Drip irrigation: a comparative study of irrigation technologies

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DRIP IRRIGATION: A COMPARATIVE STUDY OF

IRRIGATION TECHNOLOGIES

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A B S T R A C T

During the last 20 years, drip irrigation has assumed an important position amongst the various methods of field irrigation. However, for this relatively highly sophisticated irrigation technique, we still have to establish which are the most appropriate fields of application. Until this has been achieved, in many cases traditional irrigation methods will be applied where drip irrigation could give better results and vice versa.

In this study, first the main characteristics of the different irrigation methods and their conditions required for their application are stated to provide the basic data for later analysis. The environmental, economic and human requirements as well as associated cultivation practices are then related to each irrigation method. Additional data, obtained by field research work and from other case study evidence are used to demonstrate the different interrelationships between the opportunity and constraint conditions present in any given situation, and the requirements of the different irrigation methods.

More specified analysis is then extended to deal with further theoretical and practical data relevant to the application of drip irrigation. This demonstrates the complex way in which this irrigation method is influenced by diverse conditions.

Finally, these analytical results are presented in a classificatory system which allows us to introduce a relatively simple system of comparing the technical and economic appropriateness of the different irrigation methods in the context of a range of local conditions. This comparative overview also forms the basis for guidelines to the selection of the most appropriate method, with special references to drip irrigation.

A C K N O W L E D G E M E N T

I should like to record here my deep respect and gratitude to my supervisor, Professor H. Bowen-Jones, whose unremitting patience and valuable advice enabled the completion of this thesis.

I am grateful to my former colleague Dr. H. Speetzen, now project manager in Montemor - O - Velho, Portugal, without his encouragement and generous help this thesis could have not been realized.

My wife deserves deep gratitude for her unending patience while reading over and typing this thesis.

To all these, and many other peoples without whose unselfish understanding and help this thesis would have been impossible to complete, I owe a great debt.

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NOMENCLATURE

Where detailed data are not required for direct input to computations but general qualitative and quantitative levels are needed, - mainly in Figures 3.6 to 3.14 and 4.14 -, the following nomenclature is used:

Climate

humid	=	more precipitation than evaporation potential is given.
semi arid	=	more precipitation than evaporation potential during winter season and during summer season vice versa, also called 'maritime climate'.
arid	=	more evaporation potential than precipitation is given.

Water quantity

limited	=	only a limited part of the available area can be watered because of either water shortage or the very high cost of water.
moderate	=	the quantity of irrigation water is normally sufficient; however water shortage occurs occasionally during irrigation season, and / or high water costs occur.
unlimited	=	more water is available than can be used for irrigation.

Water salinity

low	=	$<$ 250 micromhos/cm at 25 °C
moderate (and medium)	=	250 - 2,250 micromhos/cm at 25 °C
high	=	2,250 - 4,000 micromhos/cm at 25 °C

Water impurity

low = the water contains solids which are bigger than the mesh-sizes of standard filters; only traces of chemical impurities.

moderate = most of the solids in the water are bigger than the mesh-sizes of standard filters; with chemical impurities, the water contains up to 0.1 mg/l dissolved iron and up to 200 mg/l dissolved carbonates.

high = most of the solids in the water are smaller than the mesh-sizes of standard filters; it contains more than 0.1 mg/l dissolved iron and/or more than 200 mg/l dissolved carbonates.

Topography -slope-

even = land levelling for surface flooding can be necessary to get the required slope.

slight = land levelling for surface flooding consists mainly in slight correctives in order to obtain an even slope.

moderate = lay out of surface irrigation must be adapted to the contours; for basin irrigation, voluminous earth moving is required.

steep = very voluminous earth moving operations are required; terraces must be normally constructed for surface irrigation.

Soil

fine = heavy clay (more than 60 % clay), silty clay, sandy clay, silty clay loam, clay loam, sandy clay loam.

medium = silt loam, loam, very fine sandy loam, fine sandy loam, sandy loam.

coarse = loamy fine sand, loamy sand, sand, coarse sand

Drainage - permeability -

high	= pervious soil, referring to the internal drainage of the root zone, which permits excess water to flow through it in a downward direction.
moderate	= semi-pervious soil, poor internal drainage, irrigation water becomes temporally stagnant in the root zone.
inhibited	= impervious soil, internal drainage of the root zone in inhibited by formation of so called perched water tables.

Plant water demand

high	= cultivations which are sensitive to water stress, e. g. vegetables for which the soil in the root zone should be kept moist or cultivations in which the yield is closely correlated to permanent water availability as with forage crops.
moderate	= cultivations such as tree crops, containing large root system with high water absorption capacities which are usually irrigated at longer intervals than vegetables or forage crops.
low	= cultivations which are possible without irrigation, such as olive trees, millet or sunflowers, but which can also be watered to obtain higher yields by supplementing the soil moisture present through precipitation.

Energy for water distribution

available	=	electricity, fuel or gravity is sufficiently available.
limited	=	because of high energy costs or limited availability of fuel, electricity or gravity, but sufficient to drive small pump units for pressure irrigation.
restricted	=	electricity, fuel or gravity is insufficient or too expensive for the frequent driving of pump units of more than 1 bar pressure.

Capital

available	=	as privately owned capital or as special long term credits at low interest rates.
limited	=	limited privately owned capital; credits are only available at high interest rates and/or at short terms.
restricted	=	little private owned capital; credits are insufficient for the proposed operations; high interest rates by short term credits.

Management

trained	=	trained and experienced in giving correct advice in the whole complex of irrigation as well as to solve problems occurring in irrigation and irrigated crop production; able to cooperate with farmers.
moderate	=	overtaxed to integrate irrigated crop production into the complex of economic and environmental conditions.
low level	=	lack of training and experience, not able to cooperate with farmers.

Labour

available = at all times and at low cost level.

restricted = during the year of irrigation season; high cost level.

trained = being able and interested to manage details and disturbances in irrigation independently; easy to be trained for handling new techniques.

moderate = low flexibility and interest level in taking up new technologies; familiarized with traditional techniques only.

low level = low level of interest in working processes; not able to take in technical details; acting on daily directions.

Agrotechnology

advanced = as being the standard of modern irrigation techniques and agrotechnological level.

moderate = mostly traditional level, but able and willing to take up modern technologies.

low level = traditional technologies with poor attitudes to change customary practices.

Spare parts

available = without problems over a short period of time.

limited = obtaining spare parts takes a time of a few days; certain spare parts are occasionally not available; special stocks of quickly wearing parts is necessary.

restricted = obtaining spare parts takes a time of more than one week, e. g. if they must be imported; voluminous stocks of spare is indispensable.

List of general abbreviations and symbols used in the text

atm	atmosphere
cm	centimetre
g	gram
h	hour
ha	hectare
km	kilometre
kW	kilowatt
kWh	kilowatt hour
l	litre
m	metre
m^3	metre cubed
mg	miligram
millimhos	reciprocal milliohms per cm
mm	millimetre
N	newton
No.	number
p. H.	the log of the reciprocal of the gram ionic
s	second
^oC	centigrade heat unit
$>$	is greater than
$<$	is less than
£	libra; pound sterling
%	per cent

I N T R O D U C T I O N

Among the different methods of field irrigation, the technique of distributing water to the plants by drip irrigation represents a sophisticated technological level which would be broadly accepted by both farmers and scientists, in arid as well as in humid regions, as being the most water saving irrigation technology, suitable for irrigating all kinds of row crops under open air conditions and in greenhouses. The trend towards the use of water saving irrigation methods has been forced by the competition between irrigated agriculture, industry and domestic demand for limited water resources, as well as by the often limited water quantities available at farm level. The savings in energy and labour inputs have also favoured the now world-wide use of drip irrigation systems.

In spite of the fact that advantages of drip irrigation as well as of other irrigation methods are known, the question of which irrigation method will be optimal in any given local conditions remains not easy to answer because of the wide range of specific requirements. Above all, failures and break-downs of drip irrigation as well as of other irrigation methods happen if the particular irrigation method employed could not be embeded into the constellation of local conditions. This thesis is an attempt to present an evaluation of comparative data about the interrelationship of conditions which influence the construction and serviceability as well as the economic and agrotechnologic aspects of drip, sprinkler and surface irrigation, the argument is developed and illustrated by different case studies.

