if vines experience drought stress during ripening. The vine stomatal is sensitive to water deficits and will close to prevent excessive loss of water through transpiration. Stomata closure during part of the day prevents carbon dioxide from entering the leaves and inhibits photosynthesis. Bravdo et al. [14] reviewed grape vine response to crop load and irrigation treatments. Three drip irrigation schedules were applied. Crop load (yield/pruning weight) was affected by irrigation due to a differential effect of irrigation on fruit bud differentiation and on vegetative growth. Ginestar et al. [32] indicated that under different levels of irrigation based on transpiration data measured using sap-flow sensors were applied to grape vines grown on a two-wire vertical system. Data for the vines on the upper and lower wire were studied separately. Leaf area, yield and water use of vines in different treatments were closely related to the intensity and duration of stress in each treatment. Irrigation increased grape yield and differences in vine water status led to differences in the leaf area to fruit weight ratio. It was concluded that data from the sap-flow sensors can be used as a basis for calculating irrigation amounts to influence vine water status, canopy size, and grape yield.

Karasov [46] defined water use efficiency (WUE), which is the ratio of economic yield to total crop water use. WUE can also be defined as the ratio of weight of harvested crop to total crop water use (cm). Sinclair et al. [74] described WUE on various scales from the leaf to the yield. In its simplest terms, it is characterized as crop yield per unit of water used. At a more biological level, it is the carbohydrate formed through photosynthesis from CO_2, sunlight, and water per unit of transpiration. Brown [16] has proposed that the upcoming benchmark for expressing yield may be the amount of water required to produce a unit of crop yield, which is simply the long-used transpiration ratio, or the inverse of WUE. Often the term WUE becomes confounded when used in irrigated agriculture.

Tosso And Torres [77] evaluated effects of four irrigation levels (0.2, 0.5, 0.8 and 1.1 class A pan evaporation, Epan) and three irrigation systems (drip, sprinkler, furrow) on Muscat Rose var. Mosada. The lowest level of irrigation resulted in soil water deficits in all irrigation systems. Water application corresponding to 0.5Epan throughout the season satisfied the grape water requirements. WUE was the highest with drip irrigation, which used 50–60% less water than sprinkler and furrow irrigation and produced up to 60 kg of grapes per mm of water applied. Araujo et al. [5] studied the response of three years old grapevines to furrow and drip irrigation; and the results were expressed in terms of water status, crop growth and WUE. Drip irrigation was applied daily according to best estimates of vineyard ET, while furrow irrigation was applied when 50% of the plant available soil water content had been depleted. Drip and furrow irrigated vines showed similar water status and shoot growth patterns throughout the season. Dry weight partitioning was not significantly different between treatments but root mass was somewhat larger for the furrow than for drip irrigated vines. Similar

WUE [kg fruit weight (FW) kg–1 water] was obtained in the two treatments indicating that drip irrigation may increase the potential for control of vine growth by making vines more dependent on irrigation and N fertilization than furrow irrigation.

Burt et al. [17] stated that irrigation was an effective means to improve WUE through increasing crop yield, especially in semiarid and arid environments. Even in subhumid and humid environments, irrigation is particularly effective in overcoming short duration droughts. However, irrigation by itself may not always produce the highest WUE possible. Masood et al. [57] stated that WUE may be improved with some management practices such as: changing sowing time, irrigation efficiency, balanced nutrition, mulching, and tillage management. They found a negative significant correlation between WUE and irrigation requirements. Veeranna et al. [79] conducted field experiments in Bangalore, Karnataka, India, during the Rabi season of 1997 and 1998 to investigate the effects of fertigation and irrigation methods on chili cv. *Byadagi Dabba*. The treatments comprised of soil application of normal fertilizers (N, P, K applied as urea, single superphosphate and muriate of potash, respectively) at 100% recommended dose, in combination with furrow irrigation or drip irrigation. WUE was significantly higher with drip fertigation of water soluble fertilizer (WSF) at 80% recommended dose (2.81 $kg.ha^{-1}.mm^{-1}$), which was closely followed by drip fertigation of 100% recommended level of WSF (2.77 $kg.ha^{-1}.mm^{-1}$). The two treatments were significantly superior to the rest of the treatments. Higher dry fruit yield coupled with lower water use (450.21 and 446.80 mm at 80% and 100% recommended level of WSF, respectively) were responsible for high WUE.

20.1.3 EFFECTS OF IRRIGATION SYSTEMS ON FERTILIZATION AND FERTILIZER USE EFFICIENCY

Barber [11] defined fertilizer efficiency as "the amount of increase in yield of the harvested portion of the crop per unit of fertilizer nutrient applied where high yields are obtained." Many factors soil, plant, and climatic contribute to the efficiency of applied fertilizer in croplands. In addition, the nature of fertilizer materials and the methods of use also affect their availability. He mentioned three important soil parameters, which are responsible for the rate of supply of nutrients from the soil to the root: diffusion coefficient, nutrient concentration in soil solution, and buffering capacity. The diffusion coefficient is the most important factor and its magnitude is influenced by volumetric water percentage, the tortuosity of the diffusion path and the buffer capacity. By increasing the water content of soil, a reduction in tortuosity was observed. Baligar and Bennett [10] stated that the efficiencies of added N, P2O5 and K2O are of the order <50%, 10%, and 40%, respectively. For enhancing efficiency of applied fertilizers, it is essential to approach the problem on many fronts, namely: (1) increasing the efficiency of crop plants to absorb and use the nutrients, (2) reducing or using existing fertilizer to improve their efficiency either by rate or method of applications, (3) use of fertilizer reaction modifiers such as nitrification and urea hydrolysis inhibitors, (4) correcting the soil acidity or alkalinity by amendments so that crops and soil microbial populations are at their greatest potentials, and (5) exploiting the nature of interaction of soil essential elements and crop growth.

Gerstl and Yaron [31] found that the adsorption and movement of chemicals in the soil are affected by several factors such as soil texture, type of soil minerals, and organic matter content. Moderately adsorbed chemicals were found concentrated around the emitters, and lateral movement of these chemicals was more pronounced than the vertical movement, after several irrigation cycles. Weekly adsorbed chemicals were uniformly distributed in the soil and leached out of the wetted zone more readily, although some retardation was noticed. These results indicate that different fertigation strategies should be used for different fertilizers and different soil types. Gad [28] reported that on active surfaces in fine textured soils absorb a portion of the fertilizer. On the other hand, coarse textured soils do not adsorb a large portion of the applied chemicals. This concludes that any fertilizer that is not absorbed by the plants in irrigation cycle might be leached out of the root zone during the following irrigation. Therefore, intelligent management of fertilizer application is a must.

Kovacs et al. [51] used the isotopic technique (N^{15}) to evaluate the effects of irrigation on the nitrogen fertilizer use efficiency for seven irrigation treatments at two fertilizer levels. Irrigations were applied at four different growth stages of maize, soyabean and potato (vegetative, flowering, yield formation and ripening) in four replications. Every irrigation treatment was equipped with neutron access tubes in two replications at a depth from 10 to 130 cm. The study compared the impact of deficit irrigation (i.e., water stress imposed during one growth stage) with normal and traditional irrigation practices. The relationships were determined between relative yield decrease and relative evapotranspiration, and between the crop yield and water use.

Neill et al. [65] reported that drip irrigation allowed the fertilizer application through the irrigation water, and this process is known as fertigation. Although adding fertilizers in a drip irrigation system is quite simple several precautions are necessary. He found also that for a successful fertigation, one should take into consideration several factors, namely: the fertilizer must be soluble in water; it does not precipitate or react to form precipitate with other soluble salts in the irrigation water; the application should place the fertilizer in the root zone at the right time; and it must be also mobile into the root zone.

Soil characteristics, moisture status, discharge rate, irrigation interval affect the status of micro and macronutrients, and type of added fertilizer.

Threadgill [76] reported the application of chemicals through irrigation systems poses several environmental benefits. Four categories of these potential environmental impacts are: Potential backflow of chemicals to the irrigation water supply or to the soil surface around the chemigation system; Potential positive and negative impacts on no point source pollutant potential of materials applied by chemigation; Potential positive and negative impacts on operator safety; and Potential effects on chemical residues in food and fiber production. The application of good management techniques by chemigation operators will allow significantly less exposure of operator to chemicals during application.

Veeranna et al. [79] found that drip fertigation of water soluble fertilizers (WSF) at 80% recommended dose produced significantly higher dry fruit yield of 1268.00 kg. ha^{-1} (chili cv. Byadagi Dabba) over all the treatments, but was on par with drip fertigation of WSF at 100% recommended dose (1237.38 kg/ha). Drip fertigation of WSF at

80% recommended dose registered 22.37 and 31.00% higher dry fruit yield over drip and furrow irrigation methods, respectively, even with the same level and method of normal fertilizer application.

Roubelakis and Kleiwer [70] stated that fruit quality may be affected due to abundant or insufficient available nitrogen. They also found that the total amount of nitrogenous compounds in grapevines depends on genetic factors, environmental conditions, and cultural practices. Atallah [7] reported that plant analysis is a diagnostic tool for optimum fertilization and indicated that no fertigation could be successful unless the soil fertility status is also considered. Guidelines integrating both crop requirements and nutrients availability are essential. Concerning the soil, the levels of major elements and the properties are liable to change such as the salinity, pH and organic matter.

Hajrasuliha et al. [34] found that most of the N organic fertilizer for both NO_3 and NH_4 applications was in the top 60 cm of soil where the vine roots were of greatest density. There was no indication of significant N leaching below 2.4 m or denitrification of fertilizer N for the trickle irrigated vines during the growing season. Mussaddak and Somi [63] stated that nitrogen fertilizer of cotton plant under different irrigation methods is the key factors for yield increase and yield quality improvement. With good management of these two factors, both production and quality can be attained simultaneously.

20.1.4 EFFECTS OF IRRIGATION SYSTEMS ON GRAPE YIELD QUALITY

Rakhlmanina et al. [69] indicated that the juice sugar content of grapes varied between 22.3 and 23.4% under drip and furrow irrigation, respectively, and ranged from 20.6 to 22.3 in the control. Saayman and Lambrechts [71] stated that the table grapes on grayish, sandy soil responded to irrigation applied N fertilization levels, patterns of N application, crop load and preplant P and K fertilization. Potassium applied in this manner was found to be ineffective due to leaching and regular irrigation-applied K fertilization had to be adopted. Increased crop load had a marked negative effect on shoot growth and grape quality, comparable in magnitude to that of too high N levels. A balanced crop load of 22 bunches per vine with a shoot mass of 1822 kg was calculated for this trial, but a crop load of 18–19 bunches per vine was maximum still ensuring the best quality. According to Pire and Ojeda [67], different irrigation regimes affected the overall grape fruit quality. They added that lower irrigation volumes consistently decreased fruit acidity and plant shoot growth.

Ashcroft et al. [6] studied the effects of irrigation methods (trickle and furrow), N and K application on fruit yield and quality of processing tomatoes were investigated in three field experiments with different cultivars (FM 785, Pacesetter and Alta), soil types (loam, clay loam and sand). Ripe fruit yield increased with increasing N application rate at all sites. The optimum yields were obtained at 280–300 kg of $N.ha^{-1}$. The number of green and rotten fruits increased significantly with increasing N rate at the two trickle-irrigated sites but not at the furrow-irrigated ones. Fruit size was not consistently affected by N or K. The TSS content increased with increasing N rate at two of the sites. Although K alone had no significant effect on TSS content, yet there was a significant N × K interaction at one site, possibly due to an osmotic effect of the potassium salt applied as a concentrated dose.

Kadam and Sahane [45] studied the effect of NPK fertilizers and irrigation methods on the growth and quality of tomato cv. Dhanshree. Treatments comprised: of 75 and 100% recommended rate of fertilizers (RRF; 160:80:80; kg of NPK ha^{-1}) in briquette and nonbriquette forms through drip or surface irrigation. The drip irrigation recorded significantly higher total soluble solids, higher plant height and higher dry matter content than surface irrigation. Treatment with NPK at 100% RRF resulted in significantly higher total soluble solids, higher plant height and higher dry matter content compared to treatment with NPK at 75% RRF. The total yield was positively correlated with yield contributing characters such as fruit weight and fruit number per plant, and quality characters such as pH.

Abou-Salama et al. [3] used different irrigation methods to conserve water consumption of sugarcane and to improve its water use efficiency under Upper Egypt conditions. They found that most of the juice quality parameters were not affected by irrigation treatments. Azzazy et al. [8] used three irrigation systems (drip, developed surface and traditional surface irrigation systems) to irrigate sweet sorghum. They found that type of irrigation system significantly affected forage yield. They added that the highest sucrose and purity percentages were obtained under drip irrigation system.

20.1.5 EFFECT OF IRRIGATION SYSTEMS ON SOIL CHARACTERISTICS

20.1.5.1 SOIL MOISTURE CONTENT AND MOISTURE DISTRIBUTION

Drip or high frequency irrigation will often maintain low soil moisture suction (high moisture content) in the effective root zone. Root growth can possibly augment the influence of low soil moisture suction and maintain more favorable soil water intake characteristics around the emitters. Gerard [30] mentioned that the wetting pattern can be affected by the soil hydrological properties. The reduction in the ability of soil to conduct water can be serious enough to create saturated soil conductions and significant loss of effective roots. Earl and Jury [22] reported that moisture profiles for the daily irrigation treatment under cropped conditions showed that downward water movement is restricted to 60 cm depth when lateral movement occurs no further than 60 cm from the emitter. They observed water movement is observed up to 100 cm from the emitter, while downward movement was restricted to about 75 cm. The rate of water application in drip irrigation will affect the distribution of the applied chemicals. By varying the parameters of the irrigation regime, different distribution may be obtained. Levin et al. [55] studied the soil moisture distribution pattern when amount of water was applied form a point source, but with different discharge rates. The continuous irrigation treatment showed a loss due to deep percolation, of 26% of the total amount of irrigation water below 60-cm depth after 12 h. The lateral distribution, in the same treatment, showed that 80% of the water in the wetted volume was distributed up to 45 and 43 cm horizontally from the point source after 12 and 24 h, respectively. Only 12% loss below 60 cm depth was found with pulsed irrigation, and 29 and 40 cm lateral distribution after 12 and 24 h, respectively. Bacon and Davy [9] observed that irrigation resulted in outward movement of water from the application point to a wetted zone in the shape of a shallow dish. The size and duration of the wetted zone depended on the length and season of irrigation while the shallow depth was caused by the low hydraulic conductivity of the subsoil. Norris and Tennessee [66] indicated that lateral movement is enhanced if the soil is stratified, the initial soil moisture is low, and the application rate is low. They also observed that at high moisture tension (low moisture content) lateral movement was more pronounced in finer soil layers than in coarser layers. El-Gindy [25] reported that the moisture content of the top soil (0–20 cm) was higher in the drip-irrigated field than those of surface, and sprinkler systems. Meanwhile the lowest moisture content in the same layer was in the surface irrigated field. Hanafy [35] indicated that the major fluctuations in soil water tension occurred in the top 30 cm of the soil profile. This is mainly due to that most crops moisture withdrawal from the soil is near the surface where more roots are normally growing.

20.1.5.2 SOIL INFILTRATION RATE

Mousavi et al. [62] stated that infiltration is an important physical property of soil affecting irrigation. Lodge and Baker [56] stated that soil physical properties of three types of golf green construction in the UK, were a sandy loam top soil with pipe drainage and two suspended water table constructions, one with a root zone of pure sand, the other with a root zone conforming to the US Golf association specifications. The irrigation treatments represented replacement of 75, 100 and 125% of evapotranspiration losses in 1990 and 60, 100, and 140% of losses in 1992. Soil pore structure of the sand-based root zone changed slowly over time. Infiltration rates fell significantly over time. Infiltration rates on the sand-based root zones were greater at higher rate of nitrogen fertilizer application (410 kg ha^{-1} per year) than the lower rate (110 kg ha^{-1} per year). The soil constructions showed a reduction in the proportion of pore spaces in the top 10–90 mm of the profile, probably due to compaction process. Infiltration rates were consistently very low, but increased for a short period following the application of a 'Verti-Drain' treatment. Yapa [85] stated that in the 'very rapid' and 'rapid' infiltration categories, the drainage problems are unlikely, so it is recommended to use overhead irrigation methods for high water use efficiency (WUE).

Wang et al. [82] mentioned that the time required to infiltrate a prescribed amount of water or chemical increased from sprinkler to furrow to drip irrigation. Furrow irrigation leached the chemical more rapidly than either drip or sprinkler irrigation. Sprinkler irrigation was less susceptible to cause ground-water contamination than furrow or drip irrigation. They added that the interactive effect of irrigation methods and spatial variability of saturated hydraulic conductivity (Ks) was determined with the combined use of a two-dimensional deterministic solute transport model and a stochastic parameter generator. In a homogeneous Ks field, the time required to infiltrate a prescribed amount of water or chemical increased from sprinkler to furrow to drip irrigation. Furrow irrigation leached the chemical more rapidly than either drip or sprinkler irrigation. Assuming the spatial distribution of Ks to be a stationary stochastic process, increased spatial variability in Ks reduced the infiltration rate. When Ks was spatially correlated, sprinkler irrigation was less susceptible to cause groundwater contamination than furrow or drip irrigation. The concentration distributions in the uncorrelated Ks field were not very different from those in the homogeneous field.

Minhas et al. [59] monitored the hydraulic conductivity (K) and related soil properties of a noncalcareous (CaCO3 0.8%) and a calcareous soils (25.7%) with similar textural constituents. The soils were subjected to six consecutive cycles of irrigation with saline waters (SW). Depth distributions of salinity, pH, dispersible clay and hydraulic head showed that disaggregation and dispersion of surface soil was the cause of reduced K in each followed by simulated rain water (SRW), whereas "washed in" subsoil became restrictive, and controlled the K values with SW under alternations of SW and SRW. Salt release (<1 meq/L) was insufficient to avoid dispersion and sustain K even in the calcareous soil.

20.1.5.3 SALT DISTRIBUTION

Abd El Razek et al. [4] demonstrated that the maximum salinity was found near the soil surface at the midpoints between emitters and laterals as well as at the deeper depths. The 70 cm emitter spacing resulted in a relative reduction in salt content after irrigation by 5.5 and 10.5% from the original values before irrigation. Ismail et al. [42] demonstrated that salt distribution varies as a function distance from the dripper and layer depth under drip irrigation system before and 24 h after irrigation. Hanson and Bendixen [36] investigated patterns of soil salinity under surface and subsurface trickle irrigation at water salinity of 2.2 dS/m. High soil salinity occurred midway between drip laterals for both irrigation methods and above the drip tape for subsurface drip irrigation. Leaching fractions of 14–26% may be needed under trickle irrigation to prevent yield reductions of vegetable and fruit crops for irrigation water of EC 2 dS/m. Minimum leaching fractions are less with lower-salinity irrigation water. Abo-soliman et al. [3] found a slight decrease in amount of water irrigation values under subsurface drip system compared to surface drip one. On the other hand the EC values decreased by about 4 and 11% for subsurface and surface drip systems, respectively.

Chandio et al. [19] stated that soil salinity developed under drip and furrow irrigation methods. Water used was less with the drip method. Soil salinization occurred at the wetted periphery under drip irrigation. The problem of secondary salinity did not occur in the furrow-irrigated plots. Hicklenton and Cairns [37] used drip, sub irrigation and sprinkler irrigated methods. They found that soil EC was highest for subirrigation, intermediate for drip and pulse irrigation, and lowest for overhead irrigation. It appears that superior growth of subirrigated plants is due more to better nutrient retention in the medium than to any effect on plant water status. El-Morsy [26] demonstrated that the salt distribution was related to the soil moisture distribution. The salt accumulated at the soil surface and at the boundaries of the wetted zone. The EC values increased in the surface layer from the source point toward the outer periphery of the wetted zone. However, the values decreased by going down in the soil profile from the surface layer to the bottom one.

Santos and Ribeiro [72] stated that irrigation and cropping affected soil properties. Chemical properties were differently affected depending upon the management practices. They added that sites with tree crops and sprinkler or drip irrigation systems showed increases in the soil pH and exchangeable bases.

20.2 MATERIALS AND METHODS

This study was conducted at the Experimental Farm of Faculty of Agriculture of Ain Shams University. It is located at Shalaqan village 1 km from El-Kanater El-Khairea

District (latitude 30.13° N, altitude 31.25° E, and 41.9 m high above sea level), Qalubia Governorate, Egypt.

TABLE 1 Soil physical properties of the experimental site.