Basic fundamental data for the comparison of different irrigation methods given in Chapter One presents an overview of the main characteristics of the most common surface irrigation methods as well as of sprinkler and drip irrigation. In Chapter Two, the effectivities of these irrigation methods, e.g. in terms of their water efficiencies as well as cost factors, are determined and finally utilized as basic data for a case study where surface, sprinkler and drip irrigation methods are compared. In Chapter Three, the main factors influencing the design of irrigation systems are analyzed and finally subsumed in an overview comparing the interrelationship of different conditions to different irrigation methods. The content of Chapter Four is concentrated on the comparison of drip irrigation with sprinkler and surface irrigation. A case study shows the possibility of integrating drip irrigation into an existing irrigation network at farm level. Samples are given of different layouts and application modes for drip irrigation. Finally, it is shown how to apply the design criteria with the ultimate aim of determining the irrigation method most appropriate to local conditions.

The main emphasis of this work, therefore, lies in establishing how drip irrigation should be applied and under which conditions. Furthermore, it may be used as a guidance for the selection of this or other irrigation method or methods which are most appropriate to local conditions.

This thesis is based on research and practical work in irrigated agriculture during my stay in Colombia S.A., Spain and North-Africa, together with the references stated at the end of each Chapter and the bibliography presented at the end of this thesis.

C H A P T E R   O N E

1. METHODS OF FIELD IRRIGATION

The problem, of supplying water to the locations of plants (irrigation) consists mainly of transporting the water to the field and of distributing the water onto the field.

Usually the methods of irrigation are classified according to the distribution characteristics. The oldest methods of irrigation utilize the field surface or subsurface and the slope of the land thus directing the water flow to the plants. The superficies of these methods are essentially two-dimensional, the third vertical dimension being fundamentally important only in affecting the plan of operation.

For this reason, land preparation, levelling and/or construction of necessary ridges and ditches to direct the water flow is usually necessary. The surface of the land and the different soils represent the main part of the irrigation systems. Irrespective the differences in soils and slopes all land preparation has to be adapted to these conditions.

Further steps in irrigation technology were taken by using pressure pipes with adapted devices to distribute the irrigation water onto the field via jets as in pseudo-rainfall. With this so called sprinkler irrigation the special preparation or rectification of the land surface with regard to the hydraulic gradients for flow irrigation is not necessary.

For the purpose of conducting the irrigation water directly to the plants, moisturing only the root zone, drip irrigation systems were constructed. These systems consist of a network of flexible surface or subsurface pipes equipped with special outlets (emitters) or porous pipe walls, thus, allowing only small amounts of water per unit of time to leave the pipe system accurately at the site of each plant.

To lay a foundation for later comparison of irrigation methods, this Chapter examines the basic characteristics of the main irrigation methods as classified by distribution techniques.

1.1 SURFACE IRRIGATION

With surface irrigation systems the water is usually applied at field level either as a broad stream or in narrow linear flows - furrows. This expression includes 'furrow irrigation'.

Each method has certain variations which are adapted to specific soil, topography, management and cultivation conditions. Surface irrigation also means that the surface zone of the soil itself represents the irrigation system by conducting and retaining the water as well as providing the growing base of the plants. The soil thus forms an active part of the irrigation method.

Usually, irrigation water has to flow from the intake of the upper part of an irrigated plot to the lower end. In order to establish such continuity, a minimum amount of water per irrigation cycle is required by all surface irrigation methods, at farm level usually some 50 mm.

Water is usually applied in cycles of 8 - 20 days to replenish depleted amounts in the soil. Therefore, neither continuous watering (in this thesis taken as meaning irrigation cycles with short intervals of less than 1 day) nor daily watering can be practiced. Precise quantification of irrigation water or in other words, an absolute control over the irrigation water, cannot be achieved by surface flooding.

1.1.1 RUN-OFF IRRIGATION

The expression 'run-off irrigation' does not strictly mean a specific method of water distribution but is rather a method of concentrating and diverting to specific areas water from precipitation falling over a relatively larger area. The run-off produced by precipitation on a catchment area may cause surface run-off which is collected by a system of ditches through which the water is conducted onto the irrigated area. Run-off irrigation represents the sole method of irrigation which works without any artificial water supply. This irrigation method, called 'water harvesting' is, for example, still in use in the Arab Republic of Yemen.

Soil and Topography

Topography, soil, vegetation and climatic conditions determine surface run-off. The topography of the catchment area and the amount of precipitation determine the run-off volume quantities which is at head in the irrigated area. The infiltration rate in the catchment area therefore should be as low as possible so that even slight precipitation can produce run-off. The best conditions are found on loamy and clay soils with very low infiltration rates. On loess soils 30% to 50%[1.1] of the precipitation, depending on the rainfall intensity, slope and degree of saturation of the soil, may be available as run-off water.

Design Criteria

The layout of the run-off irrigation system has to be designed to absorb the expected maximum precipitation intensity. If the irrigated area cannot absorb this total run-off, water storage basins may be constructed.

Information from the Negev Desert, Israel, shows that, under general arid zone conditions, the size of the catchment area is related to the size of area to be irrigated as 25 to 1.[1.1]

Supply and Distribution of Water

The distribution ditches which irrigate the area (furrows or basins) are supplied via a system of collecting ditches.

Crops

Usually forage crops, cereals, trees and row crops may be irrigated by the run-off irrigation system.

1.1.2 WILD FLOODING IRRIGATION

Wild flooding probably is one of the earliest forms of irrigation. From a head ditch along the high edge of a sloping field the irrigation water is allowed at frequent intervals of time to spill freely downhill. To provide an adequate flow the downhill may have to be corrected by subhead ditches spaced at intervals of 30 to 60 metres.

Soil and Topography

As the irrigation water runs in a broad stream downhill the time of contact with the soil for infiltration is relatively short. In order to allow a sufficient deep infiltration into the root zone the soil should have an infiltration rate of more than 10 mm/h. Therefore wild flooding should not be applied on fine textured soils, such as clays, which have a very low infiltration capacity.

On heavy soils or soils without vegetation the maximum slope is ca. 5%. On permeable sandy soils which are covered by turf, a slope to 20%[1.2] can be tolerated. Examples may be found in English water meadows, Spanish Galician grassland areas and in Latin America.

To obtain an uniform water distribution a minimum of land grading is necessary.

Design Criteria

The velocity of the water flow down the slope is normally below 0.3 m/s. If sufficient water is to reach the lower end the field should not be longer than about 100 metres. Longer than this and the upper part will be over-irrigated. In this case, the field has to be divided by parallel running subhead or feeder ditches into plots 30 to 60 metres long.[1.3] On uneven land or land with cross slopes the water has to be redistributed by spreader ditches.

Supply and Distribution of Water

The water delivery from the head ditch onto the field is usually regulated by outlets situated 2 to 3 metres apart. A continuous flow rate from 0.7 to 1.0 l/s/ha[1.3] is required.

Because of the continuous downhill flow a danger of ponding at the lowest end of the field is created. Therefore the water flow has to be interrupted before it reaches the end of the field or an end ditch has to be constructed to collect the waste water.

The main problems of this irrigation method are: a relatively high inequality of water distribution and a low irrigation efficiency resulting in local erosion and/or surface sealing of the soil. Furthermore salt leaching by wild flooding irrigation is not possible especially because water with high salt content should not be used. Wherever irrigation water accumulates a danger of water logging and oversalting is present.

Crops

The wild flooding irrigation method is mainly used for perennial crops which protect the soil against water erosion (water meadows). It is also used for irrigating low-income crops on steep lands where the amount of water and uniformity of distribution is not a major consideration.

1.1.3 BORDER IRRIGATION

Border irrigation is a method of surface irrigation in which the land is divided into parallel borders. The land surface between two borders is called a border strip. The water is supplied into each strip from a head ditch at its upper end.

The size of the strips may vary from 3 m to 30 m in width and from 50 m to 800 m in length.[1.4]

Soil and Topography

Deep permeable and medium textured soils are the most suitable. On fine textured clays or sandy soils either serious puddling or excessive water losses through heavy infiltrations at the upper end of the border strip could result.

The downslope of the border strip should be uniform and in the range of 0.2% to 4%.[1.4] The transverse profile must be uniformly level. The minimum slope required to provide the hydraulic gradient which will cause the water to flow down the border strip should not be less than 0.2% for deep rooted crops, such as trees and alfalfa and 0.3%[1.3] for shallow rooted crops.

Design Criteria

The main criterion in the design of the border strips is to achieve uniformity in the water distribution. This involves a proper balance between soil type, slope, dimensions of the border strips and flow of water. Small stream sizes, high infiltration rates and low gradient slopes require short and small sized border strips. Heavy soils or steep slopes allow bigger layouts.

There should not be cross slopes, furrows or depressions within a strip which would cause an unequal water distribution, the consequences of which would be water logging, puddling and oversalting.

The grading of the border strips and the preparation of the borders can be done by machinery.

Supply and Distribution of Water

As shown in Table 1.1, the stream flow per metre width of the border strip should be in the range of 2 l/m/s to 15 l/m/s depending on the soil texture, slope and vegetation. Too small or too large stream sizes result in the formation of rills or general erosion.

The uniformity of the distribution depends on the proper stream flow and cutting off the flow at the correct time, usually when three quarters of the field length is covered by the water.

Crops

Because of the susceptibility to erosion,border strip irrigation is mainly used for irrigating trees, vineyards and perennial forage crops.

Table 1.1 : Suggested standards for the design of border strips.

Soil type	Slope (%)	Depth applied (mm)	Strip width (m)	Strip length (m)	Flow litres/sec.
Coarse	0.25	50	15	150	240
		100	15	250	210
		150	15	400	180
	1.00	50	12	100	80
		100	12	150	70
		150	12	250	70
	2.00	50	10	60	35
		100	10	100	30
		150	10	200	30
Medium	0.25	50	15	250	210
		100	15	400	180
		150	15	400	100
	1.00	50	12	150	70
		100	12	300	70
		150	12	400	70
	2.00	50	10	100	30
		100	10	200	30
		150	10	300	30
Fine	0.25	50	15	400	120
		100	15	400	70
		150	15	400	40
	1.00	50	12	400	70
		100	12	400	35
		150	12	400	20
	2.00	50	10	320	30
		100	10	400	30
		150	10	400	20

Source: Ref. 1.5

1.1.4 BASIN IRRIGATION

This irrigation method consists of horizontally levelled field units, surrounded by borders, to form a basin.

Soil and Topography

The main technical criterion for the layout of the basin size is the infiltration rate of the soil.

On a sandy soil with a high infiltration rate a large amount of water percolates rapidly in the area close to the intake. However the flow cannot be stopped before sufficent water has reached the whole basin area. If the basin is too large water distribution will not be uniform. Heavy soils may also be easily attacked by gleying through basin irrigation. Uniform water distribution in the basin is also critically dependant on a precise surface level. To get a fast even water flow, a slope of 0.1% to 0.5% is usual.[1.3]

Where the natural slope of the land is steep, levelled terraces must be constructed to form the basins.

Design Criteria

The size of the basins depends on the following criteria:

- topography of the land
- infiltration rate of the soil
- available stream size per unit of time

The infiltration rate of the soil and the available flow rate are influential factors concerning the adequate length of the basin respective to the run length. The optimal size of the basin as influenced by these factors is shown in Table 1.2.

For seedling production in green-houses as well as under open air conditions, small sized basins of 1 m^2 to 10 m^2 are normally used.

For irrigating young trees small basins around the stems can be used, these are connected by small feeder ditches.

Supply and Distribution of Water

The water is delivered into the basin by a head ditch using syphons or gated outlets. Basins on soils with high infiltration properties have to be filled quickly.

For paddy production a continuous water delivery is used. As a consequence of the heavy flooding process the soil will clog, and puddling of the upper soil layer is unavoidable. Between the irrigation cycles the puddled upper layer dries and forms a crust which has to be removed after each irrigation. Generally, an application of less than 60 mm of water depth per irrigation is not possible because of the water has to cover the complete basin surface.

Crops

Orchards, rice, cotton, cereals, forage crops and pasture as well as seedling production are suited to this irrigation method. Crops which are sensitive to wet soil conditions are seldom irrigated by the basin irrigation method. Because of the entirely wetted soil surface, an

Table 1.2 : Suggested basin areas for different soil types and rates of water flow.

Flow rate	Soil type			
	Sand	Sandy loam	Clay loam	Clay
l/s	. . . .	hectares	. . . .	
30	0.02	0.06	0.12	0.2
60	0.04	0.12	0.24	0.4
90	0.06	0.18	0.36	0.6
120	0.08	0.24	0.48	0.8
150	0.10	0.30	0.60	1.0
180	0.12	0.36	0.72	1.2
210	0.14	0.42	0.84	1.4
240	0.16	0.48	0.96	1,6
270	0.18	0.54	1.08	1.8
300	0.20	0.60	1.20	2.0

Source: Ref. 1.3

increase of the air humidity can be observed in greenhouses or near the earthś surface under open air conditions. This represents a restrictive factor for the growth of fungus sensitive crops. (see Chapter 3.1)

1.1.5 FURROW IRRIGATION

This method of surface irrigation is accomplished by carrying the water in closely aligned parallel-furrows as it moves down or across the slope of the field. The water infiltrates the sides (lateral movement) and bottom of the furrows, soaking the soil almost entirely.

Soil and Topography

The method of furrow irrigation can be used on nearly all soil types. Restrictions appear on very sandy soils and on heavy clays because of the high infiltration rate on the former and sensitivity to erosion and clogging on the latter.

The furrow slope is usually in the range of 0.02% and 2.0% but should not be steeper than 3.0%.[1.6] On steep sloping lands the furrow direction is laid out approximately parallel to the contours.

Design Criteria

The furrow length corresponds to the infiltration rate of the soil, the topographic conditions and to the cohesivity of the soils. Corresponding data are shown in Figure 1.1.

With this method, careful land grading for uniform slopes is essential.

The furrow spacing and size depend on the particular cultivation requirements of the crops; on average the furrows are about 0.4 m high and spaced at distances of 0.3 m and 1.8 m.

A high salt content of the irrigation water or soil can create serious problems of salination. With capillary rise, soluble salts are moved upward and tend to concentrate on the surface of the ridges due to evaporation. Damage to salt sensitive crops and in particular germination inhibition, is prevented by planting seeds along one or both furrow sides, away from the ridge where the salts concentrate by capillary rise.

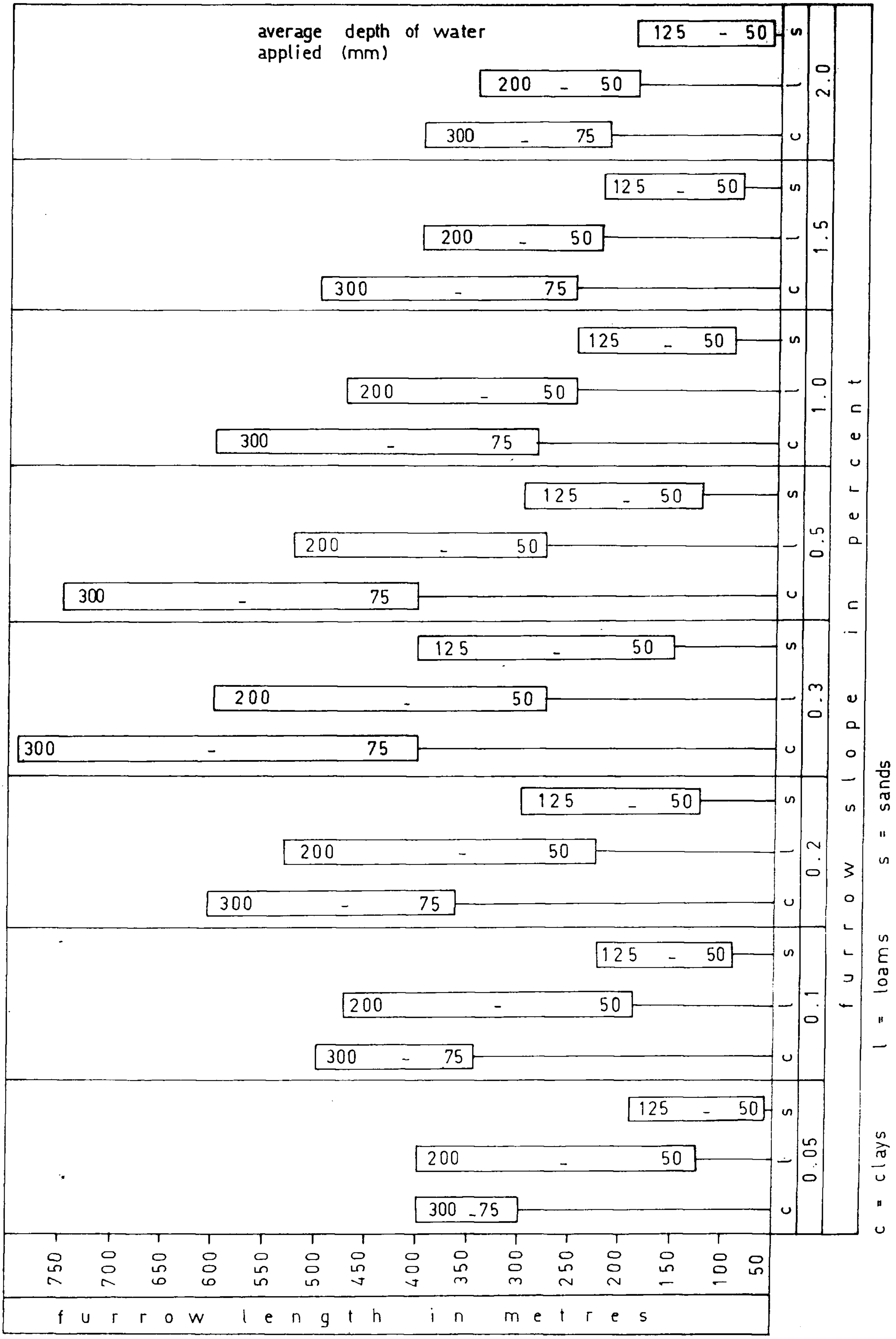
Supply and Distribution of Water

The water is supplied by a head ditch and moves down or across the slope of the field.