Soil sample Depth (cm)	**Particle size distribution (%)**				**Texture class**	*** FC**	*** PWP**	*** AW**	**BD (g/cm^3)**	**** HC (cm/h)**
	Coarse sand	**Fine sand**	**Silt**	**Clay**			**$\varnothing_{w}$%**			
0–15	0.8	27.8	41.6	29.8	SCL	35.46	19.10	16.36	1.25	3.12
15–30	0.7	27.5	41.2	30.6	SCL	35.21	19.24	15.97	1.28	2.36
30–45	0.6	27.9	38.5	33.0	CL	34.72	19.76	14.96	1.28	1.74
45–60	0.6	28.7	37.0	33.7	CL	34.78	20.10	14.68	1.29	1.56

*Determined as percentage in weight basis; **HC: Hydraulic conductivity;

SCL: Silty clay loam and CL: Clay loam.

Field experiments were carried out through two successive growing seasons (2002/2003 and 2003/2004) under three irrigation systems drip, low-head bubbler and the modified surface by using gated pipes that considered as control. Soil of experimental field represents the (Nile alluvial) silty clay loam.

Soil particle size distribution was carried out using pipette method after Gee and Bauder [26] as shown in Table 1. Soil bulk density (B.D.) was measured according to Black and Hartge [13].

Soil moisture content at field capacity (F.C) and permanent wilting point (P.W.P) were measured according to Walter and Gardener [81] as shown Table 1. The available water (AW) was calculated from the following equation:

$$AW = F.C - P.W.P \tag{1}$$

where: AW = available water ($\ominus_{w}$%), F.C = field capacity ($\ominus_{w}$%) and P.W.P = permanent wilting point ($\ominus_{w}$%).

Soil aggregate stability aggregation percentage (Agg.%) and mean weight diameter (MWD) was carried out using wet sieving technique without using a dispression agent after Kemper and Rosenau [48]. Soil hydraulic conductivity (HC) was determined under a constant head technique [48]. HC was calculating using the following formula:

$$HC = (QL)/(A.t\ .H) \tag{2}$$

where: Q = volume of water flowing through the sample per unit time (L^3/T), A = cross sectional flow area (L^2), L = length of the sample (L), and H = differences in hydraulic head across the sample (L). Soil intake rate was determined with double wall ring infiltrometer technique [50]. Kostikove equation was used to represent the infiltration process:

$$I = k\,t^{n} \tag{3}$$

$$D = k\,t^{n} \tag{4}$$

where: I = the infiltration rate at time t (mm/min), t = is the time that water is on the surface of the soil (min), k = the intercept of the curve which represents the infiltration rate at unit time (instantaneous infiltration rate, mm/min), and n = the slope of the curve which represent the relation between log I and log t; and D = accumulative intake rate (mm/min), and Soil pH and EC were measured in 1:2.5 soil water suspensions and in soil past extract, respectively, [43]. The $CaCO_3$ content, soluble Cations and anions were measured by Scheibler calcimeter [75] as shown in Table 2. Ground water was source of irrigation water. Irrigation water analysis is given in Table 3.

Grapevines farm three years old (Thomposon seedless variety) were used in the present work. Grape yield was harvested in the last half of July (2003 and 2004). The vines were grown at spacings of 2 × 3 (700-vine/fed). The plots devoted for low-head bubbler, drip, and gated pipe irrigation 50 × 27 m (1350 m^2), 50 × 27 m (1350 m^2) and 50 × 54 m (2700 m^2), respectively.

The meteorological data of the Central Laboratory for Agricultural Climate (CLAC), for Shalaqan Weather Station were used to estimate irrigation requirements as shown in Table 4.

TABLE 2 Chemical analysis of the soil.

Soil sample depths (cm)	**Cations (Meq/l)**				**Anions(Meq/l)**				**pH**	**E.C (dS/m)**
	Ca^{++}	**Mg^{++}**	**Na^{+}**	**K^{+}**	**CO_3^{--}**	**HCO_3^{-}**	**Cl^{-}**	**SO_4^{--}**		
0–15	0.40	0.48	0.41	0.19	0.00	0.63	0.49	0.30	7.7	0.26
15–30	0.46	0.35	0.51	0.18	0.00	0.76	0.51	0.24	7.6	0.23
30–45	0.57	0.55	0.62	0.20	0.00	0.79	0.75	0.40	7.4	0.25
45–60	0.48	0.66	0.67	0.16	0.00	0.86	0.66	0.46	7.2	0.27

TABLE 3 Chemical analysis of irrigation water.

Growing Season	**Cations (Meq/l)**				**Anions (Meq/l)**				**pH**	**E.C (dS/m)**	**S.A.R**
	Ca^{++}	**Mg^{++}**	**Na^{+}**	**K^{+}**	**$CO_3^{=}$**	**HCO_3^{-}**	**Cl^{-}**	**$So_4^{=}$**			
1st	2.73	1.4	2.19	0.21	0.0	2.4	2.5	1.0	7.3	0.37	1.52
2nd	2.81	1.3	2.16	0.23	0.0	2.3	2.7	1.0	7.4	0.35	1.50

TABLE 4 Water requirements for grapevines at Shalaqan (CLAC), during 2002–2003 and 2003–2004.

Month	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Season 2002–2003									
Periods(day)	**31**	**30**	**31**	**30**	**31**	**31**	**30**	**31**	**30**
ETo (mm/ day)	3.40	4.60	8.50	8.20	7.10	6.60	5.60	3.70	3.3
Kc	0.30	0.50	0.60	0.75	0.85	0.85	0.80	0.50	0.40
Kr%	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
ETc (mm/day/ vine)	**0.54**	**1.22**	**2.70**	**3.26**	**3.20**	**2.97**	**2.37**	**0.98**	**0.47**
ETc (mm/ month/vine)	**16.76**	**36.57**	83.79	97.79	99.16	92.17	71.23	30.40	13.99
Season 2003–2004									
Periods(day)	**31**	**30**	**31**	**30**	**31**	**31**	**30**	**31**	**30**
ETo (mm/ day)	3.10	5.20	7.30	7.00	6.90	7.00	6.60	4.50	2.20
Kc	0.30	0.50	0.60	0.75	0.85	0.85	0.80	0.50	0.40
Kr%	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
ETc (mm/ day/vine)	**0.49**	**1.38**	**2.32**	**2.78**	**3.11**	**3.15**	**2.80**	**1.19**	**0.70**
ETc (mm/ month/vine)	15.28	41.34	71.96	83.48	96.36	97.76	83.95	36.97	20.99

20.2.1 IRRIGATION SYSTEMS

Irrigation networks included the components that are indicated in Fig. 2. The system consisted of following subsystems:

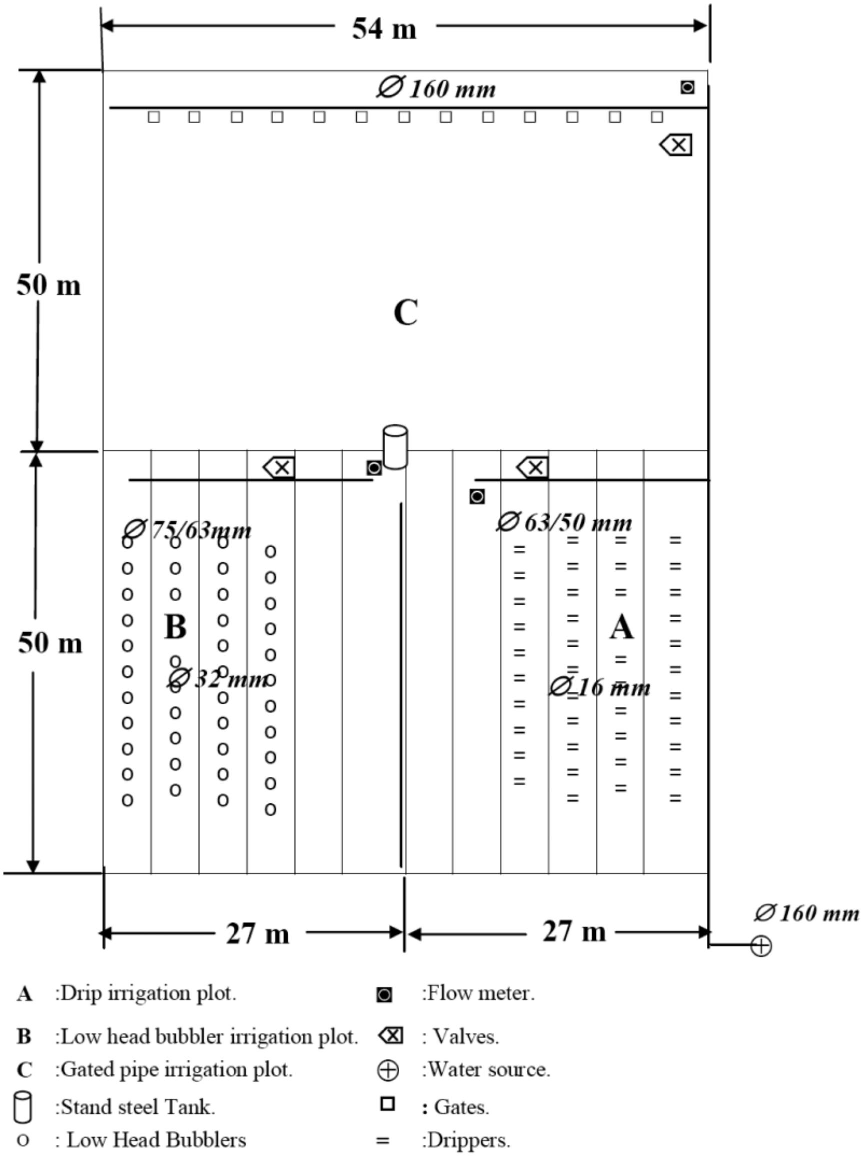


FIGURE 2 Layout of different irrigation systems for grapevines.

1. **Control head:** It was located at the water source supply. It consisted of centrifugal pump 4"/4," driven by diesel engine (pump discharge of 100 m^3/h and 50 m lift), sand media filter 48" (two tanks), screen filter 2" (120 mesh) back flow prevention device, pressure regulator, pressure gauges, flow-meter, control valves and chemical injection.

2. **Main line:** PVC pipes of 125 mm in diameter (OD) to convey the water from the source to the main control points in the field.
3. **Sub-main lines:** PVC pipes of 75 mm diameter (OD) were connected to with the main line through a control unit consists of a 2” ball valve and pressure gauges.
4. **Manifold lines:** PVC pipes of 40 mm in diameter (OD) were connected to the sub main line through control valves 1.5.”
5. **Distributor subsystem:**
    - **Emitters:** These emitters (GR) were built of PE tubes: 16 mm in diameter (OD) and 50 m in length. Emitter discharge was 4 lph at 1.0 bar operating pressure, and the emitter spacing was 50 cm.
    - **Bubblers:** PE tube 8 mm diameter (OD), with discharge of 40 lph at 0.15 bar operating pressure. These tubes were connected to PVC pipes 32 mm in diameter (OD) and 50 m in length. The head was adjusted by steel stand of 180 cm in height and 50 cm diameter. These were in the ring pattern. The spacing between bubblers was 2 m.
    - **Discharge** was 4.0 m^3/h. Distance between gates was 3 m, at 0.15 bar pressure. Water flow in furrows was at 1 °Cm from vine. The furrow dimensions were: 10 °Cm width, and 25 cm depth, 1:1 side slopes and bed slope of 0.01 with flow direction as shown in Fig. 3.

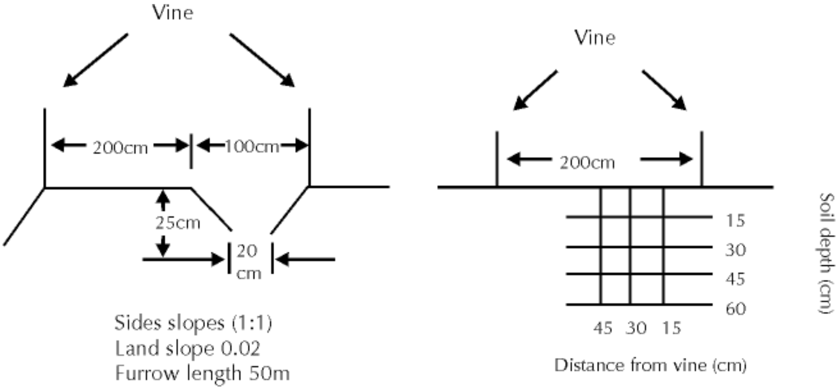


FIGURE 3 Furrow dimensions and sampling locations for the irrigation systems.

20.2.2 MATHEMATICAL EQUATIONS FOR IRRIGATION REQUIREMENTS

Table 5 indicates irrigation efficiencies for this chapter. Irrigation requirements for grapevines were calculated from the following equation [80].

$$IR=[(ETo \times Kc \times Kr \times A/Ei) + lR] \times [I] \qquad (5)$$

where: IR = irrigation water requirements, liter/tree/interval; ETo = reference evapotranspiration, mm/day; Kc = crop coefficient for grape; Kr = reduction factor due to ground cover; A = ground area per tree, m^2; Ei = irrigation system efficiency in %; LR= leaching requirements = $(EC_{iw}/EC_{dw}) \times 100$, and I = time interval, days.

TABLE 5 Irrigation efficiency for different irrigation systems.

Irrigation systems	Application efficiency, %	Distribution efficiency, %	Irrigation efficiency %
	2002–2003		
Drip	94.0	90.0	84.6
L-H Bubbler	90.0	89.0	80.1
Gated pipes	81.0	80.0	64.8
	2003–2004		
Drip	95.0	92.0	87.4
L-H bubbler	92.0	88.0	80.9
Gated pipes	80.0	79.0	63.2

L-H = Low head.

Irrigation efficiency = Application efficiency × Distribution efficiency.

20.2.3 IRRIGATION SCHEDULING

Irrigation interval was 4 days for drip and low head bubbler irrigation systems, while it was 7 days for gated pipes irrigation system. Irrigation interval was calculated using Eq. (6). The Eq. (7) was used to estimate net water depth applied per each irrigation (mm).

$$I = d/(ET_c) \tag{6}$$

$$d = MAD \times WHC \times Rd \times P \tag{7}$$

$$ET_c = ET_o \times K_c \tag{8}$$

where: d = net water depth applied per each irrigation (mm); WHC = (AW)(B.D) = water holding capacity, (mm water/m soil); MAD = management allowable deficit of 30 and 50% for drip and gated pipe irrigation, respectively; Rd = effective root zone depth (m); P = percentage of soil area wetted (%); ET_c = crop evapotranspiration (mm/day) given by Eq. (8); ET_o = reference evapotranspiration (mm/day); and K_c = crop coefficient

20.2.4 FERTILIZATION AND FERTIGATION

Fertilization scheduling was followed according to the recommended doses throughout the two growing seasons (2002/2003 and 2003/2004) for grapevines in each irrigation system by fertigation technique. The amounts of fertilizers were 350 kg/fed of ammonium sulfate (20.6%N) and 225 kg/fed of potassium sulfate (48.7% K_2O). While 175 kg/fed of super phosphate (15.5%P_2O_5) was applied in top dressing during the soil preparation. These amounts of fertilizers were divided into three doses and applied during the vegetative growth, during flowering and fruiting stage under gated pipe irrigation system, while 14 equal doses were fertigated in both drip and low-head bubbler irrigation systems (one dose every two weeks).

20.2.4 MEASUREMENT METHODS

20.2.4.1. SOIL MOISTURE DISTRIBUTION

Soil moisture percentage was determined gravimetrically on oven dry basis before and after irrigation from planting to harvesting. On each sampling date, duplicate soil samples were taken from soil at 0–15, 15–30, 30–45, 45–60 cm depths and at 0–15, 15–30,30–45 cm distance away from grape tree. The samples were immediately transferred into tightly closed aluminum cans to the laboratory. They were weighed, dried in an electrical oven at 105 °C for 24 h then reweighed and the soil moisture contents on the dry weight basis ($\ominus_w$) were determined. The data were analyzed by SURFER program under Windows computer application. The "Kriging" regression method was used for analysis and contour maps were developed.

20.2.4.2 PLANT MORPHOLOGY

Leaf area (L^2) by digital planimeter and leaves dry weight at 70 °C in (gm) were determined [15]. Both length (cm) and dry weight (gm) of branches were determined in the field after crop harvesting. The pruning weight per vine was determined in gm per vine.

20.2.4.3 YIELD AND QUALITY PARAMETERS

Grape clusters were harvested when the total soluble solids (TSS) reached about 16 to 17 (prix) in berry juice [24]. Yield per vine was recorded in kg.vine^{-1} at harvest time during July of each season. Yield productivity (kg.fed^{-1}) was determined by the following formula:

Yield product (kg/fed) = (Average Number of Clusters per vine ′ average weight cluster ′ Number of vine per fed) (9)

A sample of 100 berries was randomly selected from different bunches for each irrigation system. The berries were weighed and the average weight of berries per treatment was recorded. Volume of berries was determined by immersing the 100 berries in a graduated cylinder containing water at a fixed mark (V_1). Water level was recorded after immersion (V_2). The volume of berries in cm^3 was calculated as ($V_2 - V_1$). Juice volume was determined by blending 100 grams of berries for each irrigation method and by filtering through a fine muslin cloth. The pomace was pressed by hand until no more juice was obtained. Juice volume in cm^3 was then measured in a graduated cylinder. All observations were replicated thrice.

Sugar percentage (prix number) was carried out for the fresh extracted juice, which was obtained by blending 100 berries, and total soluble solids content was also observed using a hand refractometer [15]. The juice was thoroughly stirred and few of drops were mounted on the clean stage of the refractometer after which the readings were recorded.

Cluster volume was determined by immersing the cluster in a graduated cylinder containing water at a fixed mark. The rise in water level was recorded to obtain the volume of cluster (cm^3). The clusters were weighed on accurate balance and the average weight of clusters was calculated. Cluster density (gm/cm^3) was determined by the following formula:

$$D = W/V \tag{10}$$

where: W= weight of cluster (gm) and V= volume of cluster (cm^3). Cluster width and length were determined with a measuring tape. Berry diameter (mm) was determined by digital micrometer and the radius (r, mm) was calculated. Berry volume was calculated for a perfect sphere [Eq. (11)]. Crop load [14] was determined by Eq. (12).

$$\text{Berry volume} = 4/3\ \text{Л}\ r^3 \tag{11}$$

$$\text{Crop load} = (\text{Yield weight, } \mathbf{kg}/\text{fed})/(\text{Pruning weight, } \mathbf{kg}/\text{fed}) \tag{12}$$

20.2.5 ESTIMATION OF EFFICIENCIES (11, 38)

The water utilization efficiency ($\mathbf{WU_TE}$ in Kg/m^3) was determined with "(Yield, kg/fed) ÷ (applied water in m^3/fed)." The applied water was measured with a flow meter. The water use efficiency (WU_sE in **kg**/m^3) was determined with "(Yield, kg/fed) ÷ (calculated ET_c in cm^3/fed)." The fertilizer use efficiency (**FUE**, Kg of fruit per **kg** fertilizer) was estimated with "(Yield (kg/fed) ÷ (Fertilizer rate of N, P or K in kg/fed)."

20.2.6 ESTIMATION OF ECONOMIC FEASIBILITY COSTS FOR GRAPEVINES

Total production cost of grape yield included costs for irrigation, fertigation, weed control, and pest control. In this chapter, the Table 6 presents capital costs for different irrigation systems that were computed based on the market price for 2004.

TABLE 6 Capital cost for each irrigation method for grape crop.

Items	Life span	Cost of irrigation system		
		Drip	**L-H bubbler**	**Gated pipes**
	Year	**LE per feddan**		
Electrical pump and control head	15	800**	500	200
Main and sub main lines (PVC)	25	550	450	450
Main flood (PVC) 32 mm	15	—	350	—
Steel stand for low head	10	—	100	—
Laterals (PE) 16 mm with built in drippers	5	400	—	—

TABLE 6 *(Continued)*

Items	Life span	Cost of irrigation system		
		Drip	L-H bubbler	Gated pipes
	Year	LE per feddan		
Gated pipes	10	—	—	550
PE tubes (bubblers) 8 mm	5	—	40	—
Fertigation unit	10	100	100	100
Valves and controllers	10	200	120	30
Total capital costs LE/feddan	—	2050	1660	1330

Fed is abbreviation for feddan.

One *feddan* (non-SI Units of area in Egypt) = 1.038 acres = 0.42 hectare (ha) = 4200 m^2. 2.47 acres = 1 ha.

One LE (Egyptian currency) = 0.1437 $US or one $US = 6.94 LE.

****EXAMPLE 1.** Convert 800 LE per feddan to US$/acre and US$/ha.

800 (LE/feddan) = 800 (LE)(0.1437 US$/LE)(1/feddan)(1 feddan/1.038 acre)

= 110.8 US$ per acre.

= 110.8 US$ (1/acre)(2.47 acres/1 ha) = 273.6 US$ per ha.

The annual cost for each irrigation system consisted of fixed cost and the operating cost [83]. The annual fixed costs were calculated using Eq. (13). Depreciation cost differs from one system to another, according to the life span of the different components of each system. Depreciation was calculated with Eq. (14). Taxes and overhead ratios were assumed as 1.5–2.0% of the initial cost. Operating costs were calculated with Eq. (15).

$$F.C = D + I + T1 \tag{13}$$

$$D = (I.C. - Sv)/\,E \tag{14}$$

$$O.C. = L.C + E.C + (R\&M) \tag{15}$$

where: F.C.= annual fixed cost, LE/year; D = depreciation rate, LE/year; I = interest, LE/year = [(I.C. + Sv) × (I.R.)] ÷ [2]; T1 = taxes and overhead ratio, LE/year; I.C. = initial cost of irrigation system, LE; Sv = salvage value after depreciation, LE; E = expectancy life, year; I.R. = interest rate per year,%; O.C. = annual operating costs, LE/year; L.C = labor costs, LE/year; E.C = energy costs, LE/year; and R&M = repair and maintenance costs, LE/year.

Repair and maintenance cost was assumed as 2, 3, and 0.5% of the initial cost for bubbler, drip, and gated pipe irrigation system, respectively. Labor to operate the system and to check the system components will depend on irrigation duration, which can be different for each irrigation system according to the irrigation application rate. Labor cost was estimated with Eq. (16). Energy cost was calculated with the Eq. (17). Total annual irrigation cost was the total sum of fixed cost and operating cost.

$$L.C = T2 \times N \times P \tag{16}$$

$$E.C = Bp \times T3 \times Pr \tag{17}$$

where: L.C = annual labor cost, LE/year; T2 = annual irrigation time, hours/year; N = number of farm workers per feddan; P = labor cost, LE/hour; E.C. = energy cost, LE/year; Bp = the brake power, kW; T3 = annual operating time, hours; and Pr = cost of electrical power, LE/kW-hour.

Fertilization process was carried out by fertigation under drip and low-head bubbler and modified surface irrigation by using gated pipes irrigation for ammonium sulfate and potassium sulfate and using the traditional method (top dressing) for superphosphate. Fertilization cost was calculated with the Eq. (18). Pest control was carried with the sprayer. Pest control cost was calculated with the Eq. (19). Weed control was manual and weed control cost was calculated with the Eq. (20).

$$Fr = (Wf \times Pr) + Ac \tag{18}$$

$$Pc = (Wp \times P) + Ac \tag{19}$$

$$Wc = N \times L \times T4 \tag{20}$$

where: Fr = fertilization cost, LE/fed; Wf = amount of fertilizers, kg/fed; Pr = fertilizers price, LE/kg; Ac = application cost of fertilizers, LE/fed; Pc = pest control cost, LE/fed; Wp = amount of pesticides, kg/fed; P = pesticides price, LE/kg; Wc = weed control cost, LE/fed; N = number of farm workers per faddan; L = labor cost, LE/hour; and T4 = time used, hours/fed.

The net profit of grapevines for each irrigation system was calculated with Eq. (21) [88]. The production cost (LE/kg) was estimated with the Eq. (22).

$$P = (Yt \times d) - Ct \tag{21}$$

$$LE/kg = (\text{Total cost in LE/fed})/(\text{Total yield in } \mathbf{kg}\text{/fed}) \tag{22}$$

where: P = net profit, LE/fed; Yt = total yield, tons/fed; d = market price, LE/ton (It was assumed as 1250 LE for each one ton of grape); Ct = total production costs, LE/fed.

20.2.7 STATISTICAL ANALYSIS

The statistical analysis was conducted for all collected data for analysis of variance (ANOVA) and the least significant difference (L.S.D) among the irrigation systems at 5%. The randomized complete block design [21] was used for the experimental setup.

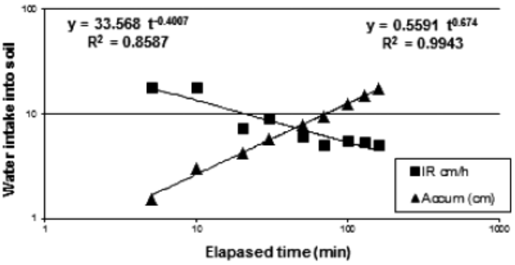
20.3 RESULTS AND DISCUSSION

20.3.1 EFFECT OF IRRIGATION SYSTEMS ON SOIL CHARACTERISTICS

20.3.1.1 WATER INTAKE

The Figs. 4 to 6 indicate the effects of drip irrigation system (DIS), low head bubbler irrigation system (LHBIS) and gated pipe irrigation system (GPIS) on water intake rate (IR) and accumulative intake rate (ACC-IR) in cm/h. In each of the three irrigation systems, IR decreased, whereas the (ACC-IR) increased with time. This general trend can be attributed to one or more of the following reasons: 1) occurrence of water column above the soil surface during measuring process may have hindered escaping the trapped air bubbles, 2) an inevitable decrease in matric gradient constituting one of the main forces drowning water into the soil which usually occurs as water intake process proceeds, 3) large easily accessible pores in the soil may have been filled with irrigation water before the smaller ones, 4) breakdown some soil aggregates due solubility and relaxation of some bonds and increasing trapped air pressure within the aggregates.

A) 2002/2003 season



B) 2003/2004 season

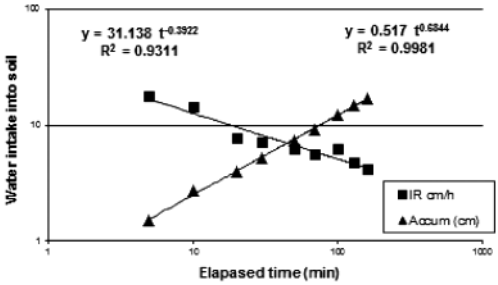
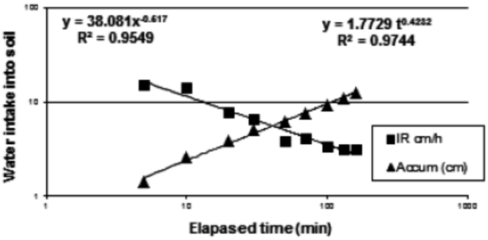


FIGURE 4 Water intake into soil in drip irrigation system.

A) 2002/2003 season



B) 2003/2004 season

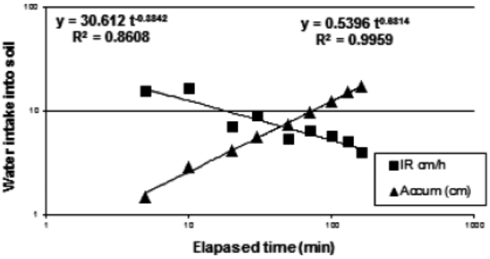
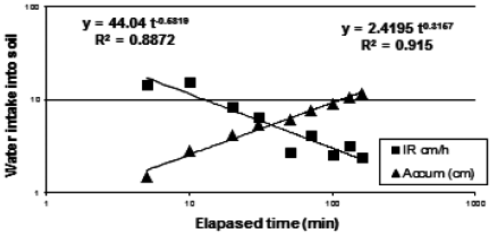


FIGURE 5 Water intake into soil in low-head bubbler irrigation system.

A) 2002/2003 season



B) 2003/2004 season

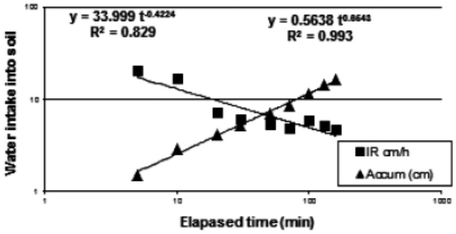
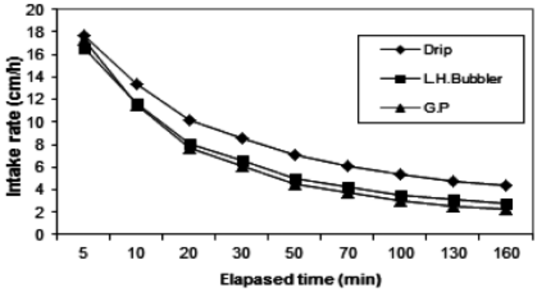


FIGURE 6 Water intake into soil in gated pipes irrigation system.

Figure 7 shows exponential relationships between water intake rate and elapsed time under different irrigation systems (DIS, LHBIS and GPIS) during 2002/2003 and 2003/2004. It can be concluded that water IR into the soil in the ascending order was GPIS<LHBIS<DIS during 2002/2003. This may be attributed to rapid soil wetting under GPIS and LHBIS relative to DIS. It will deteriorate soil aggregates and subsequently water IR into the soil. The results were similar to those of Kemper et al. [47]. At the end of season 2003/2004, the difference in water intake rate into the soil among irrigation systems disappeared. This may be due the offsetting effect of salt accumulation on aggregate disintegration.



B) 2003/2004 season

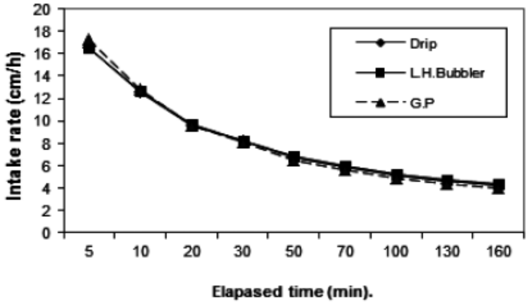


FIGURE 7 The relationship between water intake rate and elapsed time for three irrigation systems.

20.3.1.2 SOIL SALINITY

Salts distribution patterns for each irrigation system are plotted in Figs. 8 and 9. Regardless of the irrigation systems used, salt concentration before irrigation exceeded than the one after irrigation.

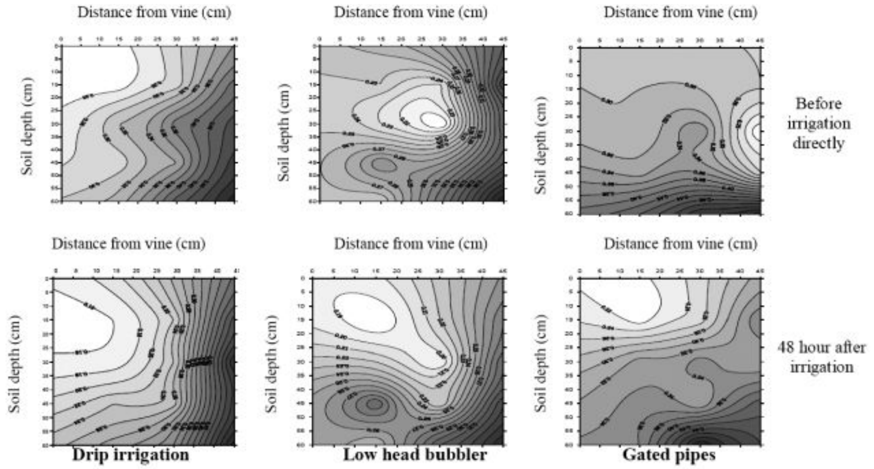


FIGURE 8 Contour maps for salt distribution patterns (dS/m) before and after irrigation in each irrigation method, during the growing season 2002–2003.

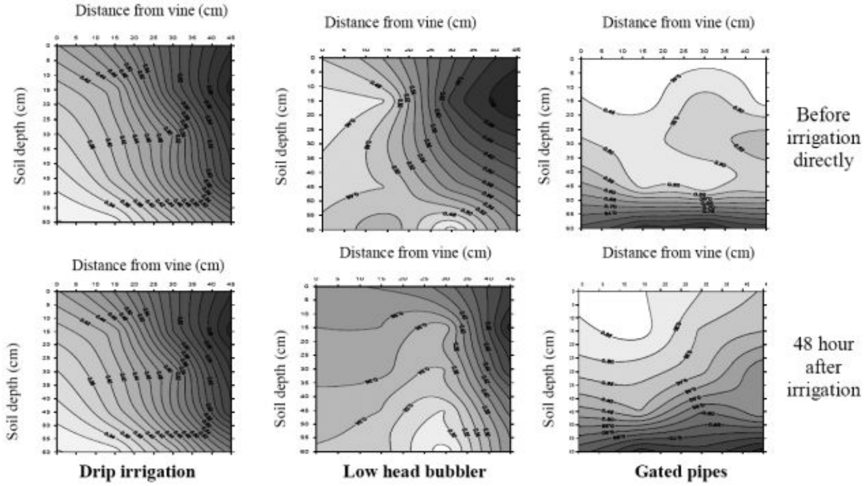


FIGURE 9 Contour maps for salt distribution patterns (dS/m) before and after irrigation in each irrigation method, during the growing season 2003–2004.

At the beginning of season 2002/2003, salt concentration increased with depth, but the opposite was true at the end of season 2003/2004. The mean soil salinity in LHBIS was lowest (0.28 dS/m), while it was highest in other two irrigation systems (DIS and GPIS) and equal (0.35 dS/m) at the beginning of season 2002/2003. In other words, the mean soil salinity in DIS and GPIS overpasses than the one in LHBIS by 25.9%.

At the end of season 2003/2004, the mean soil salinity in GPIS was highest (0.57 dS/m), followed by the values in DIS and LHBIS (0.47 dS/m). It can be concluded that the mean soil salinity increased by 34.3, 67.9, and 62.9% in DIS, LHBIS, and GPIS, respectively, within two years. This may be attributed to soil aggregation deterioration and decreasing water intake into soil. This draws our attention to the importance of attainment of the salt balance in localized irrigation systems and improving the farm drainage to facilitate salt leaching process, especially in heavy textured soils. Based on the mean soil salinity, the ascending order of three irrigation systems was: LHBIS<[DIS=GPIS] and [LHBIS=DIS]<GPIS at the beginning and end of seasons, respectively.

Differences in the mean soil salinity between LHBIS from one side and both DIS and GPIS from the other side (season 2002/2003) and between GPIS from one side and both DIS and LHBIS from the other side (2003/2004) were significant at the 5% level. Also the differences in the mean soil salinity between any two soil depths was significant at the 5% level with exception of those between the following layers: 15–30 cm and 30–45 cm under DIS, 30–45 cm and 45–60 cm under LHBIS, both at the beginning of season 2002/2003 and 15–30 cm and 30–45 cm at the end of season 2003/2004. The effect of the interaction irrigation systems × Sample depth on soil salinity showed that the maximum (0.88 dS/m) and minimum soil salinity (0.25 dS/m) were achieved in the following conditions: 1) GIPS, in soil layer 45–60 cm and at the end of season 2003/2004; and 2) LHBIS, in soil layer 15–30 cm at the beginning of season 2002/2003, respectively.

20.3.1.3 SOIL MOISTURE

Figures 10 and 11 indicate that the mean soil moisture contents ($\ominus_{w}$) were 24.76, 25.98 and 26.17% in DIS, LHBIS, and GPIS, respectively, before irrigation, whereas the values were 43.7, 45.97 and 44.93% in the same sequence, at the beginning of season 2002/2003. On the other hand, the mean $\ominus_{w}$ were 24.37, 25.42 and 25.05% before the irrigation while these were 44.59, 45.00 and 42.79% after irrigation in DIS, LHBIS and GPIS, respectively, at the end of season 2003/2004. There was slight increase in $\ominus_{w}$ with depth, whether soil moisture was measured before or after irrigation. This may be attributed to increasing clay fraction with depth.

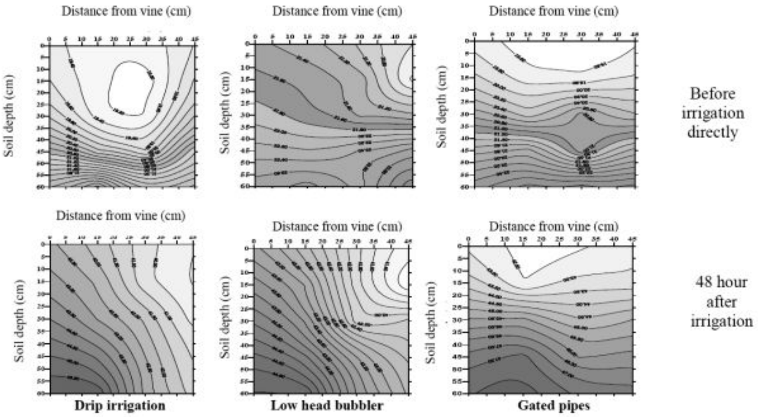


FIGURE 10 Contour maps for soil moisture distribution by weight before and after irrigation application in each irrigation system at first season 2002–2003.

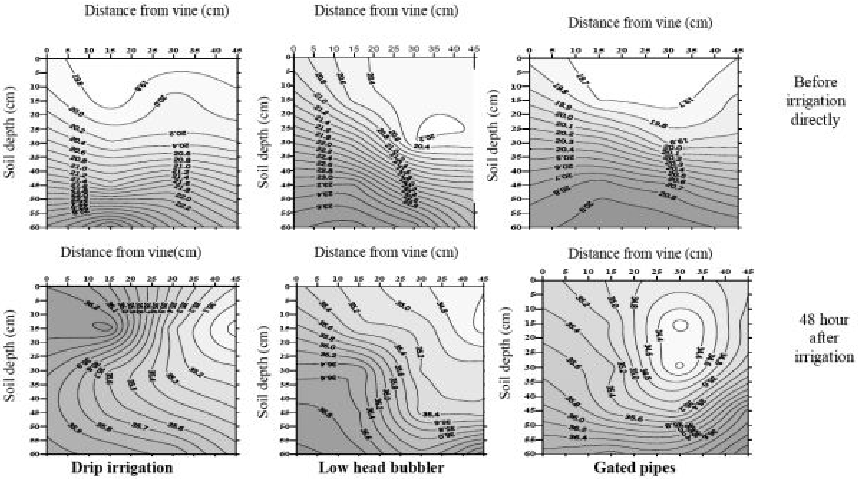


FIGURE 11 Contour maps for soil moisture distribution by weight before and after irrigation application in each irrigation system at first season 2003–2004.

According to the mean soil moisture content ($\ominus_w$), irrigation systems can be arranged in the following ascending orders: [LHBIS=DIS]<GPIS before irrigation, and GPIS<DIS<LHBIS after irrigation at the beginning of season 2002/2003. Differences in $\ominus_w$ between any two irrigation systems were significant at the 5% level except that between LHBIS and DIS before irrigation.

According to $\ominus_w$, the irrigation systems can be arranged in the following ascending orders: GPIS<LHBIS<DIS before irrigation and DIS<GPIS<LHBIS after irrigation, both at the end of season 2003/2004. Difference in $\ominus_w$ between GPIS from one side and both DIS and LHBIS from the other side was significant at the 5% level at the end of season 2003/2004. It may be due the deterioration of both soil aggregates and water intake rate into soil and increasing salt accumulation under GPIS in comparison with DIS and LHBIS.

Maximum and minimum values of moisture content $\ominus_w$ were 27.47% (45–60 cm) and 23.78% (0–15 cm) before irrigation and 47.61% (45–60 cm) and 40.80% (0–15 cm) in LHBIS and DIS, respectively, after irrigation at the beginning of season 2002/2003. However, at the end of season 2003/2004, the values of $\ominus_w$ were 26.30 (30–45 cm) and 23.88% (0–15 cm) for DIS and LHBIS before irrigation and 45.97 and 42.33% at the same depth (45–60 cm) under GPIS and LHBIS, respectively, after irrigation.

20.3.1.4 SOIL AGGREGATION

The Table 7 shows the effects of drip irrigation system (DIS), low-head bubbler irrigation system (LHBIS) and modified surface by using gated pipes irrigation system (GPIS) on both mean weight diameter (MWD) and aggregation percent (Agg.%).

TABLE 7 Effects of irrigation systems on soil aggregation.

Season	Irrigation systems	MWD (mm)	Aggregation (%)
	Drip	16.23	36.15
2002/2003	**Low-head bubbler**	17.09	38.76
	Modified gated pipes	13.86	27.79
	LSD $_{0.05}$	**0.01**	**0.001**
	Drip	17.6	32.93
2003/2004	**Low-head bubbler**	13.34	32.05
	Modified gated pipes	15.21	31.91
	LSD $_{0.05}$	**0.02**	**0.002**

Both MWD and aggregation percentage were affected each irrigation system. According to the value of the MWD and Agg.%, irrigation systems followed the ascending order of GPIS<DIS<LHBIS at the beginning of season 2002/2003. Differences in both the MWD and Agg.% between any two irrigation systems were significant at the 5% level. In other words, the changes in both MWD and Agg.% were (17.1; 30%) and (23.3; 39.5%) when DIS and LHBIS were compared with GPIS, respectively, at the beginning of season 2002/2003.

At the end of season 2003/2004, irrigation systems followed the order of DIS>GPIS>LHBIS for MWD and DIS>LHBIS>GPIS for Agg%, respectively. The changes in both MWD and Agg% were (15.6; 3.2%) and (–12.3; 4.4%), when both DIS and LHBIS were compared with GPIS, respectively. Generally, the differences in both MWD and Agg.% between any two irrigation systems were significant at the 5% level in the two seasons.