The water intake rate at the head of each furrow depends on furrow length and slope and on the infiltration rate of the soil. If erosion is to be avoided the intake rate should be in the range of 0.5 l/s to 3.0 l/s per furrow[1.3] but not exceed 6.0 l/s. The most common way of controlling the water delivery from the head ditch into the furrows is to use irrigation syphons.

Where a strict control of the water intake is required, a small ditch should be constructed parallel with and below the head ditch (forebay or auxiliary ditch). The water will flow from here through short pipes (spiles) placed across the ditch bank and into the furrows.

Figure 1.1: Suggested lengths of cultivated furrows for different soils, slopes and depths of water to be applied (After ref. 1.3)



Crops

Furrow irrigation is mainly used on row crops such as tomatoes, potatoes, vegetables under open air conditions as well as in greenhouses and orchards. As stated in Chapter 3.1, increased air humidity can result as a restrictive factor for some crops. This occours even though in comparison with basin irrigation (Chapter 1.1.4) about one quarter of the earths surface may be kept dry by furrow irrigation.

1.1.6 CORRUGATION IRRIGATION

By this method of irrigation, small amounts of water flow down the slope in small V or U-shaped furrows, called corrugations or rills.

Soil and Topography

This irrigation method is most suitable on medium and heavy soils like loam, clay and even on some noncohesive soils. The time of contact between the soil and the irrigation water is relatively long. Soils with infiltration rates of only 2.5 mm/h[1.7] may be used.

To avoid dry spaces between the corrugations, a lateral water movement is required. Therefore, this method may not be recommended for light sandy soils with high infiltration rates where an excessive amount of water will be lost by deep percolation before the entire rill is wetted.

The capillary movement of the water and subsequent evaporation will concentrate the soluble salts on the surface of the soil. Where the soil or the irrigation water contains a high amount of salts, the corrugation method should not be used.

The optimal slope of the corrugations is ca. 1%. However, slopes of 0.5% to 12.0% are possible. Cross slopes of more than 3% should be avoided.[1.7] An uniform slope in the direction of the corrugation is necessary to provide surface drainage and to prevent ponding of the areas.

Design Criteria

The corrugations are about 0.10 m deep, spaced 0.40 m to 0.75 m apart and are usually formed by a special corrugator equipment or by a ridge plough after seeding.

Table 1.3 shows the recommended length of corrugation runs and their spacing.

Supply and Distribution of Water

For releasing the water from the head ditch or an auxiliary ponding ditch into the corrugations, the use of syphons, spiles or ditch breaks is usual.

The water flow into the corrugations should be in the range of 0.06 l/s to 0.6 l/s. A high intake flow of 0.2 l/s followed by a reduced cut-back-flow of 0.05 l/s[1.8] is required.

Crops

This method is used mostly to irrigate closely growing crops such as cereals, forage crops and pasture.

Table 1.3 : Length and spacing of corrugations

	Slope	Fine-textured clay soils		Medium-textured loam soils		Coarse textured sandy soils	
	%	Length	Spacing	Length	Spacing	Length	Spacing
		. . . . metres					
Deep-rooted crops or deep soils	2	180	0.75	130	0.75	70	0.60
	4	120	0.65	90	0.75	45	0.55
	6	90	0.55	75	0.65	40	0.50
	8	85	0.55	60	0.55	30	0.45
	10	75	0.50	50	0.50		
Shallow-rooted crops or shallow soils	2	120	0.60	90	0.60	45	0.45
	4	85	0.55	60	0.55	30	0.45
	6	70	0.55	50	0.50		
	8	60	0.50	45	0.45		
	10	55	0.45	40	0.45		

Source: Ref. 1.3

1.2 PRESSURE SYSTEMS

Pressure irrigation systems conduct the irrigation water over the field by plastic or metal-pipes. The water is conducted under pressure and distributed by various devices, e.g. sprinklers, drip emitters and porous pipe walls. This pressure is produced by pumps or hydrostatic pressure from an overhead reservoir.

The water distributed over the irrigated plot can be quantified as required. Therefore, continuous closly controlled watering can be achieved.

At farm level, watering at short intervals of less than 2 or 3 days can only be practiced by the use of fixed installed irrigation equipment. Because of movement, semi fixed or mobile irrigation equipment requires a certain extra input of labour with a corresponding demand of time. Therefore, unless there is a considerable extra labour input in the use of non fixed irrigation equipment the relation between the irrigation intervals and the amount of water applied per irrigation cycle is quite similar to that found in surface flooding.

1.2.1 SPRINKLER IRRIGATION

The irrigation water is sprayed into the air through sprinklers and reaches the soil surface as drops from different heights. Perforated pipes or nozzle lines may be used instead of sprinkler heads.

Soil and Topography

In sprinkler irrigation the field does not represent an active but a passive part of the system. Sprinkler irrigation therefore may be used on all types of soils. Land grading, even on steeply sloped land, can be avoided, unless selfpropelled sprinkler systems are used and where the sprinkler equipment has to travel over the field.

Design Criteria

There are many different types and designs of sprinklers and systems available. The main differences between the sprinklers consist of the required operating pressure, the size of the jets and their radius of action. The different sprinkler systems include various kinds of permanently fixed, semi fixed systems to mobile selfpropelled rainguns.

Permanently fixed sprinkler systems are mainly used for frost protection in orchards and vineyards, also in plantations where irrigation is required at short intervals at low intensities e.g. in greenhouses and on heavy soils with low infiltration rates. Mobile systems are usually used for supplementary irrigation and for annual crops or where the intensity of application can be relatively high.

On uncovered or heavy soils, sprinklers with small jets and a low water outlet ratio are common.

If water with a high salt content is used, the leaves of the plants may be burned by precipitation of salts through evaporation. Also, cold shocks can be caused if the temperature of the water is notably lower than the ambient air temperature. Wind speeds of >10 km/h reduces the uniformity of water application.

Water Supply

The sprinklers receive their water through a closed pipe system with an over-pressure of 1.0 atm to 10.0 atm,[1.9] which is produced by pump units or by an elevated reservoir.

As stated earlier in Chapter 1.2, short intervals between the irrigation cycles under field conditions are only possible by the use of fixed installed sprinkler equipment. By semi fixed or mobile sprinkler systems, high frequency irrigation (continuous watering) cannot be realized because of the demand on labour and time for equipment moving.

Crops

Sprinkler irrigation can be used for nearly all kinds of crops. Care must be taken on plants which are sensitive to overall wetting, e.g. cotton.

In greenhouses in particular the air-moisture content will rise by using sprinklers. Because of the effect of a high air-moisture content as well as the wetting of the entire plants, plant diseases such as fungus may result.

1.2.2 DRIP IRRIGATION

Drip irrigation, also called 'Trickle Irrigation' consists of a flexible pipe system with small sized outlets (emitters) which direct the water flow to the plants. Porous or perforated pipes, where the water moves directly through the pipe wall, are also used.

Soil and Topography

Drip irrigation can be used on all soil types(except coarse sandy soils)and under varying topographical conditions. The effect of different levels or slopes can be equalized by regulating the pressure in the emitter lines or by the emitter itself.

To avoid the building up of puddles or cracks, the amount of water per time unit delivered by the emitters, should be adapted to the infiltration rate of the soil. A horizontal water movement in the soil is required. On sandy soils the emitters are therefore often substituted by micro sprinklers or sprayers.