For forming a seed bed with a good tilth, clay soil must be: 1) wetted slowly and 2) dried thoroughly. Since the GPIS in grapevines is considered furrow irrigation (broad ridges), the soil is rapidly wetted relative to DIS and LHBIS.

Also in localized irrigation systems, soil is not dried thoroughly before irrigation. This can lead to aggregates deterioration for the following reasons: 1) ion hydration and osmotic swelling forces pull water in between clay platelets pushing them apart and causing swelling of the aggregates; 2) the wetted portion of the aggregates can swell appreciably compared to the dry one causing a shear plane to accompany the wetting front which can break many of the bonds; 3) some of the bonding materials are soluble and dissolve while others are hydratable and may become weaker and more flexible as water enters the soil; and 4) displacing the O_2 and N_2 molecules by the more tightly adsorbed water molecules and joining the air entrapped inside the aggregates pores leading to increasing pressure, aggregate ruptures and emerging air bubbles.

20.3.2 VEGETATIVE GROWTH OF GRAPEVINES FOR DIFFERENT IRRIGATION SYSTEMS

This section will include vegetative growth parameters of grapevines: leaf area (cm^2), leaf dry weight (gm), branch number, branch length (cm) and pruning weight (kg/fed).

20.3.2.1 LEAF AREA

Leaf area for both seasons is shown in Fig. 12 for each irrigation system. During 2002–2003, it was 143.6 cm^2 and highest in drip irrigation system (DIS) compared to 142.8 cm^2 in the low head bubbler irrigation system (LHBIS). The lowest value was 142.7 cm^2 for gated pipes irrigation system (GPIS). There was significant difference at the 5% level in leaf area between DIS from one side and both of LHBIS and GPIS from the other side. During 2002–2003, it was 151 cm^2 and highest in DIS compared to 148.6 cm^2 in LHBIS. The lowest value was 145.3 cm^2 for GPIS. There were significant differences at the 5% level in leaf area between any two irrigation systems. The increase in leaf area during 2003/2004 were 5.2, 4.1 and 1.8% in comparison with season 2002/2003 in DIS, LHBIS, and GPIS, respectively.

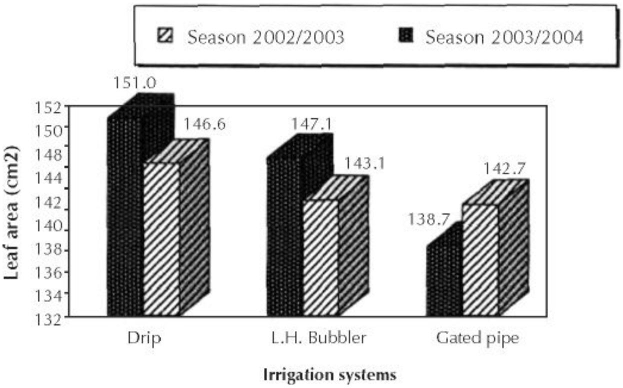


FIGURE 12 Leaf area in each irrigation method during the 2002–2003 and 2003–2004.

20.3.2.2 LEAF DRY WEIGHT

In each DIS, LHBIS, and GPIS, the leaf dry weight was 1.52, 1.24, and 1.23 gm (season 2002/2003) and 1.83, 1.65 and 1.29 gm (season 2003/2004), respectively, (Fig. 13). In both seasons, the difference in leaf dry weight between any two-irrigation systems was significant at the 5% level. The increases in leaf dry weight for 2nd season were 20.4, 33.1 and 4.9% in DIS, LHBIS and GPIS, respectively.

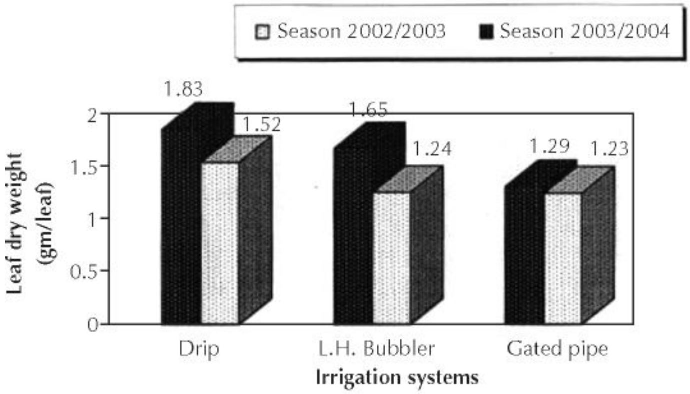


FIGURE 13 Leaf dry weight (gm/leaf) for each irrigation.

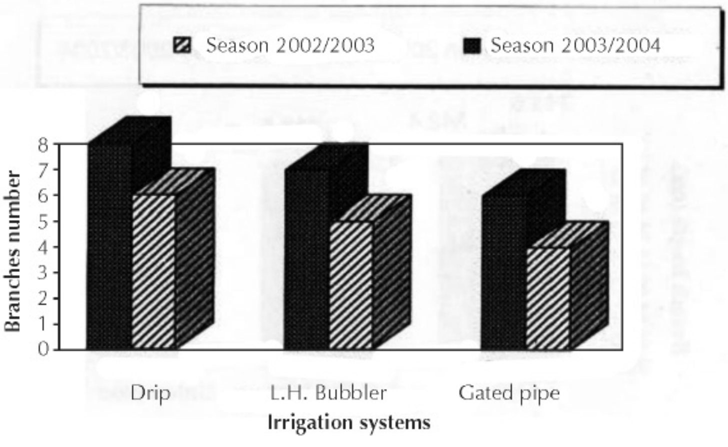


FIGURE 14 Number of branches per vine in each irrigation system.

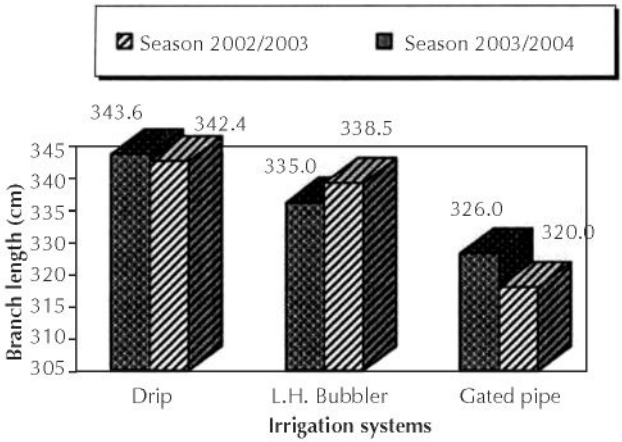


FIGURE 15 Effect of type of irrigation system on branch length.

20.3.2.3 NUMBER OF BRANCHES

Number of branches per grapevine (Fig. 14) was 6, 5, and 4 in DIS, LHBIS and GPIS, respectively, during 2002/2003. Number of branches per grapevine was 8, 7, and 6 in DIS, LHBIS and GPIS, respectively, during 2003/2004. The difference in number of branches/vine between DIS and GPIS was significant at the 5% level only at the 1st season. The increase in number of branches/vine was 33.33, 40 and 50% in DIS, LHBIS and GPIS, respectively, during 2nd season compared to the 1st season.

20.3.2.4 BRANCH LENGTH

Figure 15 shows the effects of irrigation systems on branch length (cm). In DIS, LHBIS, and GPIS, the branch length was 342.4, 338.5, and 320 cm during the first season and 343.6, 335, and 326 cm during the 2nd season, respectively. Based on the branch length, irrigation systems were in the following ascending order: GPIS<LHBIS<DIS in both seasons. There were significant differences in branch length between any two irrigation systems, in both seasons. The changes in branch length at the 2nd season relative to the 1st one were 0.35, −1.03 and 1.88% for DIS, LHBIS and GPIS, respectively. The small changes and the negative one can be attributed to variation in vine pruning process.

20.3.2.5 PRUNING WEIGHT

Pruning weights (PW) for two seasons are shown in Fig. 16. In under DIS, LHBIS, and GPIS, the PW was 984, 978 and 959 kg/fed during first season; and 1190, 1176 and 1066 kg/fed during the 2nd season, respectively. The PW for DIS exceeded that the value for GPIS. Based on pruning weights, the irrigation systems can be arranged in the following ascending order: GPIS<LHBIS<DIS. Difference in pruning weights between any two irrigation systems were significant at the 5% level except those between LHBIS from one side and both DIS and GPIS from the other side at the 1st season. The pruning weights in 2003/2004 exceeded that for 2002/2003 by 20.9, 20.27

and 11.09% in DIS, LHBIS, and GPIS, respectively. The superiority of the studied growth parameters for DIS and LHBIS compared to GPIS may be attributed to aggregate and water intake into the deterioration and salt accumulation.

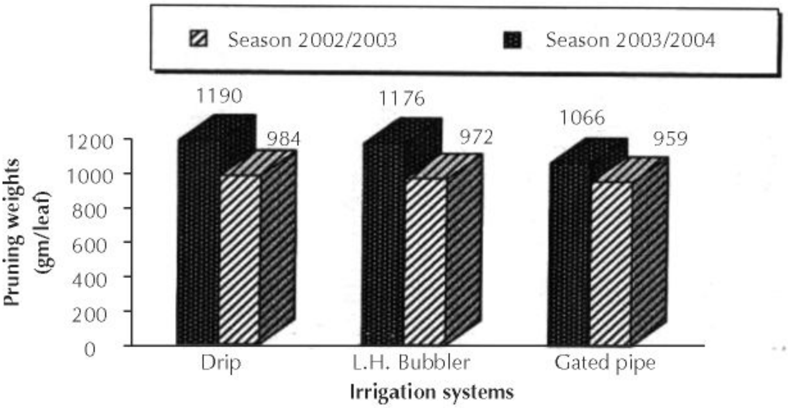


FIGURE 16 Effects of irrigation methods on pruning weight (kg/fed).

20.3.2.6 CROP LOAD

Crop load of the vineyard in the 1st season was 1.4 and highest for drip system. The value was 1.2 for low head bubbler irrigation system, and 1.1 for gated pipe irrigation system. Crop load of the vineyard in the second season was 3.3 and highest for drip system. The value was 2.6 for low head bubbler irrigation system, and 2.1 for gated pipe irrigation system.

The LSD at P = 0.05 value was 0.12 and it shows that there are significant differences in crop loads among all irrigation systems, with the exception of that between low head bubbler and gated pipes irrigation systems in the 1st season. The increases in crop load for 2003/2004 were 135.7, 116.6 and 90.9% compared to the values for 2002/2003 in DIS, LHBIS, and GPIS, respectively.

20.3.3 EFFECT OF IRRIGATION SYSTEMS ON CROP YIELD

The Fig. 17 shows the crop yield (kg per feddan) for each irrigation system. During 2002–2003, the highest yield was 2166.4 for drip irrigation system (DIS), followed by low-head bubbler irrigation system (LHBIS: 2059.3 kg/fed). The lowest yield was 1982.2 kg/fed for gated pipes irrigation system (GPIS). During 2003–2004, the highest yield was 3776.3 for drip irrigation system (DIS), followed by low-head bubbler irrigation system (LHBIS: 3506 kg/fed). The lowest yield was 2888.5 kg/fed for gated pipes irrigation system (GPIS).

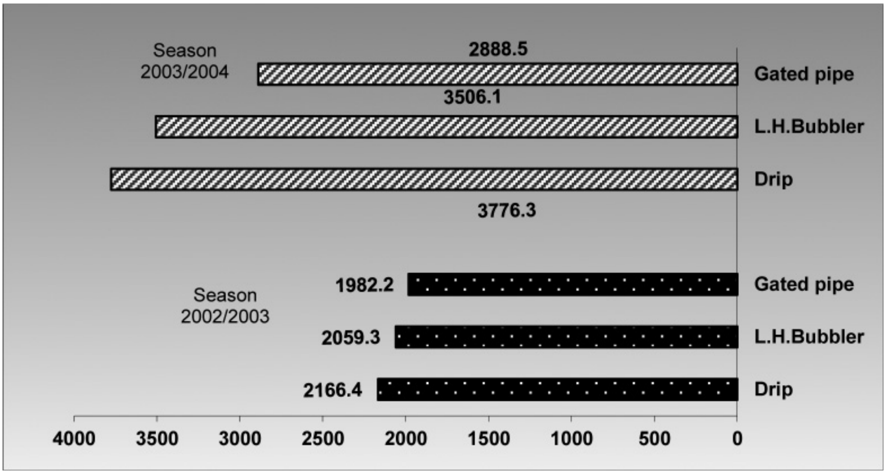


FIGURE 17 Effects of type of irrigation method on grape yield (kg per fed).

The differences in yield between any two-irrigation systems were significant at the 5% level in the two seasons. The results are in agreement with Ginestar et al. [32]. The data showed that yield increase for 2nd season compared to the 1st season was maximum for DIS (42.64%), followed by LHBIS (41.26%), while the lowest percentage of increase was 31.37% for GPIS.

20.3.4. WATER USE EFFICIENCY (WU_sE) AND WATER UTILIZATION EFFICIENCY (WU_TE)

Table 8 and Fig. 18 indicate the effects of irrigation methods on water use efficiency (kg/m^3) and water utilization efficiency (kg/m^3). During 2002–2003, the WU_sE was 0.84 and highest in DIS compared to 0.8 in LHBIS and 0.77 for GPIS. The WU_TE was 1.07 and highest in DIS compared to 0.97 in LHBIS and 0.51 for GPIS.

During 2003–2004, the WU_sE was 1.45 and highest in DIS compared to 1.35 in LHBIS and 1.1 for GPIS. The WU_TE was 1.87 and highest in DIS compared to 1.54 in LHBIS and 0.76 for GPIS.

TABLE 8 Effects of irrigation systems on water use efficiency and water utilization efficiency.

Irrigation systems	Crop water requirements (m^3/fed)	Crop yield (Kg/fed)	WU_sE	WU_TE
	Actual applied		(kg/m^3)	
First season 2002/2003				
Drip	2019.0	2166.4	0.84	1.07
L-H. Bubbler	2110.0	2059.3	0.80	0.97
Gated pipe	3820.0	1982.2	0.77	0.51
$LSD_{0.05}$		0.9	0.001	0.002

TABLE 8 *(Continued)*

Irrigation systems	Crop water requirements (m^3/fed)	Crop yield (Kg/fed)	WU_sE	WU_TE
	Actual applied		(kg/m^3)	
Second season 2003/2004				
Drip	2016.0	3776.3	1.45	1.87
L-H. Bubbler	2277.0	3506.1	1.35	1.54
Gated pipe	3763.0	2888.5	1.11	0.76
$LSD_{0.05}$		2.7	0.002	0.002

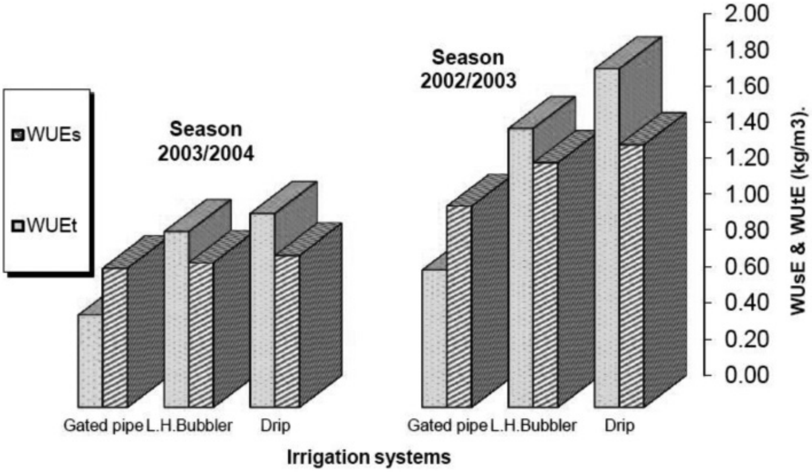


FIGURE 18 Effects of irrigation methods on water use efficiency (WU_sE) and water utilization efficiency (WU_TE).

$LSD_{0.5}$ value for WU_sE was 0.001 in 2002–2003, and 0.002 in 2003–2004 for the three different irrigation systems. $LSD_{0.5}$ value for WU_TE was 0.002 in 2002–2003, and 0.002 in 2003–2004 for the three different irrigation systems. The results are in agreement with Brown [16] and Hiler et al. [40]. The increase at the 2nd season compared to the 1st season was 42% for WU_sE and 43% for WU_TE. These values were maximum in DIS and minimum in GPIS.

20.3.5. FERTILIZERS USE EFFICIENCY (FUE)

The effects of irrigation systems on fertilizers use efficiency (FUE, kg yield/kg fertilizers) for two growing seasons are shown in Table 9 and Fig. 19. During the 2002–2003season, drip irrigation system (DIS) gave highest values of FUE as 35.06, 93.18 and 22.24 for N, P_2O_5, K_2O, respectively, In the low head bubbler irrigation system (LHBIS), FUE was 33.32 for N, 88.57 for P_2O_5 and 21.15 for K_2O, respectively.

The lowest FUE was 32.07 for N, 85.26 for P_2O_5, and 20.36 for K_2O, respectively, in gated pipe irrigation system (GPIS).

TABLE 9 Effects of irrigation systems on fertilizer use efficiency for two growing seasons.

Irrigation System	**N, P, K fertilizer rate, kg/fed**			**Crop Yield (Kg/fed)**	**Fertilizers use efficiency (kg yield/ kg fertilizer)**		
	N	**P_2O_5**	**K_2O**		**N U E**	**P U E**	**K U E**
First season 2002/2003							
Drip	—	—23.25	—97.4	2166.4	35.06	93.18	22.24
L-B. Bubbler	61.8	—	—	2059.3	33.32	88.57	21.15
Gated pipe	—			1982.2	32.07	85.26	20.36
LSD $_{0.05}$				0.9	0.7	0.3	0.6
Second season 2003/2004							
Drip	—	—31.1	—121.7	3776.3	45.83	121.42	31.03
L-h. Bubbler	82.4	—	—	3506.1	42.55	112.74	28.81
Gated pipe	—			2888.5	35.06	92.88	23.74
LSD $_{0.05}$				2.7	0.1	0.1	0.02

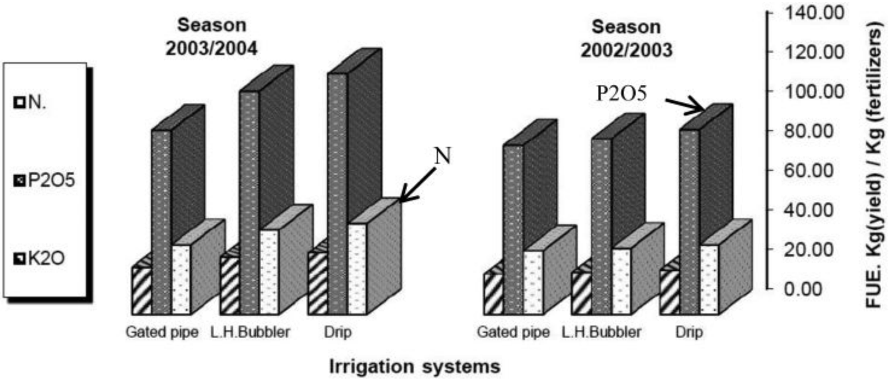


FIGURE 19 Fertilizer use efficiency (N, P, K) for each irrigation system.

During the 2003–2004season, drip irrigation system (DIS) gave highest values of FUE and was 45.83, 121.42 and 31.03 for N, P_2O_5, and K_2O, respectively, In the low head bubbler irrigation system (LHBIS), FUE was 42.55 for N, 112.74 for P_2O_5

and 28.81 for K_2O, respectively. The lowest FUE was 35.06for N, 92.88 for P_2O_5, and 23.74 for K_2O, respectively, in gated pipe irrigation system (GPIS). These data are in agreement with Baligar et al. [10] and Barbar [11]. In both seasons, the differences were at P = 0.05 significant both WU_SE and WU_TE among the irrigation systems.

The increase in FUE in DIS and LHBIS compared to FUE in GPIS may be attributed to negative effect of GPIS on MWD, aggregation%, IR, and soil salinity. FUE in the 2nd season exceeded the FUE in the 1st season one due to age of grapevines and the increase in yield (45.7–74.4%) according to irrigation systems overpassed that in fertilizers applied (24.2–33.8%). In other wards 1% increase in fertilizer application increased the yield by 2% under the experiment conditions.

20.3.6 EFFECT OF IRRIGATION SYSTEMS ON FRUIT QUALITY

The parameters for fruit quality were: Juice volume (cm^3), TSS (prix number), sugar percentage (prix number), cluster density (gm/cm^3) and crop load.

Figure 20 shows the **juice volume** for both seasons. During 2002–2003 and in drip irrigation system (DIS), it was highest (40.7 cm^3), followed by low head bubbler irrigation system (LHBIS, 39.8 cm^3), while lowest value was 38.8 cm^3 in gated pipe system (GPIS). The differences in juice volume between any two irrigation systems were significant at the 5% level.

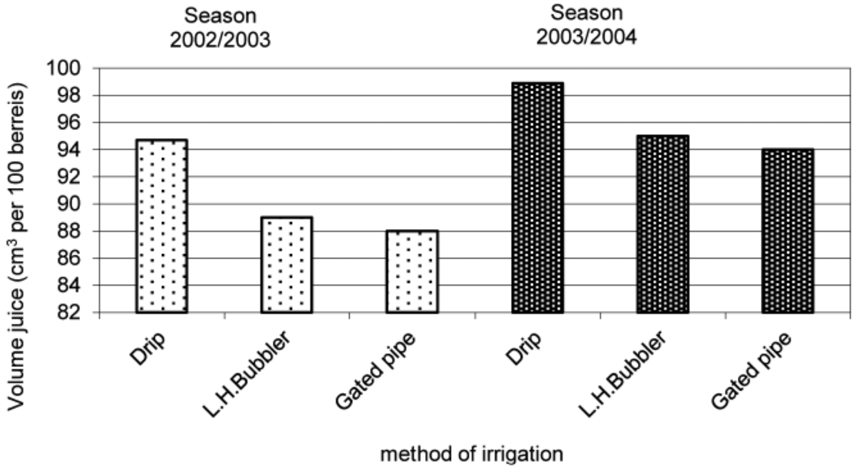


FIGURE 20 Effect of irrigation methods on volume of juice of grape.

During 2003–20034 and in drip irrigation system (DIS), it was highest (46.9 cm^3), followed by low head bubbler irrigation system (LHBIS, 45.5 cm^3), while lowest value was 44.4 cm^3 in gated pipe system (GPIS). There were significant differences at 5% level in juice volume between DIS from one side and both LHBIS and GPIS from the other side. High of juice volume in the fruit berries under DIS and LHBIS irrigation systems may be due to great volume of berries under ones. The increase in juice volume during 2003–2004 was 15.2, 14.3 and 14.40% in DIS, LHBIS, and GPIS compared to 2002–2003, respectively.

For both seasons and each irrigation system, sugar percentage (prix number) is shown in Fig. 21. During 2002–2003, it was 21.8 prix and highest in DIS, followed by 21.1 prix in LHBIS. The lowest sugar percentage was 20.2 prix for GPIS. During 2003–2004, it was 23 prix and highest in DIS, followed by 21.5 prix in LHBIS. The lowest sugar percentage was 21 prix for GPIS. LSD at P = 0.05 was 0.02 showing significant differences in sugar content among all irrigation systems. High content of sugar percentage in the DIS and LHBIS system may be due to greater values of WUE and FUE compared to the values in GPIS. The sugar percentage during 2003/2004 exceeded that for 2002/2003 by 5.5, 1.86 and 3.96% in DIS, LHBIS, and GPIS, respectively. For both seasons and each irrigation system, TSS (prix number) is shown in Fig. 22.

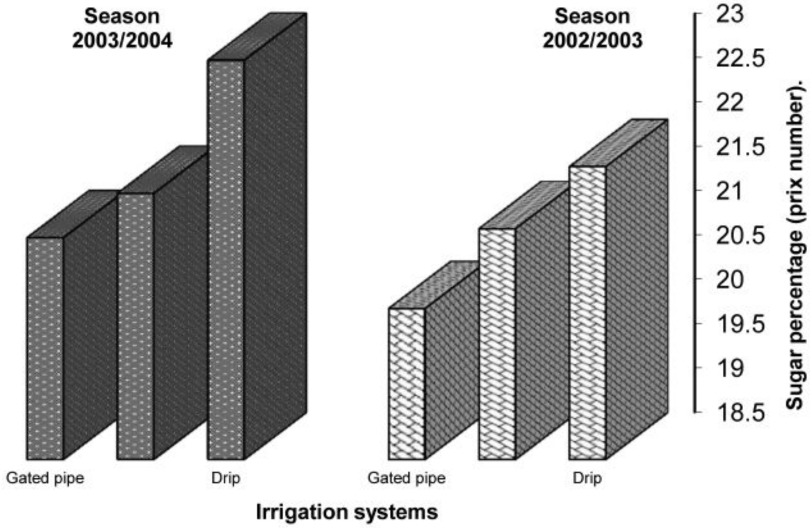


FIGURE 21 Effects of irrigation methods on sugar content in grape berry during 2002–2003 and 2003–2004.

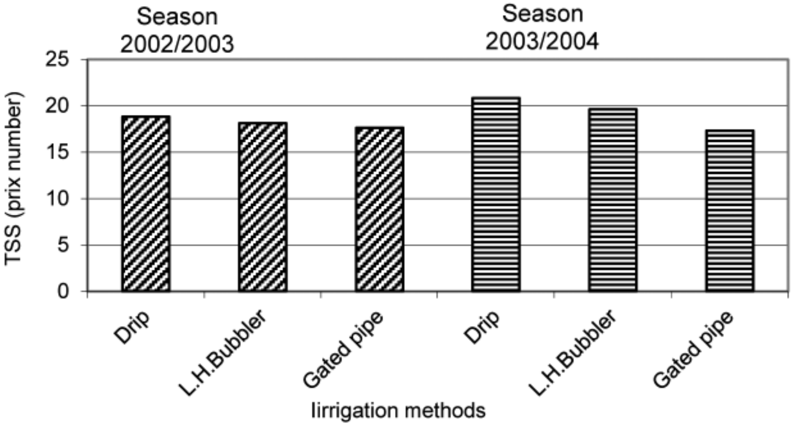


FIGURE 22 Effects of irrigation methods on TSS in grape berry.

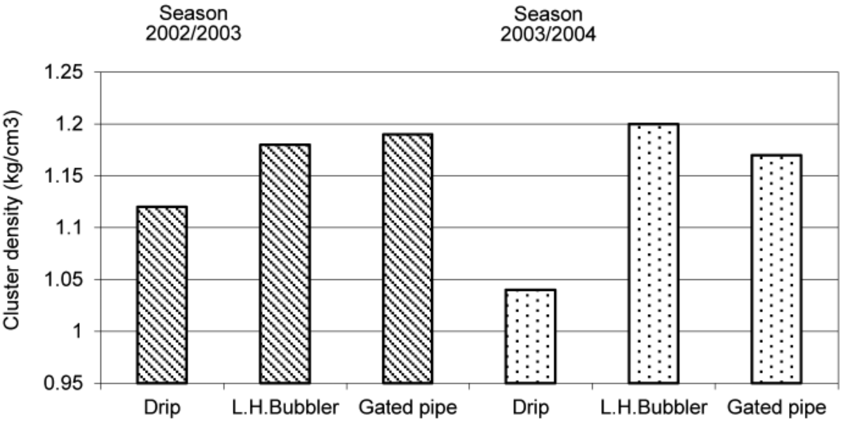


FIGURE 23 Effects of irrigation methods on cluster density.

The cluster density (gm/cm^3) is shown in Fig. 23 for irrigation methods and both seasons. During 2002–2003, it was 1.12 and lowest in DIS, 1.18 in LHBIS, and 1.19 gm/cm^3 in GPIS. LSD value at P = 0.05 was 0.02, thus indicating significant differences in cluster density for LHBIS and in any of DIS and GPIS. During 2003–2004, it was 1.04 and lowest in DIS, 1.2 in LHBIS, and 1.17 gm/cm^3 in GPIS. LSD value at P = 0.05 was 0.02, thus indicating significant differences in cluster density for LHBIS and in any of DIS and GPIS. Highest value of cluster density in GPIS may be due to small volume of berries compared to other irrigation systems. The reductions in cluster density were −7.14 for DIS and –1.7% in GPIS, respectively. The increase in cluster density was 1.6% in LHBIS during the second season compared to the first season.

The cluster width increased by 4.7 in DIS and 3.5% in LHBIS compared to the one in GPIS during 2002–2003. During the second season, the average increase was 3.2% in DIS and 2.1% in LHBIS compared to the one in GPIS. Based on the cluster width, irrigation systems followed the descending order: DIS>LHBIS>GPIS for both seasons. The differences between any two irrigation systems were significant at the 5% level in both seasons. The cluster length increased by 6.8% in DIS and 6.2% in LHBIS compared to the one in GPIS during the first season. The average increase was 7.3 in DIS and 1.1% in LHBIS compared to the one in GPIS. There was significant difference among the irrigation systems at the 5% level in the two growing seasons.

Figure 24 shows that berry diameter increased by 32.9 in DIS and 24.1% in LHBIS than the one in GPIS through the first season. During the second season, the average increase was 31.7 and 20.7% in DIS and LHBIS, respectively, compared to the one in GPIS. Based on the berry diameter, irrigation systems can be written in the ascending order of DIS>LHBIS>GPIS in both seasons.

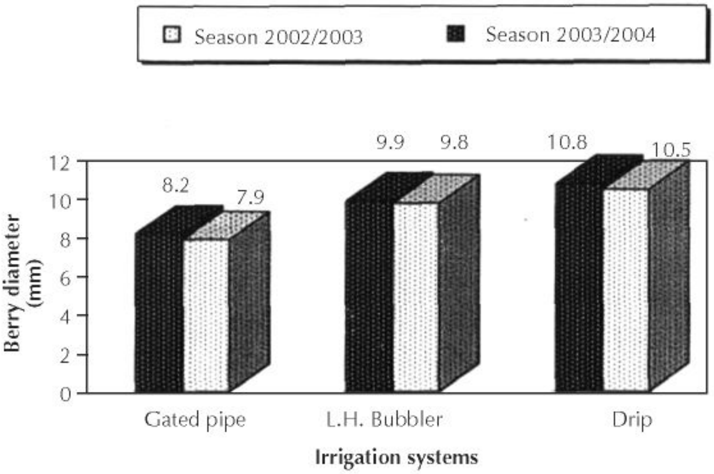


FIGURE 24 Effects of irrigation systems on berry diameter (mm).

Figure 25 shows that the highest value of berry volume in DIS was 4.85 during 2002–2003, and 5.27 cm^3), respectively; and the lowest berry volume in GPIS was 2.06 in first season and 2.31 cm^3 in the second season. LSD value at P = 0.05 show that there were significant differences in berry volume among all irrigation systems. High value of berry volume in DIS and LHBIS system may be due to greater WUE and FUE compared to DIS.

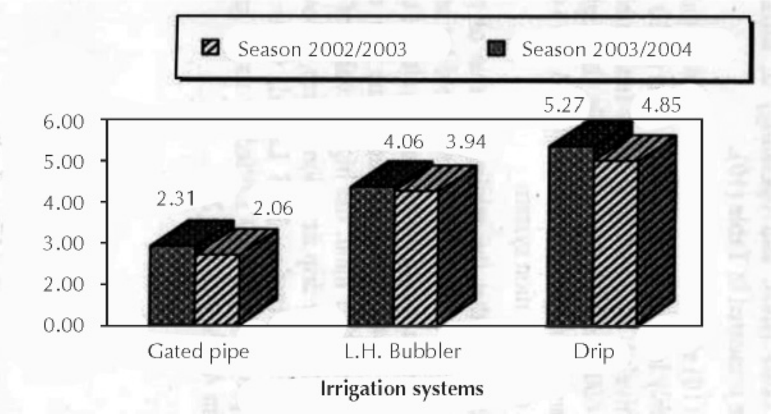


FIGURE 25 Effects of irrigation systems on the berry volume (cm^3).

20.3.7 COST OF IRRIGATION SYSTEMS

The cost of production of grapevines indicated that the grape yield varies according to the irrigation systems. Total irrigation cost is a major capital input for most farms and for most crops. The capital and annual costs (fixed and operating) for three irrigation systems are presented in Table 10.

The results in Table 10 indicates that capital and annual costs were 1330 and 300.1 LE/fed, respectively, and were considerably lower for the gated pipes irrigation system (GPIS), followed by the LHBIS (1660 and 417 LE/fed), while the highest value of capital and annual irrigation costs was (2050 and 544.3 LE/fed) for the drip irrigation system.

Table 11 illustrates that the total production cost was 1260.1 LE/fed and was minimum in gated pipes irrigation system, while the maximum value was 1414.3 LE/fed for the drip irrigation system. The highest value of net profit was 3335.7 LE/fed in drip irrigation system, followed by 3058 LE/fed in the low head bubbler irrigation, while the lowest net profit was 2364.9 LE/fed in gated pipes irrigation system (Fig. 26).

TABLE 10 The annual cost for different irrigation systems.

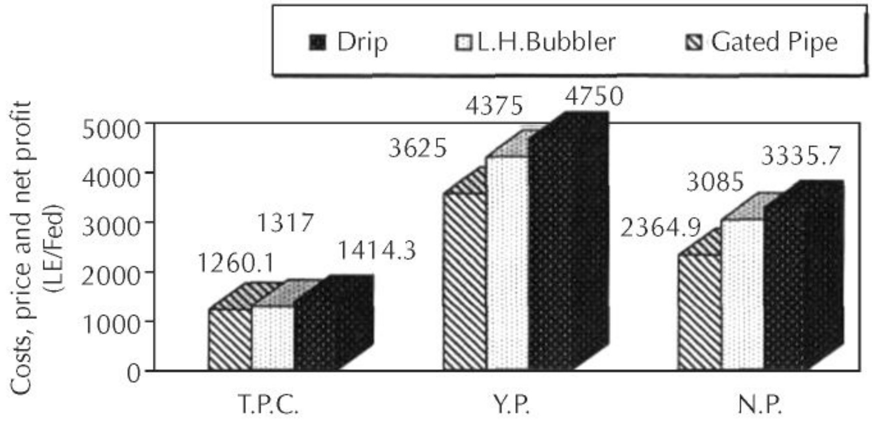
Items	**Irrigation system**		
	Drip	**Low head bubbler**	**Gated pipe**
Annual cost, LE per feddan			
Capital cost, LE/fed.	2050	1660	1330
Fixed cost:			
–Depreciation	199.2	156.0	78.6
–Interest	122.6	94.6	58.3
–Taxes, etc.(2% of capital costs)	41.0	33.2	26.6

TABLE 10 *(Continued)*

Items	**Irrigation system**		
	Drip	**Low head bubbler**	**Gated pipe**
A = Subtotal	362.8	283.8	163.5
Operating cost:			
Labor	40.0	40.0	100.0
Power	80.0	60.0	30.0
Repair and maintenance	61.5	33.2	6.65
B = Subtotal	181.0	133.2	136.6
Total cost = A + B, LE/fed.	**544.3**	**417.0**	**300.1**

TABLE 11 Total production cost for grapevines for different irrigation systems.

Items		**Irrigation system**		
Drip		**L-H. bubbler**	**Gated pipes**	
Irrigation costs, A		544.3	417.0	300.1
Fertilization cost, B		710.0	710.0	710.0
Pest control cost, C		100.0	100.0	100.0
Weed control cost, D		60.0	90.0	150.0
Total production cost, A + B + C + D = E		**1414.3**	**1317.0**	**1260.1**
Total sale, F	LE/fed	4750.0	4375.0	3625.0
Net profit, F – E =		**3335.7**	**3058.0**	**2364.9**
Grape yield	**ton/fed**	**3.8**	**3.5**	**2.9**



T.P.C.: Total production costs (LE/fed).
Y.P.: Yield price (LE/fed).
N.P.: Net profit (LE/fed).

FIGURE 26 Economic cost for each irrigation system.

20.4 SUMMARY

The field research was conducted during two successful growing seasons 2002/2003 and 2003/2004 at the Experimental Farm of Agriculture Faculty of Ain Shams University. It is located at Shalaqan village 1 km from El Kanater El Khairea District, Qalubia Governorate. Three years old grapevines (700 vines.fed^{-1}) were irrigated using drip irrigation system (DIS), low head bubbler irrigation system (LHBIS) and gated pipes irrigation system (GPIS). Soil at site represents the Nile alluvial, and silty clay loam. Irrigation requirements were calculated according to the procedures by Nakayama et al. [33]. The objectives of this research were: to encourage replacing the surface irrigation system by a localized irrigation systems in the old lands of the Delta and Valley in Egypt; increase the water and fertilizers use efficiencies; study the changes in some soil physical properties; and to study the performance of grapevines for three irrigation systems. Data obtained were subjected to statistical analysis. Also, the costs were economically evaluated.

The irrigation systems in this study can be arranged in the ascending order GPIS<LHBIS<DIS, according to the values of the water intake rate (IR) into the soil during 2002/2003. According to the average soil salinity, the irrigation systems can be arranged in ascending order LHBIS<DIS=GPIS and LHBIS=DIS<GPIS at the beginning and end of seasons, respectively. Differences in soil moisture percentage between any two irrigation systems were significant at 5% level except that between LHBIS and DIS before irrigation.

For the two seasons 2002/2003 and 2003/2004, the leaf area differences between any two irrigation systems were significant at 5% level. The increase in leaf area for the 2nd season compared to the 1st season was 5.2, 4.1 and 1.8% for DIS, LHBIS and GPIS, respectively. The differences in leaf dry weight between any two irrigation systems were significant at the 5% level. The increase in leaf dry weight for the 2nd season compared to the 1st season was 24.84, 16.93 and 4.87% in LHBIS, DIS and GPIS, respectively. The differences in pruning weights between any two irrigation systems were significant at 5% level except those between LHBIS from one side and both DIS and GPIS from the other side for the 1st season. The increase in pruning weight for the 2nd season was 20.9, 20.27 and 11.09% in DIS, LHBIS and GPIS, respectively.

Based on crop yield, WU_SE, WU_TE and FUE, irrigation systems can be arranged in the ascending order DIS>LHBIS>GPIS during 2002/2003 and 2003/2004. The differences in yield between any two irrigation systems were significant at 5% level for both seasons. The increase in crop yield for the 2nd season compared to the 1st season was maximum in DIS (42.64%), followed by LHBIS (41.26%), while the minimum value (31.37%) was obtained under GPIS. Also the increases in both WU_SE and WU_TE for the 2nd season compared to the 1st season were maximum in DIS (42 and 43%, respectively), followed by the LHBIS (40.7 and 37%), while the minimum increase in WU_SE and WU_TE was (30.6 and 32%, respectively) for GPIS. The increase in FUE of N, P_2O_5, and K_2O for 2nd season compared to the 1st season was (24, 23, 28%), (22%, 21%, 27%) and (9%, 8%, 14%) for DIS, LHBIS and GPIS, respectively.

The data reveal that total production cost was minimum (1260.1 LE/fed) in GPIS, while the maximum value was 1414.3 LE/fed in DIS. On the other hand, total production cost in LHBIS was 1317 LE/fed.

Net profit of grape yield was 3335.7, 3058 and 2364.9 LE/fed in DIS, LHBIS and GPIS, respectively.

The effects of both DIS and LHBIS were favorable on: water intake rate into the soil, both moisture and salt pattern distributions, grapevine growth (leaf area, leaf dry weight, branch number/vine, branch length, pruning weight, and crop load), yield, water use efficiency, water utilization efficiency, fertilizer use efficiency, yield quality (juice volume, TSS, sugar content, cluster density, cluster length, cluster width, berry diameter; berry volume). Since the net profit in DIS and LHBIS exceeded than that of GPIS, therefore DIS and LHBIS can be recommended to irrigate the old lands in both the Delta and the Valley in Egypt.

KEYWORDS

- **Ain Shams University**
- **Annual fixed cost**
- **Annual Labor cost**
- **Annual operating time**
- **Berry diameter**
- **Berry volume**
- **Brake power**
- **Branch length**
- **Branch number**
- **Bubbler irrigation system**
- **Central Laboratory for Agricultural Climate, Egypt**

- **Citrus farm**
- **Cluster density**
- **Cluster length**
- **Cluster width**
- **Crop load**
- **Depreciation**
- **Drip irrigation system**
- **Egypt**
- **Energy costs**
- **Expectancy life**
- **Feddan**
- **Fertilization cost**
- **Fertilizers use efficiency**
- **Gated pipe irrigation system**
- **Grape crop growth parameters**
- **Grape fruit quality**
- **Grape fruit yield**
- **Hydraulic conductivity**
- **Irrigation system**
- **Irrigation time**
- **Juice volume**
- **Leaf area**
- **Leaf dry weight**
- **Pest control**
- **Pesticides**
- **Pruning weight**
- **RSS, recommended rate of fertilizers**
- **Saline water rain water**
- **Salvage value**
- **Soil characteristics**
- **Sugar percent**
- **Total soluble solids**
- **Water use efficiency**
- **Water utilization efficiency**
- **Weed control**

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CHAPTER 21

MICRO-IRRIGATION SYSTEMS FOR POT-IN-POT ORNAMENTAL NURSERY PRODUCTION

SUSMITHA NAMBUTHIRI, AMY FULCHER, and ROBERT GENEVE

CONTENTS

21.1 INTRODUCTION

The nursery and floricultural industry is highly dependent on container plant production. Utilizing sustainable inputs and adopting sustainable practices have become a significant trend for horticultural production world-wide. This has led to a significant increase in pot-in-pot (PIP) nursery production, especially for large caliper trees traditionally produced as field-produced balled and burlapped crops [27]. PIP tree production is a combination of traditional container and field production where the growing container (production pots) is placed tightly within a semipermanent, underground socket pot [26, 31, 37, 38]. Pot sizes have varied from 3 to 30 gallons (Fig. 1). A plant is usually in the production container from six to nine months but not more than two years.