Design Criteria

To ensure efficacy, drip irrigation systems require a very high standard of general and technical capacity, and the design criteria requires a somewhat more detailed examination at this stage.The space between the emitter lines has to be adapted to the plant distances of the crop. The required amount of equipment (pipes and emitters) per ha as well as the water consumption per time unit is relatively small in orchards and is high with some field crops, e.g. vegetable production.

Precautions have to be taken if the water contains chemical impurities like carbonates or other compounds of iron, manganese, calcium or magnesium.

If there is more than 0.1 mg/l iron, normally in the form of iron bicarbonate $FeCO_3$, or iron sulphate $Fe_2(SO_4)_3$ in the water, in contact with oxygen, there is a transformation to water insoluble ferri-lll-compounds.[1.10]

A marked temperature rise in the pipes, followed by an escape of CO_2, allows the calcium or magnesium carbonates to precipitate on the water.

Thus compounds formed by a chemical process in the emitter lines may encrust the water outlet channels of the emitters and cause total blockage.

The design of a drip irrigation system therefore has to include an entire chemical water analysis.

Chemical reactions with a compound formation may also be caused by a reaction between injected fertilizer and the chemical water impurities, as for example, $Ca(H_2PO_4)_2$ (superphosphate) and $CaCO_3$ will result as $Ca_2(HPO_4)_2$ (bi calcium phosphate). Sulphuric acid in the superphosphate (H_2SO_4) in contact with $CaCO_3$ will compound as gypsum ($CaSO_4$) .

To prevent emitter blockage by solid impurities in the water, filtration is obviously required before the water enters the pipe system. Filter selection is dependant on the types of impurities (suspended or sediment substances or algeae) .

The infiltration into the soil is initiated by a small pond around the emitter. To avoid a puddle formation, the water discharge of the emitter, 1 l/h to 10 l/h, and the infiltration rate of the soil have to be balanced.

By the use of drip irrigation, the surrounding soil surface remains dry and surface evaporation is excluded. The water is directed to where most of the roots are located. Consequently the resulting irrigation efficiency is very favourable. Up to 95 % of the water delivered is used by the crop. The small wetted areas produced by the emitters also define the limits of total amount of water available to the plants. Proper monitoring of the irrigation water is necessary to prevent too dry or excessively wet conditions in the root zone.

If irrigation water contains a high salt content, a strict control of the soil moisture in the wetted root zone is required. A decrease of this moisture, for example through evapo-transpiration, will allow the salts in the soil water to increase in concentration and may prove toxic to the plants. Thus if the soil moisture can be carefully controlled, water with a higher salt content than used with other irrigation methods can be applied. A precise moisture control can only be achived by instruments, because of the limited number of wetted zones. These must be regarded as one of the most important parts of a drip irrigation system.

Pipes laid on the soil surface may obstruct mechanised cultivation operations.

Supply and Distribution of Water

The water is conducted to the field by the main pipes on which the flexible black ultra violet resistant emitter pipes are fitted. The irrigation water usually has to be filtered and if necessary treated by chemical additives to avoid blockage in the emitters by mechanical or chemical compounds.

The water is distributed to the plants through a network of flexible pipes by an overpressure of usually 1 atm. These pipes are equipped with small outlets of various designs,,having outlet diameters of 0.5 mm to 1.5 mm through which the water escapes at a flow rate of about 1.0 l/h to 10.0 l/h. There are also pipes with porous walls instead of emitters in use.

The pipes are normally laid out on the soil surface but hanging or burying of the pipes is also practiced.

As drip irrigation usually will be a fixed installation, watering at high frequency cycles can be realized without added demand on labour and time for equipment moving. Hence, no irrigation follow-up operations like crust breaking are required for watering. Therefore, irrigation cycles of a few hours interval can be easily achieved without post watering demand on cultivation work.

If the emitters are located below the earths surface, the system can also be classified as a subsurface irrigation method. (See Chapter 1.3)

Crops

All kinds of trees, orchards and row crops are suitable for drip irrigation. As drip irrigation will keep the earths surface nearly dry, high air humidity can be prevented and fungus sensitive crops can be grown. Therefore, this system can be very suitable for application in greenhouses as well as under open air conditions. Because of the high number of pipes and emitters, required by meadows, cereals or forage crops like alfalfa, drip irrigation is impractical to use.

1.3 SUBSURFACE IRRIGATION

This method of irrigation distributes the water in the root zone without infiltration from the surface.

Soil and Topography

The hygroscopicity of the soil is the most limiting factor for this irrigation method. Soils with low hygroscopic characteristics such as sandy soils, and soils which are highly hygroscopic but show a capillary movement which is very slow, such as clays, are not suitable for subsurface irrigation.[1.11] The most suitable soils are sandy loams, loams and peaty soils.

The irrigated field must be level. The depth of the groundwater table should not be lower than 1.20 m. Optimal conditions are given on soils where an impermeable layer is situated at a depth of 0.6 m to 2.0 m.

Design Criteria

Permanent movement of water from the water table to the soil surface by capillary rise can cause a salt accumulation in the upper soil layers. Since leaching in most cases will not be possible, subsurface irrigation cannot be used where the irrigation water or the soil contains even a low amount of salt minerals.

Supply and Distribution of Water

The irrigation water can be supplied from

- controlled ground-water table
- ponding up furrows
- buried tubes or emitters

Except where a natural or controlled ground-water table is present, the irrigation water has to be distributed from furrows or tubes in a horizontal direction to cover the complete subsurface of the soil. From this position the water has to rise by capillary forces to reach the root zone of the plants.

A complete wetting pattern in the upper soil layer is usually not possible and therefore water is not generally available in a shallow seed germination zone. Although subsurface irrigation can be determined as an irrigation method where a permanent watering, through water movement from the water table to the soil surface, is realized, an absolute control over the irrigation water cannot be achieved. The amount of water, conducted into the water table to replenish the depleted water source below the soil surface, has to reach the root zone by capillarity. As horizontal movement requires a certain time, immediate wetting of the root zone as well as any influence upon the capillarity water rise is not possible.

Crops

This method can be used for irrigating orchards, vineyards or crops which are planted in furrows as well as in greenhouses.

It may not be used for shallow rooted crops or for cultivations where the seed has to germinate in the upper soil layer, for example cereals.

Remarks

The successful use of subsurface irrigation depends on topographic, soil and water conditions as well as on specific plant-water requirement in the upper soil layer. Furthermore, if ponding up furrows are used, this irrigation method represents a modified surface irrigation system; if buried pipes or emitters are used, a modified pressure system. The possibility of controlling the ground-water table is very slight because of the specific conditions of ground-water, topography and soil required. By using a buried drip irrigation system, it is difficult to prevent plant roots from blocking the water outlet devices. Therefore, subsurface irrigation is now seldom utilized.

1.4 DRAINAGE

This is the removal of excess surface or ground-water from any area.

Purpose of Drainage in Irrigated Areas

In irrigation the main attention is directed to the water supply. Drainage is therefore often looked upon as a secondary problem or even unnecessary.

In arid zones where low rainfall or a low ground-water table produce no requirement for drainage the main purpose of removing water from the area consists of controlling the salt balance of the soil.

Salt enrichments on irrigated areas may be caused by mineral weathering of rocks (primary salination). Excessive salination can also be produced where saline ground-water reaches the surface through capillary rise. The massive changes in the hydrological situation and in the salt balance of the soil caused by irrigation water have often been underestimated.

Usually, all irrigation water contains a certain amount of salts. Given a salt content of 1 g/l, the total amount of salt distributed on 1 ha would be in the range of 6,000 kg salt per ha annually by the application of 6,000 m^3 of water per ha (secondary salination).

The control of the salt balance in the soil requires frequent leaching of the accumulated salts. This can be realised if excess water (irrigation or precipitation) percolates through the root zone and washes down the salts, carrying them horizontally or vertically, out of the root zone.

Horizontal movement of water for leaching may be possible through natural conditions if horizontal ground-water movement on a lower impermeable interface is present. Without this, evacuation of the salt water has to be rendered by drainage operations.

Deep vertical percolation can be enforced by loosening or breaking impermeable layers if they are sited over a permeable submaterial.

Other functions of a drainage system consist of

- controlling the surface run-off, caused by excessive rainfall or excessive irrigation water
- controlling the subsoil run-off from the ground-water table, including leaching and seepage from irrigation ditches.

It can be stated that drainage on irrigated areas is alway necessary. The function of natural drainage depends on the soil, ground-water and topographic conditions. On heavy, fine textured soils, high ground-water table, impermeable soil layers, drainage has to be installed artificially, e.g. surface drainage (open ditches) subsurface drainage (brick or perforated plasic pipes, mole drains).

1.5 FIELD IRRIGATION METHODS IN RELATION TO THE DIFFERENT PATTERNS OF INPUT

On the basis of this first identification of the critical and significant characteristics of the various field irrigation methods, we can now indicate comparatively their relationship to irrigation inputs as a whole. In irrigated crop production, the factor, water, has to be treated as a production input like any other, for example fertilizer, seed, machine work, labour.

To distinguish the specific inputs for irrigation, one can select the following components:

- water lifting (well and pump station)
- water storage (reservoir)
- water conduit to the field
- construction work on land preparation
- irrigation devices such as sprinkler or drip irrigation systems
- running expenses
- depreciation / amortisation
- labour input

The costs of these inputs can be divided into

- fixed cost of construction and depreciation
- variable cost, such as operating expenses, cost of water, labour and machinery input.

Cost of construction (fixed costs) often represents a bottle-neck because the investment has to be made at one time even though theoretically these costs may be accounted for over a period of years.

The operating expenses, i.e. the variable costs of water and input of labour and machinery, depend on the crop and production intensity, environmental conditions, water availability, the particular irrigation system used, labour and management.

Finally, it should be noted that the different irrigation methods can also be classified into

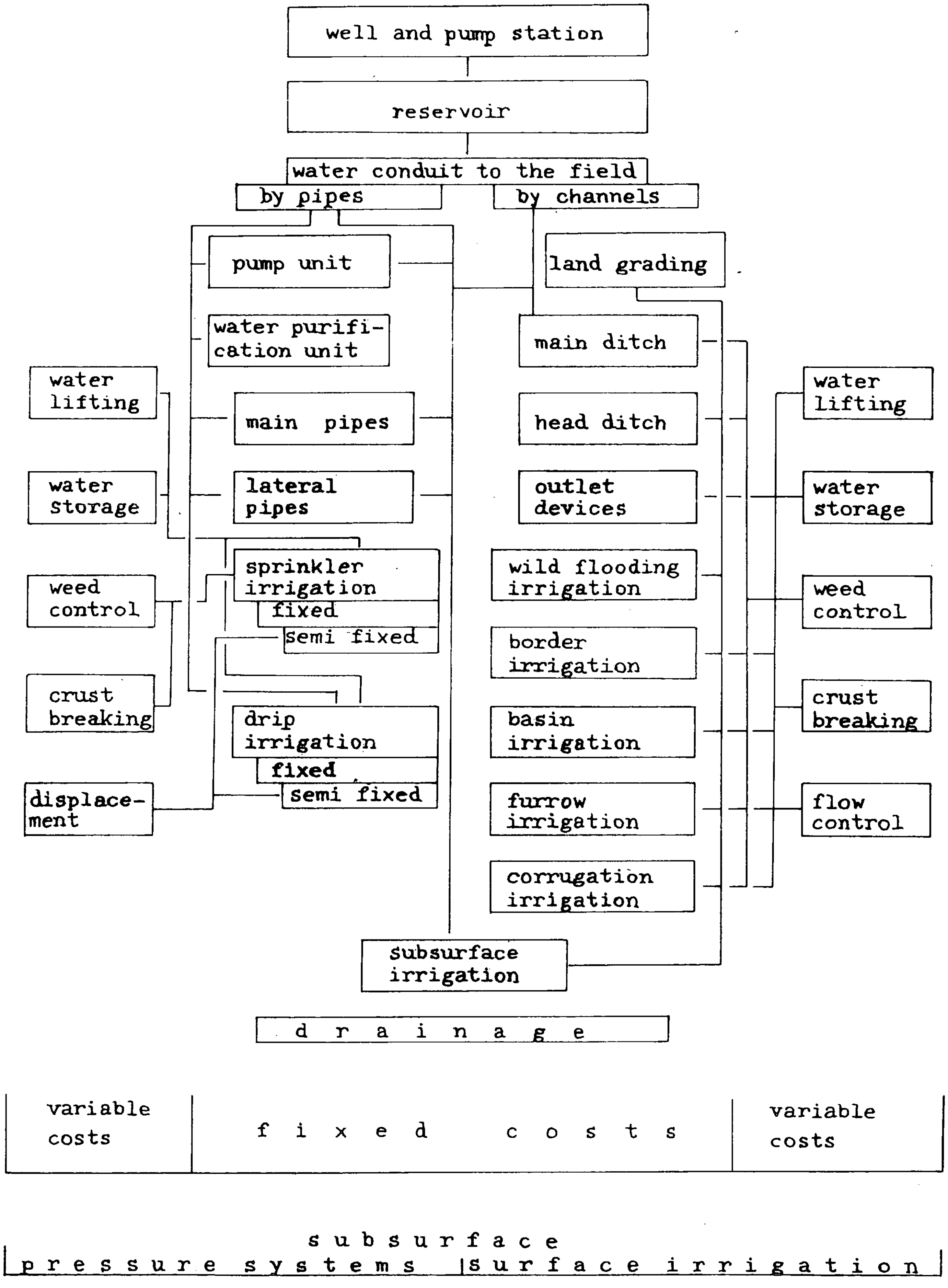
- those in which a permanent watering associated with an absolute control over the irrigation water can be achieved (as by pressure irrigation) ; and
- those where a certain amount of water per irrigation cycle has to be distributed as a consequence of specific flow conditions (as given by surface flooding).

Subsurface irrigation in this sentence takes an intermediate position, depending on the layout which may consist of buried pressure irrigation systems, a modified gravity system of surface irrigation, or controlled ground-water table.

As we shall see later in Chapter 3 and 4, the precision with which the irrigation water can be applied has to be considered as an important factor in the design and maintenance of different irrigation systems. Other factors of significance are, the extent to which the soil surface as well as the plants will be wetted by each watering process.

Figure 1.2 schematically summarises the fixed and variable cost factors as well as their interrelationship on different irrigation systems.

Figure 1.2 : General overview of the inputs of and to the different irrigation systems.



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CHAPTER TWO

2. EFFECTIVITY OF FIELD IRRIGATION SYSTEMS

Generally speaking, one field irrigation system cannot be considered more effective than another. The degree to which any irrigation system can be regarded as appropriate and effective depends on its technical adaption to specific environmental conditions such as climate, soil, topography, water quantity and quality, requirements of the crops as well as the economic (management) and labour conditions. An appropriate irrigation system can be determined as adapted to the environmental conditions which satisfy their individual user in the aspects of production capacity, labour demand and economy. Therefore, working out a standard solution is not possible.

The selection of the most effective irrigation system or method and its best usage has to be based on the following local conditions:

- Production capacity, e.g.:
  - how great is the production capacity when using a specific amount of water?
  - are there any restrictions because of water quality, climate, energy or topographic conditions?
- Management and labour situation
  - is there trained and experienced management (regional and at farm level) available, controlling and directing the impact of water management on the progress of irrigated agriculture?
  - is there sufficient labour capacity available?

. qualitatively, are there any trained or willing labour sources available?

. does additional irrigation work become an insurmountable labour peak?

- Economic situation

. is there money available to invest in irrigation?

. is there a local or regional market for the products, produced by irrigated agriculture?

. are there any restrictions in obtaining spare parts?

. is a capital feed-back assured?

Very often the economic situation of the farmers represents a restrictive factor in selecting an effective and appropriate irrigation system. To avoid financial loss of initial capital outlay installing any irrigation method or altering an already existing system, the size of basic units (pumps, water storage basins, canals, main pressure pipes etc) must be considered in terms of the entire area to be irrigated. Only the operations for water distribution of the irrigated land such as levelling or the installation of lateral pressure pipes equipped with sprinklers or drip emitters can be financed gradually. Because of the relatively high initial investment costs, false economies, such as the construction of canals and storage basins without protection devices against seepage losses, and unequal land levelling are initiated. These and peasant mentality can prevent not only high irrigation efficiency but also the introduction of the most appropriate irrigation system and method.

Hence, in old, traditional irrigated regions, the new established irrigation units are often orientated in their layout and management to traditional used orthodox practices of irrigation. It can be frequently observed that in such cases the best of the poorest irrigation methods will suffice. At Al Hassa you have the super imposition of an integrated design of irrigation and drainage on top of pre-existing farm and field layout which results in low irrigation effectivity. Since the old plots are only suitable for basin irrigation, this method results in a restriction of viable irrigation (see Ref. 2.1 and 2.2). Generally, an irrigation system can be determined most effective if the growth of the plants can be optimized by the adequate supply of water using a system which is:

- easy to handle for the operator
- adapted to the volume of labour
- adapted to the plants specific and environmental conditions
- economic
- suitable for minimizing unproductive water losses
- safe to operate
- easy to repair

Nevertheless, there are some basic premises which one must use in working this analysis and later in the thesis the case studies and examples will be used to test these preliminary evaluations.