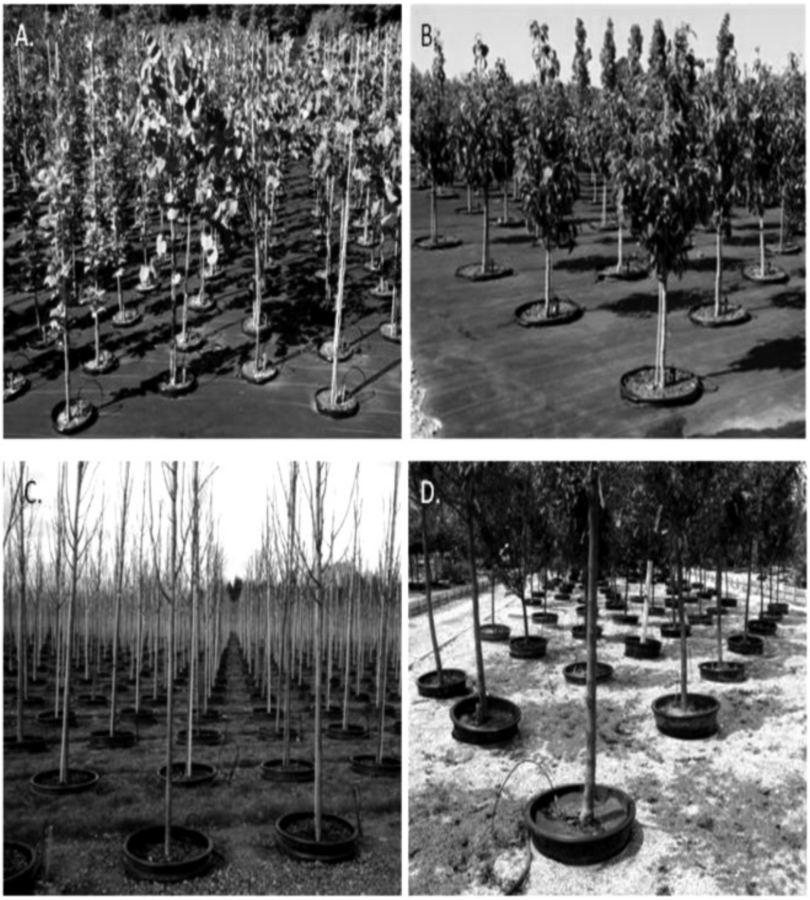

FIGURE 1 Pot-in-pot nursery production in various size containers using micro irrigation: (A, B) – Small caliper size shade trees with nursery fabric between the containers; (C, D) – Large caliper size shade trees grown with a turf strip (C) or gravel (D) between the rows.

PIP was originally developed as the "Minnesota System" in the 1980s [32] as an alternative to field and above-ground container production for tap-rooted shade trees [33]. The system proved to be equally useful for general shade tree production [45]. Although initially costly to establish [27], PIP is arguably the most sustainable production system for nursery shade trees. Compared to field produced trees, PIP uses water and fertilizer more efficiently and eliminates "soil mining" because it uses a renewable bark-based growing substrate rather than digging trees from the nursery field. For large caliper tree production, about 170 metric tons of soil is removed per hectare of production [7]. Compared to above-ground container production, PIP results in a reduced use of plastic where Quonset structures are required for overwintering.

This chapter describes the current features of pot-in-pot nursery production systems with particular emphasis on micro irrigation.

21.2 POT IN POT (PIP) NURSERY PRODUCTION SYSTEM

Establishing a PIP nursery can involve extensive first year preparation. Installation procedures are detailed step-by-step in the University of Kentucky video available on-line at: <http://www.youtube.com/watch?v=wNeBurkznIk>. PIP systems are either established in extremely well-drained soils or a drainage line must be installed just below the bottom of the socket pot. PIP system allows closer spacing and permits precision application of irrigation and fertilizer compared to typical field production. Production pots with plants are easily harvested at any time of year providing marketing flexibility and potential profits whereas field-grown plants require machines, and harvesting cannot occur during very dry or wet periods as that could cause root damage [19]. Other advantages of PIP compared to above ground container production include: no blowing over as plants are anchored in the ground saving labor and money required to upright plants. Under PIP system, roots experience a moderated temperature similar to the soil temperature below ground, which reduces evapotranspiration, and ensures higher root quality and faster plant growth than above ground container production [24, 39, 58]. The system protects roots from temperature extremes avoiding the need for moving to an overwintering structure or to provide shade during hot summer. Table 1 presents a comparison of key features of PIP with field and above-ground containers.

TABLE 1 Comparison of key features of pot-in-pot nursery production compared to above-ground or in-ground shade tree production.

Production system	**Irrigation type**	**Substrate**	**Staking**	**Over wintering**	**Harvest time**	**Plants per hectare**[**]	**Cost per plant ($)**[**]
Pot-in-pot	Micro irrigation	Bark-based	For plant structure	No special requirements	Any time of year	950	21.50

TABLE 1 *(Continued)*

Production system	Irrigation type	Substrate	Staking	Over wintering	Harvest time	Plants per hectare**	Cost per plant ($)**
Field	Principally overhead irrigation	Soil	For plant structure	No special requirements	Primarily Spring and Fall	770	23.71
Above-ground container	Overhead irrigation	Bark-based	For plant structure and blow over support	Quonset structures in Northern production areas	Any time	870	23.73

** Plants per hectare and costs were from a 1996study for three-year crape myrtle (Lagerstroemia) production on a typical 15 acre (6 hectare) USA nursery with plants grown on a spacing of 5.6, 6.3, and 6.2 plants per m^2 for pot-in-pot, field and above-ground containers, respectively [27].

21.3 IRRIGATION OVERVIEW OF SHADE TREE NURSERIES

Many container nurseries irrigated with overhead sprinklers [4] even those growing larger trees. Overhead irrigation has great disparity in water output across an individual zone [55]. Yeager et al. [54] reported that irrigation zones can have as much as 300% variability in water output within a single zone. Container nurseries using overhead irrigation could use more than 40,000 gallons of water per acre per day during the peak-growing season with 40% to 90% losses through evaporation and runoff [52]. Also, efficiency and nonuniform wetting decrease with increasing container volume [4] along with nonuniform wetting pattern. Beeson and Knox [4] reported overhead-irrigation application efficiency of 37% when plants were adjacent to each other and 25% at a spacing of 3.0 inches (7.6 cm) between containers. It is estimated that 50% to 75% of the water applied through overhead irrigation systems misses the containers completely [59].

Nurseries have two main strategies for alleviating competition for water: improved irrigation efficiency and use of alternative, possibly lower-quality water from non-traditional sources. Many practices influence efficiency, including irrigation scheduling, irrigation system selection and delivery, substrate composition, plant spacing, and plant grouping based on water requirements within irrigation zones [15]. Increasing irrigation efficiency can reduce both over and under irrigation, which cause issues during nursery production. Over irrigation can cause problems related to wasted water and environmental pollution due to nutrient and pesticide contaminated runoff (removing nutrients and pesticides from the foliage, root zone and production surfaces), energy costs for pumping water, vulnerability to biotic and abiotic stresses; reduced plant growth and consequent increased production duration. The potential consequences of under-irrigation include reduced plant quality and growth and consequent increased production duration and increased susceptibility to diseases and arthropods.

PIP uses an alternative to standard overhead irrigation by using either trickle emitters or spray stakes in each individual container (Fig. 2) alleviating some of the problems associated with container production for water application, water use and nutrient runoff [38, 39]. Loss from wind and evaporation is considerably reduced in this type of micro irrigation system because only the container surface is watered, not the entire container yard surface [6]. Weatherspoon and Harrell [52] reported that irrigation application efficiencies of overhead sprinklers averaged 13% to 26% over the course of a year. Typically irrigation application efficiency is around 90% for PIP. Haydu and Beeson Jr. [20] reported that microirrigated plants reached market size in significantly shorter time than those irrigated with conventional overhead systems (28 weeks versus 82 weeks for live oak). However, irrigation practices with PIP production method have raised concerns over water use efficiency because of drainage water loss through the containers is not readily detectable [57]. Nurseries can be a source of pollution that runoff water can contain pesticides, fertilizers and other chemicals released into surface and ground water. To obtain high water use efficiency and to automate irrigation control, it is important to implement various water management strategies.

21.4 MICRO-IRRIGATION MANAGEMENT OPTIONS FOR PIP

Although micro irrigation is the standard method for irrigating trees in PIP, there is limited research based information on irrigation automation and scheduling. Limited rooting volume and low water holding capacity of the porous substrate necessitates irrigation scheduling in PIP to be much more frequent with lower volumes per irrigation event, compared with growing similar species in field soils [5]. There is potential for increasing irrigation application efficiency through improved irrigation scheduling [49] by improving water management within a container. Grower-friendly irrigation strategies to optimize water use efficiency for PIP production that will minimize water use while maximizing high quality plant growth are presented in the following sections.

Irrigation scheduling is the method used to determine the amount of water (how much?) to be applied to a plant and the timing (when to irrigate?) and length (how long irrigation should last?) of application. Irrigation scheduling has a significant impact on water use efficiency. Inadequate irrigation management can result in inefficient water use and excessive irrigation result in nutrient and pesticide leaching into ground water. Scheduling can be relatively static and arbitrary (timer-driven), substrate moisture-based, based on environmental models, or plant-based. The goal of an efficient irrigation program is to supply the crop with enough water to maximize crop growth while minimizing water waste due to runoff and leaching.

21.4.1 STATIC SCHEDULING

The conventional container production practice is to irrigate once per day by automatic timers or based on growers' experience. Many growers continue to follow fixed predetermined schedules with quantities of water that often exceed crop needs [10]. With static irrigation, application is not linked directly to plant or substrate moisture status and thus may result in short drought periods during critical crop stages leading to serious consequences: increase production time, lower plant quality and plant diseases. Irrigation is not adjusted often for changes in evaporative demand due to weather changes, but rather is limited to gross changes when the seasons change [16].

FIGURE 2 Micro-irrigation systems for pot-in-pot nursery production: (A) typical micro irrigation system with main lines running adjacent to the container row and single spray stakes from the main line to the container; (B) pot-in-pot prior to planting. The main irrigation line is under the nursery fabric; (C) microsprinkler; and (D) spray stakes in each individual container.

21.4.2 SUBSTRATE MOISTURE-BASED SCHEDULING

Substrate moisture sensors (SMS) have emerged as a smart tool for implementing precision irrigation in intensive agriculture. SMS measure real time substrate moisture status, whenever a preset threshold water content is reached, an irrigation controller calculates the timing, amount and duration of irrigation required to replenish the water in a growing substrate to a preset level (generally container capacity) as evaluated in *Hydrangea quercifolia* 'Alice' [18] and in *H. macrophylla* 'Fasan' and *Gardenia Jasminoides* 'Radicans' [48]. SMS match plant water requirements considering evapotranspiration, substrate water storage changes, plant available water, rainfall, etc. SMS-based irrigation works for any type of plant, as long as the set-points for the irrigation controller are correctly chosen and there is no variation in factors that affect drying, such as uneven substrate compaction at potting, uneven shading, etc. Types of sensors that have been employed to automatically control irrigation events based on preset substrate matric potential limits include tensiometers, which measure substrate suction directly without calibration for substrate type, salinity or temperature but have contact issues with coarse and dry substrates [43] and dielectric sensors [28, 30]. Use of SMS was reported to be very promising in the cultivation of plants under PIP. SMS significantly reduced water use and improve plant growth of many crops under PIP [8].

21.4.3 ENVIRONMENTAL-BASED SCHEDULING

Most commonly used environmentally based irrigation scheduling methods are based on real time or historic weather and consider various weather parameters (light radiation, temperature, wind speed, relative humidity, rainfall, etc.) to estimate the evapotranspiration (ET) as a function of weather conditions and plant type. ET is defined as the quantity of moisture that is both transpired by the plant and evaporated from the substrate surface. Since the two processes occur simultaneously and are very difficult to separate, they are combined into one process [2]. In this method rainfall and irrigation are balanced with withdrawals such as ET and runoff. The water balance technique involves determining the change in soil moisture over time based on reference evapotranspiration (ET_0) adjusted with a crop coefficient (Kc) specific to growth and/or developmental stage, canopy coverage, plant population and exposure [34].

Irrigation based on crop ET values requires periodic modifications by the grower as the method is specific to plant type, growth stage, microclimate, and is subject to variations in local conditions such as plant spacing, canopy coverage, cultivar, root depth, and production practices [2]. Additionally, time-costly manual field observations are required to develop accurate crop coefficients. Lack of sufficiently local weather data and the programs necessary to use it to schedule irrigation lead to errors in calculating ET_0 and with a resulting misapplication of water [1, 2].

Scheduling irrigation based on crop ET has limited utility under nursery production because of the diversity of crop species being grown, the lack of crop coefficient information for woody shade trees [36], and the open canopy.

21.4.4 PLANT-BASED SCHEDULING

Innovative methods based on the direct monitoring of plant water relations have been considered to be highly relevant and allow for environmental influence. Irrigation control devices have been designed to exploit micro measurements of stem sap flow and stem diameter [44], leaf temperature [35], plant water potential [17], and modeling based on empirically derived plant characteristics [29] are plant-based techniques that have been used to gauge water loss in horticultural crops. But the plant-based irrigation systems are still scarcely employed in commercial operations as low plant water status induced by high vapor pressure deficit conditions could trigger irrigation when the substrate moisture is not limiting [13], they lack the ability to assess the volume of water required for irrigation and are difficult to automate [21].

21.5 SUBSTRATE MOISTURE BASED IRRIGATION STRATEGIES FOR PIP

21.5.1 DAILY WATER USE REPLACEMENT (DWU)

The DWU irrigation system was developed to replace water used during the previous day's use for container production [51]. DWU is the combined loss of water due to plant transpiration and evaporative water loss from the substrate [47]. Irrigation based on DWU has been conducted on nursery crops using daily pre and postirrigation substrate moisture probe or gravimetric measurements to determine DWU [51, 56]. Warsaw et al. [51] used a SMS to determine daily water use requirements in container production for 24 taxa of commonly used woody shrubs. Additionally, irrigating based on 100% DWU or alternating with up to 2 days at 75% DWU followed by 100% DWU did not reduce plant growth of woody ornamental shrubs in 10-L containers and possibly increased nutrition of plants compared to a well-watered control [51]. Using DWU to schedule irrigation reduced the amount of irrigation applied by as much as 75%, runoff volume by up to 79%, nitrate quantity by up to 59% and phosphate quantity moving in runoff by as much as by 74% compared to standard nursery irrigation practices (19 mm per application) [51].

21.5.2 SET POINT ON-DEMAND IRRIGATION

A plant demand-based irrigation system models plant response to environmental changes to predict amount and timing of irrigation. A simple on-demand irrigation scheduling system has been developed to calculate an irrigation set point adjusted to the substrate water content at which plant photosynthetic rate began to be reduced by water deficit [12]. It is assumed that growth is not be compromised when an irrigation set point was used based on the substrate water content where photosynthesis begins to decline due to water stress. Because photosynthesis is closely linked with stomatal conductance, and stomatal conductance is controlled by both root to shoot signaling and the environment, photosynthesis is a sensitive indicator of water status. An irrigation model was developed using *Hibiscus rosa-sinensis* [13]. An irrigation set point was established that reflected the substrate water content at which photosynthesis began to drop (photosynthetic rate was reduced to 98% of maximum), which corresponded with a reduction in stomatal conductance. By maintaining the substrate moisture content just above this set point, a crop could be produced using 27% less water than the control, and without adversely impacting quality, or production time [14]. Development of an irrigation system based on photosynthetic rates would require a minimum of data collection for model development and could easily be modified for use with other species. The plant on-demand irrigation scheduling system has since been employed successfully on a number of crops including dogwood (*Cornus sp.*), oakleaf hydrangea (*Hydrangea quercifolia*), and boxwood (*Buxus sp.)* for example, in *Boxwood (Buxus microphylla* 'Green Ice'), overall water use as well as water use efficiency (WUE) were improved using either the DWU or demand-based scheduling system without reducing plant biomass and plant quality under outdoor nursery conditions. An irrigation system predicated on maximizing photosynthesis has also been developed for container-grown apple (*Malus* x*domestica* Borkh.) trees. This system uses sap flow and stem diameter variations to predict the amount of water required by the plant and established a set point based on the relationship between maximum photosynthesis and midday stem water potential [44] to control timing of irrigation.

Both the photosynthesis-based irrigation scheduling system [12] and daily water replacement irrigation [51] appear to meet water conservation criteria compared to a timer-based irrigation strategy. The major difference between the photosynthesis-based irrigation system vs. daily replacement is that the photosynthesis-based system irrigates based on instantaneous water use, while daily water replacement only applies irrigation once per day. Therefore, plants irrigated under daily replacement could experience periods of water stress on days with significant transpirational demand at the expense of plant growth and water use efficiency. In contrast, the photosynthesis-based model was developed to schedule irrigation on-demand whenever container moisture was reduced to a level where stomata were predicted to begin to close restricting carbon.

21.6 ADVANCED IRRIGATION STRATEGIES TO ENHANCE IRRIGATION EFFICIENCY

21.6.1 CYCLIC IRRIGATION

Cyclic irrigation is a conservative irrigation strategy for PIP production system whereby plant's daily water allotment is applied as multiple smaller volume of water at predetermined intervals instead of a conventional single application [8, 55, 25]. Most soilless container substrates have a low capacity for retaining nutrients and water, and large irrigation volume results in significant nutrient loss, particularly nitrates [11]. Cyclic irrigation was found to improve irrigation application efficiency by allowing time for water to move through the micropore system of container substrate [22] by around 38% over single water applications [47].

Tayler et al. [46] reported that cyclic irrigation increased plant height and relative caliper growth of *Pinus strobus* by over 80% and 35%, respectively, compared with once-daily irrigation. Nursery studies testing cyclic irrigation on woody ornamentals have attributed the resulting increase in growth to cumulative reductions in midday water stress [41] and subsequent maintenance of stomatal conductance rates, therefore increasing net photosynthesis [50]. In a study conducted using 'Okame' cherry multiple irrigation cycles resulted in increased stem diameter, shoot dry weight and total biomass compared to a single irrigation application [40]. A PIP study reported about 25% increase in the trunk diameter of red maple and oak plants [8, 23] receiving three-cycle irrigation compared to those trees grown with single irrigation.

Cyclic irrigation was found to reduce nutrient leaching by 41% and irrigation runoff by 30% [11]. A 30% to 89% reduction in nitrate and ammoniacal nitrogen leaching was observed with cyclic irrigation by allowing efficient plant nitrogen uptake compared to a single watering [9, 22] and by decreasing runoff volume [11]. A wireless sensor-controlled set-point based cyclic irrigation in PIP was found to reduce daily water applications to dogwood (*Cornus florida* 'Cherokee Brave') and red maple (*Acer rubrum* 'Autumn Blaze') trees by 63% and 33%, without affecting the growth of either species and with significant labor savings in daily irrigation management, which translated into an annual net savings of $5,263 for this operation and a payback period of 2.7 years [5].

21.6.2 IRRIGATION TIMING

Most of the plants grown in PIP require irrigation on a daily basis considering low water holding capacity and high porosity of container substrate. Current best management practices in the US on above ground container production recommend single irrigation to occur during early morning hours to reduce drift and evaporative loss of water [55]. Beeson [3] reported increased growth of four woody ornamentals when irrigation was applied during the day in contrast to early morning irrigation. Irrigation during the afternoon hours increased top and root growth of *Rhododendron* × 'Hershey's Red' compared to an evening irrigation by reducing substrate heat load and minimizing water stress during later part of the day [50]. A PIP study conducted using *Cotoneaster dammeri* 'Skogholm' showed that plants that were irrigated both during the afternoon and all day significantly outperformed plants irrigated during predawn hours [53] showed that plants that were irrigated both during the afternoon and all day significantly outperformed plants irrigated during predawn hours. However, some sources [42] recommend, from a water conservation standpoint, daytime as a poor time to irrigate considering high water loss due to evapotranspiration during the hottest ours of the day (10:00 am to 4:00 pm). These studies suggest a lack of information on optimal irrigation timing under PIP conditions and growers may want to consider irrigating at times other than early morning to increase growth by minimizing substrate dry down and reducing heat load in the later part of the day.

21.7 CASE STUDY

A PIP study was conducted at the University of Kentucky Horticulture Research Farm in Lexington, KY (lat. 38°3'N, long. 84°30'W, msl elevation 381 m) to evaluate timing of cyclic irrigation in redbud (*Cercis canadensis*). Hourly weather data were obtained from an on-farm weather station and monthly mean air temperature, solar radiation and cumulative precipitation were reported as August (23 °C, 624 MJ m^{-2}, 18 cm), and September (20 °C, 549 MJ m^{-2}, 3.6 cm). Liners were grown in either 7-gallon or 15 gallon containers filled with 85% pine bark: 15% peat (vol/vol) in PIP systems. Substrate moisture content were continuously monitored using EC5 (Decagon, IL) sensors inserted into three representative containers per irrigation treatment. Acquisition and control of water content were carried out using a Campbell CR–1000 data logger. Irrigation was scheduled to replace 100% daily water used for evapotranspiration [51].

The quantity of water determined by the daily water use method was applied in three equal amounts and applied at the following times: cyclic irrigation starting at (i) 7, 8, and 9 am; (ii) 12, 1, and 2 pm; or (iii) at 5, 6,and 7 pm. A timer and switches in the control unit regulates the irrigation valve in calculated pulse intervals, for example, 8–12 min and cease operation and reset the system, awaiting the next 'on' signal at the specified time. Irrigation in each treatment replicate was controlled by a solenoid valve (The Toro Co., Riverside, CA). Irrigation was delivered with one Tornado ray jet emitter at ~6 gph (Plastro Irrigation Systems Ltd.) per container. Substrate water content and crop water use were monitored at a 15 min frequent interval throughout the season. Main stem diameter (caliper) was measured at 3 feet above the substrate surface after initial potting and at the end of growing season.

As expected, 15 gallon containers have higher water usage than 7 gallon containers and that could be due to higher evapotranspiration rate of plants in them compared to plants grown in 7 gallon containers (Fig. 3). It is evident from the figure that during warm periods of the year the daily water usage is significantly higher but it started to decline as the temperature cooled down in September in both container sizes. Thus the daily water use was well correlated with environmental factors such as air temperature and solar radiation.

Volume of irrigation water applied was influenced by the timing of irrigation in 7 gallon containers (Table 2). Irrigation volume applied per day was highest in the noon followed by PM and AM. Total water use for the irrigation treatment beginning in noon was approximately 15% more than AM irrigation and about 10% more than PM irrigation. But the variation in water use was not reflected in main stem diameter even though plants watered beginning at noon were the biggest. No change in stem diameter could be attributed to a higher evaporative water loss even though cooling of substrate in noon irrigation is an advantage. Total water use and daily water use were not different between different timings of cyclic irrigation in a 15 gallon container. Main stem diameter also did not differ between AM and noon treatments, however plants irrigated in the evening (PM) had 30% smaller stem diameter compared to AM and noon irrigations. Optimal irrigation timing could not be derived mainly due to high precipitation and mild weather during the study period. This could be because the plants might have experienced a mild water deficit during midday period before irrigation as Scagel et al. [41] noticed in container grown *Rhododendron*. From a water conservation perspective, AM irrigation is better than other times and also plant growth was similar to irrigation at other times of the day.

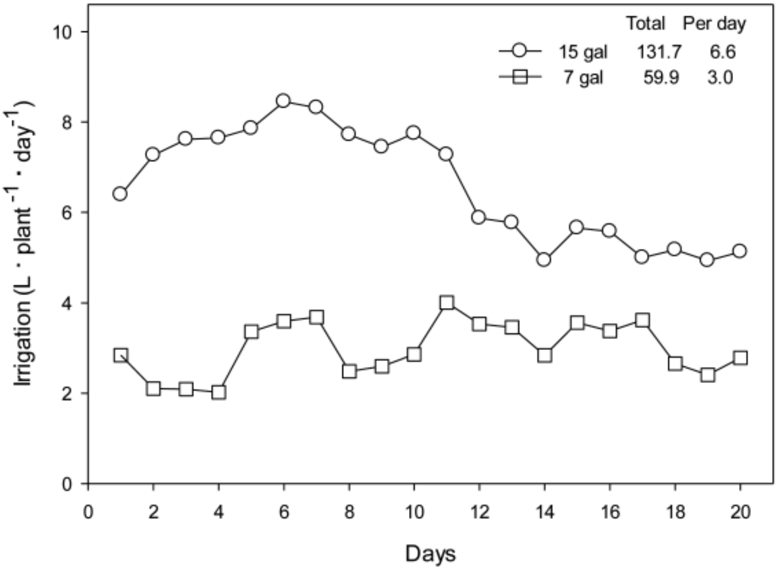

FIGURE 3 Water use (Liters per day) in redbud liners produced in 7 or 15 gallon pot-in-pot containers over a 20 day period in August-September, 2013.

TABLE 2 Total and daily water use as well as final stem diameter in eastern redbud plants exposed to a three-part cyclic irrigation event at three irrigation times (AM – 7 to 9 AM; Noon – noon to 2 PM; PM – 5 to 7 PM).

Irrigation time	Total water use (L × plant $^{-1}$ × day^{-1})	Daily water use (L × plant $^{-1}$ × day^{-1})	Main stem diameter (cm)
	7 – gallon container size		
AM	59.9c^{z}	3.°C	0.29a
Noon	71.1a	3.6a	0.36a
PM	64.9b	3.2b	0.30a
	15 – gallon container size		
AM	131.7	6.6	0.51a
Noon	136.5	6.8	0.51a
PM	129.4	6.5	0.35b

^{z}It means followed by the same letter within a column were not different using Turkey's test (a = 0.05).

21.8 CONCLUSIONS

This chapter discusses: Micro-irrigation scheduling strategies under PIP; and the need to consider plant, environment, and substrate conditions in making accurate irrigation decisions on a daily or more frequent basis. A case study has been presented. Recent advances in substrate moisture sensing and wireless data communication may play a major role in saving water and enhancing economic and environmental sustainability of the PIP production system.

21.9 SUMMARY

Pot-in-Pot is an emerging sustainable nursery production system being used as an alternative to field production for large shrubs and shade trees. Pot-in-Pot tree production is a combination between traditional container production and field production where the growing container is placed within a semipermanent, underground socket pot. This system allows closer spacing compared to field production and permits precision application of irrigation and fertilizer. Pot-in-Pot has unique substrate water-plant-atmospheric relationships compared to other nursery production methods. The chapter discusses current micro irrigation practices for Pot-in-Pot nursery production and highlight the impact of conservative irrigation scheduling strategies such as controlled irrigation using substrate moisture sensors and cyclic irrigation on crop growth, water and nutrient use efficiency. A case study has been presented.

KEYWORDS

- **Container nursery**
- **Cyclic irrigation**
- **Daily irrigation timing**
- **Irrigation scheduling**
- **Micro-irrigation**
- **Nutrient use efficiency**
- **Pot in pot**
- **Set point irrigation**
- **Socket pot**
- **Substrate moisture sensor**
- **Sustainable nursery production**
- **University of Kentucky**
- **Water use efficiency**

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APPENDICES

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APPENDIX A

CONVERSION SI AND NON-SI UNITS

To convert the	Column 1	Column 2	To convert the Column
Column 1 in the	Unit	Unit	2 in the Column 1
Column 2,	SI	Non-SI	Multiply by
Multiply by			

LINEAR

0.621 ------ kilometer, km (10^3 m) miles, mi ------------------ 1.609
1.094 ------ meter, m yard, yd ------------------- 0.914
3.28 ------- meter, m feet, ft ---------------------- 0.304
3.94×10^{-2} ---- millimeter, mm (10^{-3}) inch, in ------------------- 25.4

SQUARES

2.47 ------- hectare, he acre --------------------- 0.405
2.47 ------- square kilometer, km^2 acre --------------------- 4.05×10^{-3}
0.386 -------- square kilometer, km^2 square mile, mi^2 ------------ 2.590
2.47×10^{-4} ---- square meter, m^2 acre --------------------- 4.05×10^{-3}
10.76 -------- square meter, m^2 square feet, ft^2 -------------- 9.29×10^{-2}
1.55×10^{-3} ---- mm^2 square inch, in^2 -------------- 645

CUBICS

9.73×10^{-3} ---- cubic meter, m^3 inch-acre ----------------- 102.8
35.3 -------- cubic meter, m^3 cubic-feet, ft^3 ---------------- 2.83×10^{-2}
6.10×10^{4} ---- cubic meter, m^3 cubic inch, in^3 ------------- 1.64×10^{-5}
2.84×10^{-2} ---- liter, L (10^{-3} m^3) bushel, bu ------------------ 35.24
1.057 -------- liter, L liquid quarts, qt ------------ 0.946
3.53×10^{-2} ---- liter, L cubic feet, ft^3 -------------- 28.3
0.265 -------- liter, L gallon -------------------- 3.78
33.78 -------- liter, L fluid ounce, oz ------------- 2.96×10^{-2}
2.11 ------- liter, L fluid dot, dt --------------- 0.473

WEIGHT

2.20×10^{-3} ---- gram, g (10^{-3} kg)	pound, --------------------	454
3.52×10^{-2} ---- gram, g (10^{-3} kg)	ounce, oz ------------------	28.4
2.205 ------ kilogram, kg	pound, lb -----------------	0.454
10^{-2} ------- kilogram, kg	quintal (metric), q ----------	100
1.10×10^{-3} ---- kilogram, kg	ton (2000 lbs), ton ----------	907
1.102 ------ mega gram, mg	ton (US), ton --------------	0.907
1.102 ------ metric ton, t	ton (US), ton --------------	0.907

YIELD AND RATE

0.893 ------- kilogram per hectare	pound per acre ------------	1.12
7.77×10^{-2} --- kilogram per cubic meter	pound per fanega ----------	12.87
1.49×10^{-2} --- kilogram per hectare	pound per acre, 60 lb -----	67.19
1.59×10^{-2} --- kilogram per hectare	pound per acre, 56 lb -----	62.71
1.86×10^{-2} --- kilogram per hectare	pound per acre, 48 lb -----	53.75
0.107 ------- liter per hectare	galloon per acre ---------	9.35
893 ---------- ton per hectare	pound per acre ----------	1.12×10^{-3}
893 ---------- mega gram per hectare	pound per acre ----------	1.12×10^{-3}
0.446------- ton per hectare	ton (2000 lb) per acre -----	2.24
2.24 ---------- meter per second	mile per hour ------------	0.447

SPECIFIC SURFACE

10 --------- square meter per kilogram	square centimeter per gram ------------------	0.1
10^{3} ---------- square meter per kilogram	square millimeter per gram ------------------	10^{-3}

PRESSURE

9.90 ---------- megapascal, MPa	atmosphere -----------	0.101
10 --------- megapascal	bar -------------------	0.1
1.0 ---------- megagram per cubic meter	gram per cubic centimeter --------------	1.00
2.09×10^{-2} ---- pascal, Pa	pound per square feet ------	47.9
1.45×10^{-4} ---- pascal, Pa	pound per square inch -----	6.90×10^{3}

To convert the	Column 1	Column 2	To convert the column
column 1 in the	Unit	Unit	2 in the column 1
Column 2,	SI	Non-SI	Multiply by
Multiply by			

TEMPERATURE

1.00 (K-273)--- Kelvin, K	centigrade, °C -------- 1.00 (C+273)
(1.8 C + 32)--- centigrade, °C	Fahrenheit, °F -------- (F--32)/1.8

ENERGY

9.52×10^{-4} ---- Joule J	BTU ----------------- 1.05×10^{3}
0.239 -------- Joule, J	calories, cal ------------ 4.19
0.735 -------- Joule, J	feet-pound ------------ 1.36
2.387×10^{5} --- Joule per square meter	calories per square centimeter --- 4.19×10^{4}
10^{5} ---------- Newton, N	dynes ---------------- 10^{-5}

WATER REQUIREMENTS

9.73×10^{-3} --- cubic meter	inch acre --------------- 102.8
9.81×10^{-3} --- cubic meter per hour	cubic feet per second ------ 101.9
4.40 ---------- cubic meter per hour	galloon (US) per minute ---- 0.227
8.11 ---------- hectare-meter	acre-feet --------------- 0.123
97.28 ------- hectare-meter	acre-inch ---------------- 1.03×10^{-2}
8.1×10^{-2} ---- hectare centimeter	acre-feet --------------- 12.33

CONCENTRATION

1 ----------- centimol per kilogram	milliequivalents per 100 grams -------------- 1
0.1 --------- gram per kilogram	percents ---------------- 10
1 ----------- milligram per kilogram	parts per million --------- 1

NUTRIENTS FOR PLANTS

2.29 -------- P	P_2O_5 --------------------	0.437
1.20 -------- K	K_2O --------------------	0.830
1.39 -------- Ca	CaO --------------------	0.715
1.66 -------- Mg	MgO -----------------	0.602

NUTRIENT EQUIVALENTS

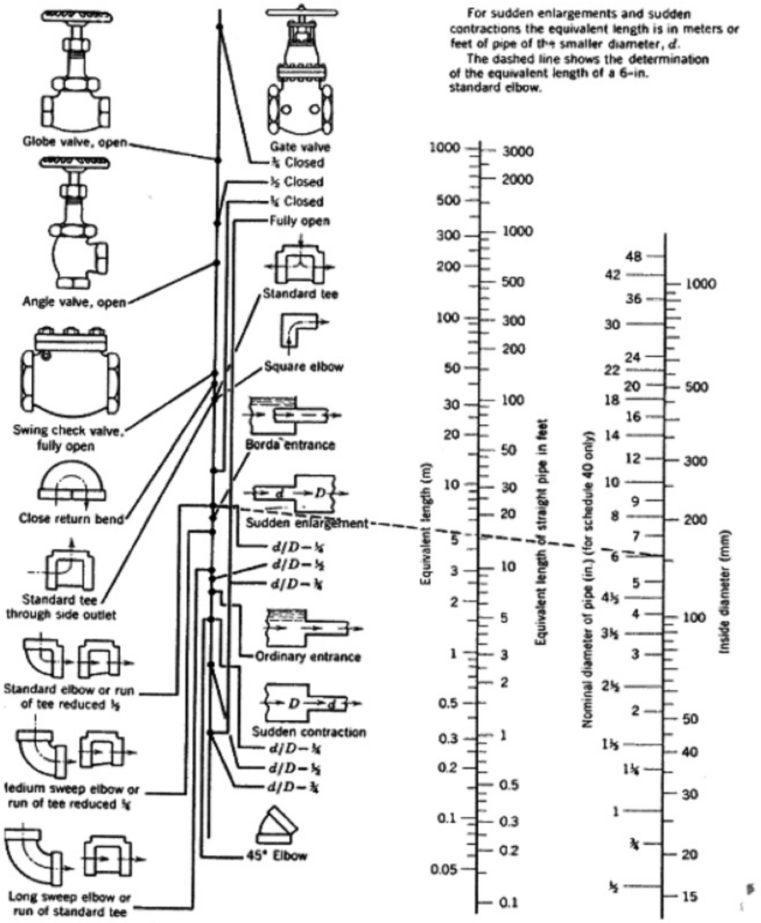
		Conversion	**Equivalent**
Column A	**Column B**	**A to B**	**B to A**
N	NH_3	1.216	0.822
	NO_3	4.429	0.226
	KNO_3	7.221	0.1385
	$Ca(NO_3)_2$	5.861	0.171

Column A	Column B	Conversion A to B	Equivalent B to A
	$(NH_4)_2SO_4$	4.721	0.212
	NH_4NO_3	5.718	0.175
	$(NH_4)_2$ HPO_4	4.718	0.212
P	P_2O_5	2.292	0.436
	PO_4	3.066	0.326
	KH_2PO_4	4.394	0.228
	$(NH_4)_2$ HPO_4	4.255	0.235
	H_3PO_4	3.164	0.316
K	K_2O	1.205	0.83
	KNO_3	2.586	0.387
	KH_2PO_4	3.481	0.287
	Kcl	1.907	0.524
	K_2SO_4	2.229	0.449
Ca	CaO	1.399	0.715
	$Ca(NO_3)_2$	4.094	0.244
	$CaCl_2 \times 6H_2O$	5.467	0.183
	$CaSO_4 \times 2H_2O$	4.296	0.233
Mg	MgO	1.658	0.603
	$MgSO_4 \times 7H_2O$	1.014	0.0986
S	H_2SO_4	3.059	0.327
	$(NH_4)_2$ SO_4	4.124	0.2425

Column A	Column B	Conversion A to B	Equivalent B to A
	K_2SO_4	5.437	0.184
	$MgSO_4 \times 7H_2O$	7.689	0.13
	$CaSO_4 \times 2H_2O$	5.371	0.186

APPENDIX B

PIPE AND CONDUIT FLOW



For sudden enlargements and sudden contractions the equivalent length is in meters or feet of pipe of the smaller diameter, d.

The dashed line shows the determination of the equivalent length of a 6-in. standard elbow.

APPENDIX C

PERCENTAGE OF DAILY SUNSHINE HOURS: FOR NORTH AND SOUTH HEMISPHERES

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NORTH												
0	8.50	7.66	8.49	8.21	8.50	8.22	8.50	8.49	8.21	8.50	8.22	8.50
5	8.32	7.57	8.47	3.29	8.65	8.41	8.67	8.60	8.23	8.42	8.07	8.30
10	8.13	7.47	8.45	8.37	8.81	8.60	8.86	8.71	8.25	8.34	7.91	8.10
15	7.94	7.36	8.43	8.44	8.98	8.80	9.05	8.83	8.28	8.20	7.75	7.88
20	7.74	7.25	8.41	8.52	9.15	9.00	9.25	8.96	8.30	8.18	7.58	7.66
25	7.53	7.14	8.39	8.61	9.33	9.23	9.45	9.09	8.32	8.09	7.40	7.52
30	7.30	7.03	8.38	8.71	9.53	9.49	9.67	9.22	8.33	7.99	7.19	7.15
32	7.20	6.97	8.37	8.76	9.62	9.59	9.77	9.27	8.34	7.95	7.11	7.05
34	7.10	6.91	8.36	8.80	9.72	9.70	9.88	9.33	8.36	7.90	7.02	6.92
36	6.99	6.85	8.35	8.85	9.82	9.82	9.99	9.40	8.37	7.85	6.92	6.79
38	6.87	6.79	8.34	8.90	9.92	9.95	10.1	9.47	3.38	7.80	6.82	6.66
40	6.76	6.72	8.33	8.95	10.0	10.1	10.2	9.54	8.39	7.75	6.72	7.52
42	6.63	6.65	8.31	9.00	10.1	10.2	10.4	9.62	8.40	7.69	6.62	6.37
44	6.49	6.58	8.30	9.06	10.3	10.4	10.5	9.70	8.41	7.63	6.49	6.21
46	6.34	6.50	8.29	9.12	10.4	10.5	10.6	9.79	8.42	7.57	6.36	6.04
48	6.17	6.41	8.27	9.18	10.5	10.7	10.8	9.89	8.44	7.51	6.23	5.86
50	5.98	6.30	8.24	9.24	10.7	10.9	11.0	10.0	8.35	7.45	6.10	5.64
52	5.77	6.19	8.21	9.29	10.9	11.1	11.2	10.1	8.49	7.39	5.93	5.43
54	5.55	6.08	8.18	9.36	11.0	11.4	11.4	10.3	8.51	7.20	5.74	5.18
56	5.30	5.95	8.15	9.45	11.2	11.7	11.6	10.4	8.53	7.21	5.54	4.89
58	5.01	5.81	8.12	9.55	11.5	12.0	12.0	10.6	8.55	7.10	4.31	4.56
60	4.67	5.65	8.08	9.65	11.7	12.4	12.3	10.7	8.57	6.98	5.04	4.22
SOUTH												
0	8.50	7.66	8.49	8.21	8.50	8.22	8.50	8.49	8.21	8.50	8.22	8.50
5	8.68	7.76	8.51	8.15	8.34	8.05	8.33	8.38	8.19	8.56	8.37	8.68
10	8.86	7.87	8.53	8.09	8.18	7.86	8.14	8.27	8.17	8.62	8.53	8.88
15	9.05	7.98	8.55	8.02	8.02	7.65	7.95	8.15	8.15	8.68	8.70	9.10
20	9.24	8.09	8.57	7.94	7.85	7.43	7.76	8.03	8.13	8.76	8.87	9.33
25	9.46	8.21	8.60	7.74	7.66	7.20	7.54	7.90	8.11	8.86	9.04	9.58
30	9.70	8.33	8.62	7.73	7.45	6.96	7.31	7.76	8.07	8.97	9.24	9.85
32	9.81	8.39	8.63	7.69	7.36	6.85	7.21	7.70	8.06	9.01	9.33	9.96
34	9.92	8.45	8.64	7.64	7.27	6.74	7.10	7.63	8.05	9.06	9.42	10.1
36	10.0	8.51	8.65	7.59	7.18	6.62	6.99	7.56	8.04	9.11	9.35	10.2
38	10.2	8.57	8.66	7.54	7.08	6.50	6.87	7.49	8.03	9.16	9.61	10.3

40	10.3	8.63	8.67	7.49	6.97	6.37	6.76	7.41	8.02	9.21	9.71	10.5
42	10.4	8.70	8.68	7.44	6.85	6.23	6.64	7.33	8.01	9.26	9.8	10.6
44	10.5	8.78	8.69	7.38	6.73	6.08	6.51	7.25	7.99	9.31	9.94	10.8
46	10.7	8.86	8.90	7.32	6.61	5.92	6.37	7.16	7.96	9.37	10.1	11.0

APPENDIX D

PSYCHOMETRIC CONSTANT (Γ) FOR DIFFERENT ALTITUDES (Z)

$$\gamma = 10^{-3}\ \mathbf{[(C_p.P) \div (\varepsilon.\lambda)] = (0.00163) \times [P \div \lambda]}$$

γ, psychrometric constant [kPa C^{-1}] $c_{p,}$ specific heat of moist air = 1.013

[kJ kg^{-10}C^{-1}] P, atmospheric pressure [kPa].