2.1 EFFECTIVITY OF IRRIGATION IN TERMS OF WATER

The effectivity of the irrigation water can be defined according to the following scheme adapted from Garbrecht (Ref. 2.3)

A For macro - economic purpose = e_o

$$e_o = \frac{\text{value of the expected crop increase (£)}}{\text{cost of the water including investments for irrigation systems and labour input (£)}}$$

B For the development of water resources = e_1

$$e_1 = \frac{\text{plant - water requirement } (m^3)}{\text{available water intake into the irrigation system } (m^3)}$$

C For specific farm - water management = e_2

$$e_2 = \frac{\text{yield increase (kg)}}{\text{water intake into the irrigation system } (m^3)}$$

D For the determination of the irrigation effectivity

D_1 storage effectivity % = $e_{3/1}$

$$e_{3/1} = \frac{\text{amount of water diverted from storage for irrigation } (m^3)}{\text{amount or water supplied to storage reservoir } (m^3)} \times 100$$

D_2 canal effectivity % = $e_{3/2}$

$$e_{3/2} = \frac{\text{amount of water available at the irrigated plots } (m^3)}{\text{amount of water diverted into the canal system } (m^3)} \times 100$$

D_3 irrigation effectivity % = $e_{3/3}$

$$e_{3/3} = \frac{\text{amount of water maintained in the root zone } (m^3)}{\text{amount of water delivered into the irrigated plot } (m^3)} \times 100$$

Note: in these calculations, no water requirement for leaching to prevent soluble mineral accumulation in the soil is taken into account.

The basic theoretical prerequisite of irrigation effectivity is if 100% of the water available at source is utilized by the plants for growth and transpiration. This can only be possible by optimal irrigation management and controlled environmental conditions such as salt free water and neutral plant rooting material.

Water losses in general, and according to the different methods of irrigation, are caused by the following factors:

water losses in the storage basin ($e_{3/1}$) by

- evaporation from the water surface
- transpiration by weeds
- seepage

and can be estimated in the range of 5% to15%

Water losses in the canals and field ditches ($e_{3/2}$) by

- evaporation from the water surface
- evapo-transpiration by phreatophytes
- seepage
- management

and can be estimated in long earthen canal systems as up to 40%

Water losses on the irrigated area ($e_{3/3}$) by

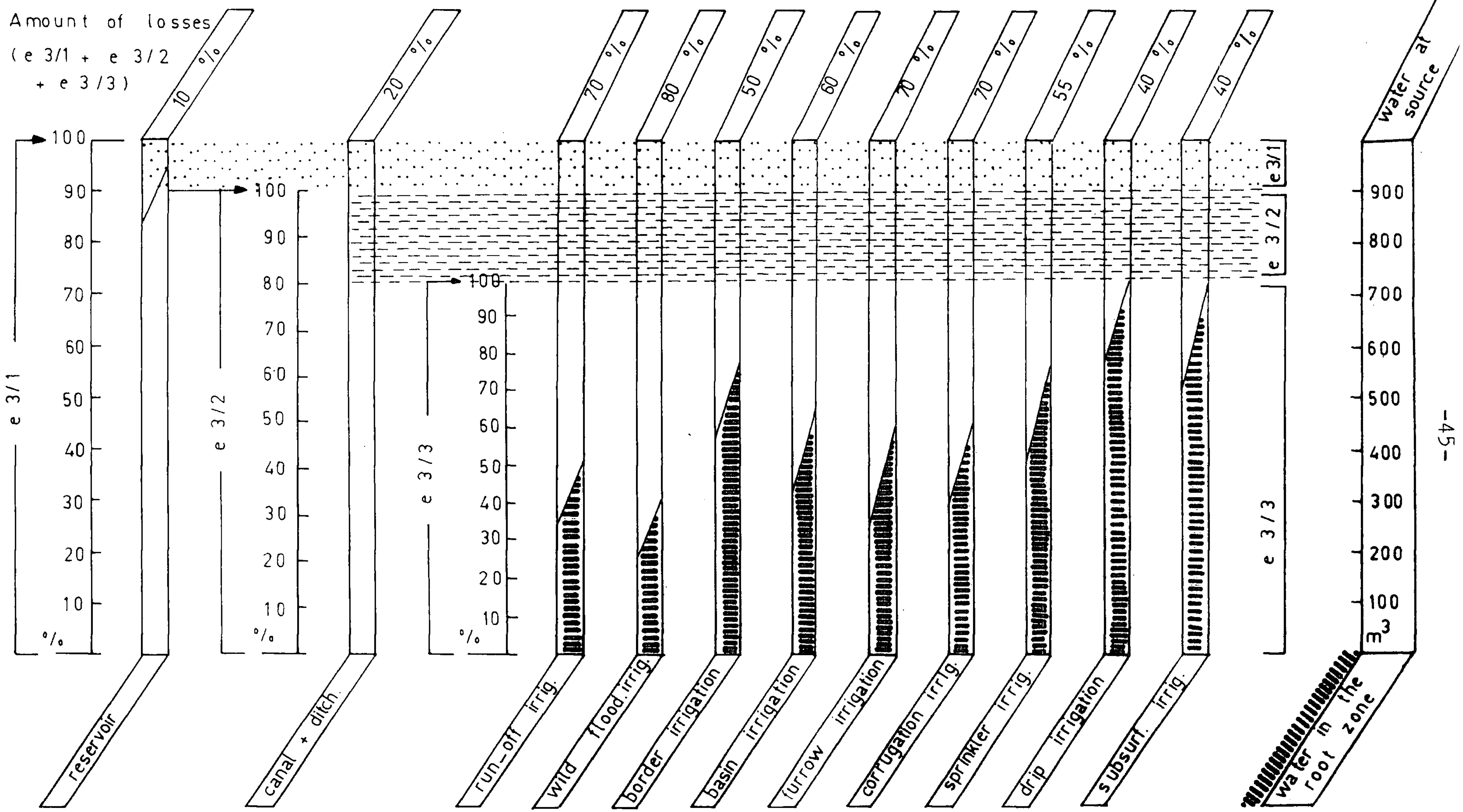
- inadequate irrigation method
- evaporation from the soil surface
- management failures with regard to:
  - . irrigation intervals and amount of water applied
  - . specific irrigation follow-up operations in soil preparation

- inadequate maintenance of irrigation equipment
- seepage and drainage

can be estimated in the range of 10% to 80%.

The factor affecting irrigation effectivity in terms of water are shown in Figure 2.1. If we apply the basic formulae postulated on page 42 in this Figure, the amount of water loss through storage ($e_{3/1}$) and through canals ($e_{3/2}$) are in the range of 30% for all irrigation methods. If water storage basins or canals are not used, these losses are nil. For example, in basin irrigation the proportion of water maintained in the root zone by using storage basin and canals can be determined on the scale $e_{3/1}$ as 25% to 45%. If there is basin irrigation practised without storage basins the scale $e_{3/2}$ should be used. In this case, the proportion of water maintained in the root zone is in the range of 30% to 50%. Without the use of water storage basins and canals, as is usually the case with drip irrigation, the scale $e_{3/3}$ should be used. The scale 'water at source' shows the corresponding amount of water in m^3 by an estimated water amount at source of 1,000 m^3. It can be stated that wild flooding represents the highest amount of water losses, some 80%. The border irrigation method shows with 50% water losses given the use of storage basin and canals, or 30% losses without using storage basin and canals, e.g. by utilizing a closed pipe system, the most effective of the surface irrigation methods.

Figure 2.1: Effectivity of irrigation in terms of water



2.2 COSTS OF CONSTRUCTION AND INSTALLATION

The basic investment for field irrigation consists of exploiting the existing water resources which are mainly composed of:

a) surface water

collection and storage of precipitation

a.1 in the soil (run-off irrigation or dry farming)

a.2 in a reservoir

a.3 taking off water from rivers and lakes

b) ground-water

b.1 springs

b.2 wells (different types)

These types of investment cannot be translated to generally accepted cost factors because of different environmental and economic conditions, e.g. depth of the ground-water table, geological formations, amount of precipitation and labour costs.

The distance of the water source to the irrigated area, the topographic conditions and amount of water to be transported influence the costs of water conduction, e.g. by canals, pipes and, if necessary lifting stations.