ε, ratio molecular weight of water

vapor/dry air = 0.622 λ, latent heat of vaporization [MJ kg^{-1}]

= 2.45 MJ kg^{-1} at 20°C.

Z (m)	**γ kPa/°C**	**z (m)**	**γ kPa/°C**	**z (m)**	**γ kPa/°C**	**z (m)**	**γ kPa/°C**
0	0.067	1000	0.060	2000	0.053	3000	0.047
100	0.067	1100	0.059	2100	0.052	3100	0.046
200	0.066	1200	0.058	2200	0.052	3200	0.046
300	0.065	1300	0.058	2300	0.051	3300	0.045
400	0.064	1400	0.057	2400	0.051	3400	0.045
500	0.064	1500	0.056	2500	0.050	3500	0.044
600	0.063	1600	0.056	2600	0.049	3600	0.043
700	0.062	1700	0.055	2700	0.049	3700	0.043
800	0.061	1800	0.054	2800	0.048	3800	0.042
900	0.061	1900	0.054	2900	0.047	3900	0.042
1000	0.060	2000	0.053	3000	0.047	4000	0.041

APPENDIX E

SATURATION VAPOR PRESSURE [e_s] FOR DIFFERENT TEMPERATURES (T)

Vapor pressure function = e_s = [0.6108]*exp{[17.27*T]/[T + 237.3]}

T °C	**e_s kPa**	**T °C**	**e_s kPa**	**T °C**	**e_s kPa**	**T °C**	**e_s kPa**
1.0	0.657	**13.0**	1.498	**25.0**	3.168	**37.0**	6.275
1.5	0.681	**13.5**	1.547	**25.5**	3.263	**37.5**	6.448
2.0	0.706	**14.0**	1.599	**26.0**	3.361	**38.0**	6.625
2.5	0.731	**14.5**	1.651	**26.5**	3.462	**38.5**	6.806

3.0	0.758	**15.0**	1.705	**27.0**	3.565	**39.0**	6.991
3.5	0.785	**15.5**	1.761	**27.5**	3.671	**39.5**	7.181
4.0	0.813	**16.0**	1.818	**28.0**	3.780	**40.0**	7.376
4.5	0.842	**16.5**	1.877	**28.5**	3.891	**40.5**	7.574
5.0	0.872	**17.0**	1.938	**29.0**	4.006	**41.0**	7.778
5.5	0.903	**17.5**	2.000	**29.5**	4.123	**41.5**	7.986
6.0	0.935	**18.0**	2.064	**30.0**	4.243	**42.0**	8.199
6.5	0.968	**18.5**	2.130	**30.5**	4.366	**42.5**	8.417
7.0	1.002	**19.0**	2.197	**31.0**	4.493	**43.0**	8.640
7.5	1.037	**19.5**	2.267	**31.5**	4.622	**43.5**	8.867
8.0	1.073	**20.0**	2.338	**32.0**	4.755	**44.0**	9.101
8.5	1.110	**20.5**	2.412	**32.5**	4.891	**44.5**	9.339
9.0	1.148	**21.0**	2.487	**33.0**	5.030	**45.0**	9.582
9.5	1.187	**21.5**	2.564	**33.5**	5.173	**45.5**	9.832
10.0	1.228	**22.0**	2.644	**34.0**	5.319	**46.0**	10.086
10.5	1.270	**22.5**	2.726	**34.5**	5.469	**46.5**	10.347
11.0	1.313	**23.0**	2.809	**35.0**	5.623	**47.0**	10.613
11.5	1.357	**23.5**	2.896	**35.5**	5.780	**47.5**	10.885
12.0	1.403	**24.0**	2.984	**36.0**	5.941	**48.0**	11.163
12.5	1.449	**24.5**	3.075	**36.5**	6.106	**48.5**	11.447

APPENDIX F

SLOPE OF VAPOR PRESSURE CURVE (Δ) FOR DIFFERENT TEMPERATURES (T)

$$\Delta = [4098.\ e^{0}(T)] \div [T + 237.3]^{2}$$
$$= 2504\{\exp[(17.27T) \div (T + 237.2)]\} \div [T + 237.3]^{2}$$

T °C	**Δ kPa/°C**	**T °C**	**Δ kPa/°C**	**T °C**	**Δ kPa/°C**	**T °C**	**Δ kPa/°C**
1.0	0.047	13.0	0.098	25.0	0.189	37.0	0.342
1.5	0.049	13.5	0.101	25.5	0.194	37.5	0.350
2.0	0.050	14.0	0.104	26.0	0.199	38.0	0.358
2.5	0.052	14.5	0.107	26.5	0.204	38.5	0.367
3.0	0.054	15.0	0.110	27.0	0.209	39.0	0.375
3.5	0.055	15.5	0.113	27.5	0.215	39.5	0.384
4.0	0.057	16.0	0.116	28.0	0.220	40.0	0.393
4.5	0.059	16.5	0.119	28.5	0.226	40.5	0.402
5.0	0.061	17.0	0.123	29.0	0.231	41.0	0.412
5.5	0.063	17.5	0.126	29.5	0.237	41.5	0.421
6.0	0.065	18.0	0.130	30.0	0.243	42.0	0.431

6.5	0.067	18.5	0.133	30.5	0.249	42.5	0.441
7.0	0.069	19.0	0.137	31.0	0.256	43.0	0.451
7.5	0.071	19.5	0.141	31.5	0.262	43.5	0.461
8.0	0.073	20.0	0.145	32.0	0.269	44.0	0.471
8.5	0.075	20.5	0.149	32.5	0.275	44.5	0.482
9.0	0.078	21.0	0.153	33.0	0.282	45.0	0.493
9.5	0.080	21.5	0.157	33.5	0.289	45.5	0.504
10.0	0.082	22.0	0.161	34.0	0.296	46.0	0.515
10.5	0.085	22.5	0.165	34.5	0.303	46.5	0.526
11.0	0.087	23.0	0.170	35.0	0.311	47.0	0.538
11.5	0.090	23.5	0.174	35.5	0.318	47.5	0.550
12.0	0.092	24.0	0.179	36.0	0.326	48.0	0.562
12.5	0.095	24.5	0.184	36.5	0.334	48.5	0.574

APPENDIX G

NUMBER OF THE DAY IN THE YEAR (JULIAN DAY)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29	(60)	88	119	149	180	210	241	272	302	333	363
30	30	—	89	120	150	181	211	242	273	303	334	364
31	31	—	90	—	151	—	212	243	—	304	—	365

APPENDIX H

STEFAN-BOLTZMANN LAW AT DIFFERENT TEMPERATURES (T):

$[\sigma^*(T_K)^4] = [4.903 \times 10^{-9}]$, MJ K^{-4} m^{-2} day^{-1}
Where: $T_K = \{T[°C] + 273.16\}$

T	$\sigma^*(T_K)^4$	T	$\sigma^*(T_K)^4$	T	$\sigma^*(T_K)^4$
		Units			
°C	MJ m^{-2} d^{-1}	°C	MJ m^{-2} d^{-1}	°C	MJ m^{-2} d^{-1}
1.0	27.70	**17.0**	34.75	**33.0**	43.08
1.5	27.90	**17.5**	34.99	**33.5**	43.36
2.0	28.11	**18.0**	35.24	**34.0**	43.64
2.5	28.31	**18.5**	35.48	**34.5**	43.93
3.0	28.52	**19.0**	35.72	**35.0**	44.21
3.5	28.72	**19.5**	35.97	**35.5**	44.50
4.0	28.93	**20.0**	36.21	**36.0**	44.79
4.5	29.14	**20.5**	36.46	**36.5**	45.08
5.0	29.35	**21.0**	36.71	**37.0**	45.37
5.5	29.56	**21.5**	36.96	**37.5**	45.67
6.0	29.78	**22.0**	37.21	**38.0**	45.96
6.5	29.99	**22.5**	37.47	**38.5**	46.26
7.0	30.21	**23.0**	37.72	**39.0**	46.56
7.5	30.42	**23.5**	37.98	**39.5**	46.85
8.0	30.64	**24.0**	38.23	**40.0**	47.15
8.5	30.86	**24.5**	38.49	**40.5**	47.46
9.0	31.08	**25.0**	38.75	**41.0**	47.76
9.5	31.30	**25.5**	39.01	**41.5**	48.06
10.0	31.52	**26.0**	39.27	**42.0**	48.37

T	$\sigma^*(T_K)^4$	T	$\sigma^*(T_K)^4$	T	$\sigma^*(T_K)^4$
Units					
10.5	31.74	**26.5**	39.53	**42.5**	48.68
11.0	31.97	**27.0**	39.80	**43.0**	48.99
11.5	32.19	**27.5**	40.06	**43.5**	49.30
12.0	32.42	**28.0**	40.33	**44.0**	49.61
12.5	32.65	**28.5**	40.60	**44.5**	49.92
13.0	32.88	**29.0**	40.87	**45.0**	50.24
13.5	33.11	**29.5**	41.14	**45.5**	50.56
14.0	33.34	**30.0**	41.41	**46.0**	50.87
14.5	33.57	**30.5**	41.69	**46.5**	51.19
15.0	33.81	**31.0**	41.96	**47.0**	51.51
15.5	34.04	**31.5**	42.24	**47.5**	51.84
16.0	34.28	**32.0**	42.52	**48.0**	52.16
16.5	34,52	**32.5**	42.80	**48.5**	52.49

APPENDIX I

THERMODYNAMIC PROPERTIES OF AIR AND WATER

1. Latent Heat of Vaporization (λ)

$$\lambda = [2.501 - (2.361 \times 10^{-3})\ T]$$

Where: λ = latent heat of vaporization [MJ kg^{-1}]; and T = air temperature [°C].

The value of the latent heat varies only slightly over normal temperature ranges. A single value may be taken (for ambient temperature = 20°C): $\lambda = 2.45$ MJ kg^{-1}.

2. Atmospheric Pressure (P)

$$\mathbf{P = P_o\ [\{T_{Ko} - \alpha(Z - Z_o)\} \div \{T_{Ko}\}]^{(g/(\alpha.R))}}$$

Where: P, atmospheric pressure at elevation z [kPa]

P_o, atmospheric pressure at sea level = 101.3 [kPa]

z, elevation [m]

z_o, elevation at reference level [m]

g, gravitational acceleration = 9.807 [m s^{-2}]

R, specific gas constant == 287 [J kg^{-1} K^{-1}]

α, constant lapse rate for moist air = 0.0065 [K m^{-1}]

T_{Ko}, reference temperature [K] at elevation z_o = 273.16 + T

T, means air temperature for the time period of calculation [°C]

When assuming P_o = 101.3 [kPa] at z_o = 0, and T_{Ko} = 293 [K] for T = 20 [°C], above equation reduces to:

$$\mathbf{P = 101.3[(293–0.0065Z)\ (293)]^{5.26}}$$

3. Atmospheric Density (ρ)

$$\rho = [1000P] \div [T_{Kv}\ R] = [3.486P] \div [T_{Kv}], \text{ and } T_{Kv} = T_K[1–0.378(e_a)/P]^{-1}$$

Where: ρ, atmospheric density $[kg\ m^{-3}]$

R, specific gas constant = 287 $[J\ kg^{-1\ K-1}]$

$T_{Kv,}$ virtual temperature [K]

$T_{K,}$ absolute temperature [K]: $T_K = 273.16 + T$ [°C]

$e_{a,}$ actual vapor pressure [kPa]

T, mean daily temperature for 24-hour calculation time steps.

For average conditions (e_a in the range 1–5 kPa and P between 80–100 kPa), T_{Kv} can be substituted by: $T_{Kv} \approx 1.01\ (T + 273)$

4. Saturation Vapor Pressure function (es)

$e_s = [0.6108]*\exp\{[17.27*T]/[T + 237.3]\}$

Where: e_s, saturation vapor pressure function [kPa]

T, air temperature [°C]

5. Slope Vapor Pressure Curve (Δ)

$$\Delta = [4098.\ e^{\circ}(T)] \div [T + 237.3]^2$$
$$= 2504\{\exp[(17.27T) \div (T + 237.2)]\} \div [T + 237.3]^2$$

Where: Δ, slope vapor pressure curve $[kPa\ C^{-1}]$

T, air temperature [°C]

$e^0(T)$, saturation vapor pressure at temperature T [kPa]

In 24-hour calculations, Δ is calculated using mean daily air temperature. In hourly calculations T refers to the hourly mean, T_{hr}.

6. Psychrometric Constant (γ)

$$\gamma = 10^{-3}\ [(C_p.P) \div (\varepsilon.\lambda)] = (0.00163) \times [P \div \lambda]$$

Where: γ, psychrometric constant $[kPa\ C^{-1}]$

c_p, specific heat of moist air = 1.013 $[kJ\ kg^{-10}C^{-1}]$

P, atmospheric pressure [kPa]: equations 2 or 4

ε, ratio molecular weight of water vapor/dry air = 0.622

λ, latent heat of vaporization $[MJ\ kg^{-1}]$

7. Dew Point Temperature (Tdew)

When data is not available, T_{dew} can be computed from e_a by:

$$T_{dew} = [\{116.91 + 237.3Log_e(e_a)\} \div \{16.78–Log_e(e_a)\}]$$

Where: T_{dew}, dew point temperature [°C]

e_a, actual vapor pressure [kPa]

For the case of measurements with the Assmann psychrometer, T_{dew} can be calculated from:

$$T_{dew} = (112 + 0.9T_{wet})[e_a \div (e^0\ T_{wet})]^{0.125}–[112–0.1T_{wet}]$$

8. Short Wave Radiation on a Clear-Sky Day (Rso)

The calculation of R_{so} is required for computing net long wave radiation and for checking calibration of pyranometers and integrity of R_{so} data. A good approximation for R_{so} for daily and hourly periods is:

$R_{so} = (0.75 + 2 \times 10^{-5} z)R_a$

Where: z, station elevation [m]

$R_{a,}$ extraterrestrial radiation [MJ m^{-2} d^{-1}]

Equation is valid for station elevations less than 6000 m having low air turbidity. The equation was developed by linearizing Beer's radiation extinction law as a function of station elevation and assuming that the average angle of the sun above the horizon is about 50°.

For areas of high turbidity caused by pollution or airborne dust or for regions where the sun angle is significantly less than 50° so that the path length of radiation through the atmosphere is increased, an adoption of Beer's law can be employed where P is used to represent atmospheric mass:

$$\mathbf{R_{so} = (R_a) \exp[(-0.0018P) \div (K_t \sin(\Phi))]}$$

Where: K_t, turbidity coefficient, $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t = 1.0$ for extremely turbid, dusty or polluted air.

P, atmospheric pressure [kPa]

Φ, angle of the sun above the horizon [rad]

$R_{a,}$ extraterrestrial radiation [MJ m^{-2} d^{-1}]

For hourly or shorter periods, Φ is calculated as:

$\sin \Phi = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega$

Where: φ, latitude [rad]

δ, solar declination [rad] (Eq. (24) in Chapter 3)

ω, solar time angle at midpoint of hourly or shorter period [rad]

For 24-hour periods, the mean daily sun angle, weighted according to R_a, can be approximated as:

$$\sin(\Phi_{24}) = \sin[0.85 + 0.3\,\varphi \sin\{(2\pi J/365)–1.39\}–0.42\,\varphi^2]$$

Where: $\Phi_{24,}$ average Φ during the daylight period, weighted according to R_a [rad]

φ, latitude [rad]

J, day in the year

The Φ_{24} variable is used to represent the average sun angle during daylight hours and has been weighted to represent integrated 24-hour transmission effects on 24-hour R_{so} by the atmosphere. Φ_{24} should be limited to ≥ 0. In some situations, the estimation for R_{so} can be improved by modifying to consider the effects of water vapor on short wave absorption, so that: $R_{so} = (K_B + K_D) R_a$ where:

$K_B = 0.98\exp[\{(–0.00146P) \div (K_t \sin \Phi)\}–0.091\{w/\sin \Phi\}^{0.25}]$

Where: K_B, the clearness index for direct beam radiation

K_D, the corresponding index for diffuse beam radiation

$K_D = 0.35–0.33\,K_B$ for $K_B \geq 0.15$

$K_D = 0.18 + 0.82\,K_B$ for $K_B < 0.15$

R_a, extraterrestrial radiation [MJ m^{-2} d^{-1}]

K_t, turbidity coefficient, $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t = 1.0$ for extremely turbid, dusty or polluted air.

P, atmospheric pressure [kPa]

Φ, angle of the sun above the horizon [rad]

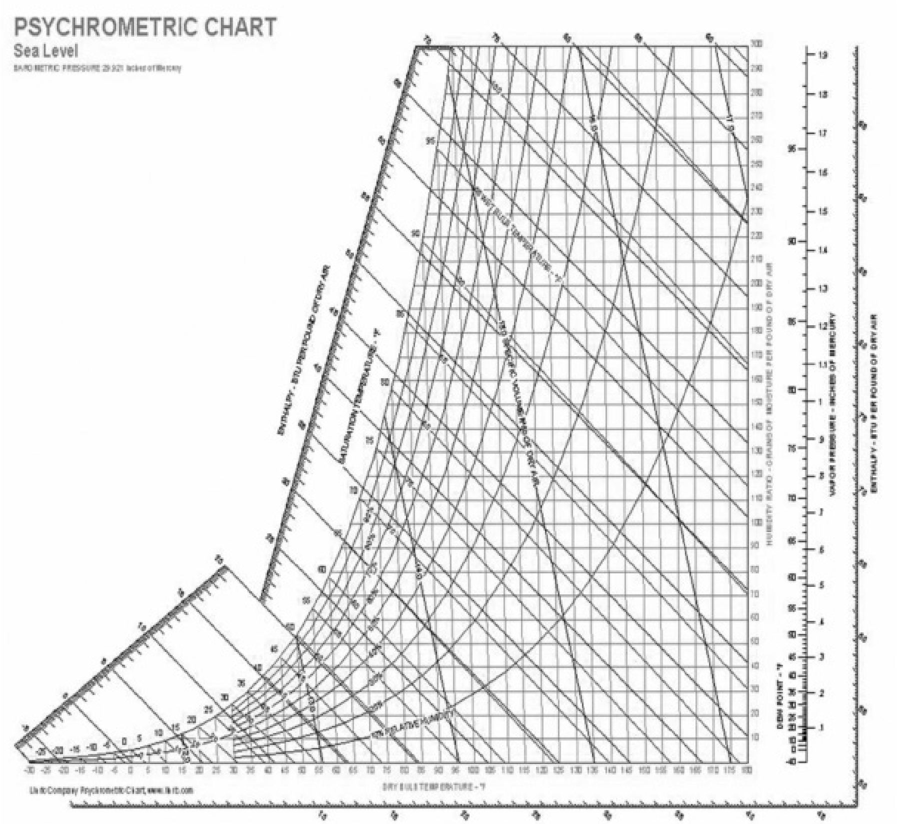
W, perceptible water in the atmosphere [mm] = $0.14\ e_a\ P + 2.1$

e_a, actual vapor pressure [kPa]

P, atmospheric pressure [kPa]

APPENDIX J

PSYCHROMETRIC CHART AT SEA LEVEL



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ABOUT THE SENIOR EDITOR-IN-CHIEF

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