For the irrigation systems themselves, investment in construction costs can be divided between surface irrigation systems or pressure systems. In addition there are common expenses of depreciation, for water distribution, e.g. labour and/or energy and specific irrigation cultivation operations like crust breaking, annual construction of furrows or corrugations.

Table 2.1 shows relative data of different cost factors for different irrigation methods. This demonstrates an overview of main cost factors. Here, basin irrigation represents the highest subsumed costs. By pressure irrigation systems, drip irrigation represents the lowest subsumed costs.

Figure 2.2 shows schematically,data of observed construction and installation costs of different irrigation systems. It illustrates the ranges of variations which are typical of particular irrigation development projects, e.g. found in different irrigation schemes in Morocco, Spain (Campo de Cartagena). These are calculated from German market prices of irrigation equipment.[2.4] According to different environmental conditions and price levels, there will be some differences in the prices for the same construction work or irrigation equipment.

In surface irrigation systems, investment in land grading, construction of ditches and the size of the plots are related to the topographic and soil conditions. Therefore, the expenses of these cannot be standardized as the systems have to be adapted in their layout to these factors.

The investment cost of pressure irrigation systems can be calculated according to the amount of materials required which are mostly independent of the environmental conditions.

In subsurface irrigation, costs must be related to the soil and topographic conditions.

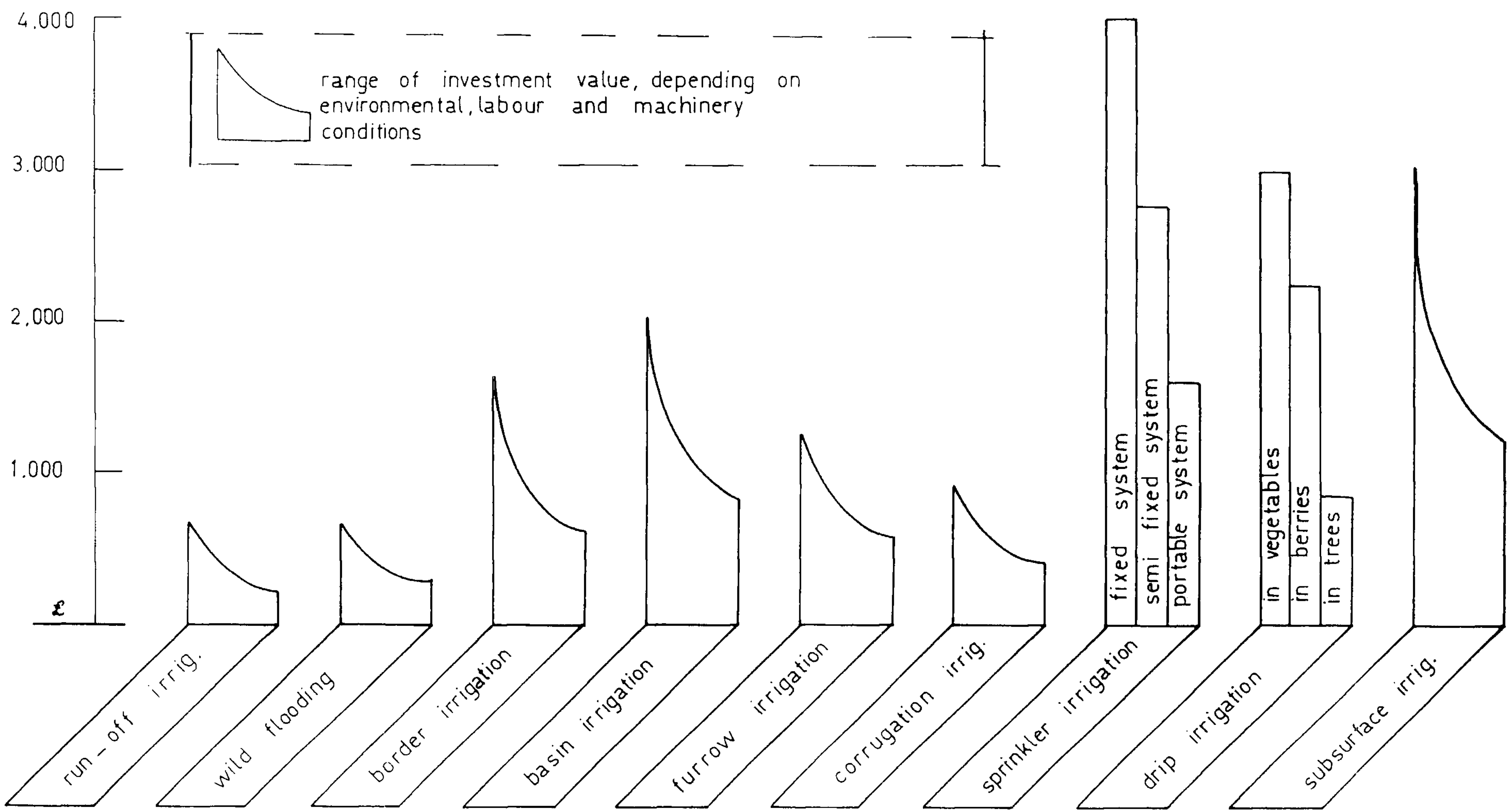
Generally it can be observed that the initial investment costs for surface irrigation systems are lower than those for

Table 2.1

cost factors of different irrigation systems										
irrigation system	initial cost		annual cost							
			perennial crops				annual crops			
	land grading	pipes canals ditches	land grad.	earth constr.	crust break.	water distrib.	land grad.	earth constr.	crust break.	water distrib.
run-off irrigat.	X	XX	X	X	X	X	-	-	X	XX
wild flooding	X	XX	-	X	X	X	-	-	X	XX
border irrigat.	XX	XX	X	X	X	X	X	-	XX	XX
basin irrigation	XXX	XXX	XX	XX	XX	XX	XX	X	XX	XXX
furrow irrigation	XXX	XXX	-	-	-	-	X	XX	X	XXX
corrugation irrig.	XX	XXX	-	-	-	X	X	XX	X	XX
sprinkler irrig.	-	XXX	-	-	XX	X	-	-	XXX	X
drip irrigation	-	XXX	-	-	-	X	-	-	-	X
subsurface irrig.	XX	XXX	XX	X	-	X	XX	X	-	X

X = low cost
XX = medium cost
XXX = high cost
\- = not relevant

Figure 2.2 : Estimated costs of construction and installation per hectare



pressure irrigation systems. Pressure irrigation therefore cannot be installed using low initial investments.

Drainage and its ensuing expenses has been proved necessary for all types of irrigation systems.

2.3 COSTS OF MAINTENANCE

In surface irrigation if a constant water distribution is to be achieved then maintenance must primarily consist of reconstruction the soil surface. This not only includes levelling and/or construction of borders, furrows and ditches, but also weed control in the irrigation canals and ditches.

The costs of such operations are closely related to the required precision of water distribution. For furrow or basin irrigation, the labour input is higher than for e. g. wild flooding. On small irrigation plots, the labour input necessary for maintenance is much higher than for large sized plots where most of the maintenance work can be done by machinery.

If an inadequate irrigation method is used, e. g. furrow irrigation on a heavy clay soil, the necessary maintenance is much higher than for the same irrigation method on sandy loam.

On newly established irrigation schemes the required maintenance is high and needs more attention than on older well-established irrigation areas.

The maintenance of surface irrigation systems is labour intensive. Neglected maintenance results in higher water losses and therefore a decrease in irrigation efficiency.

Maintenance problems in surface irrigation systems are primarily caused by:

- lack of labour during the irrigation season
- inadequate irrigation method
- labour intensive earth moving operations and weed control
- lack of special earth moving machinery
- inadequate irrigation practice or heavy precipitation (the earthen dams and borders can be destroyed through heavy erosions)

Pressure irrigation systems require maintenance of their mechanical parts to keep the system serviceable. The greater the precision of the water distribution system the more important its servicing and maintenance. This means that a drip irrigation system with small water outlets, of e. g., 3 l/h per emitter, requires more attention to prevent blockages than a water outlet for 10 l/h per emitter or even a sprinkler.

The maintenance problems of pressure irrigation systems are primarily caused by:

- high need for spare parts due to mishandling the equipment
- non availability of spare parts
- need of skilled mechanics
- the maintenance of pressure irrigation systems is not only a factor of money input but essentially a question of the availability of trained craftsmen.

Subsuming the maintenance elements, different kinds of requirements can be attached to different irrigation methods. These can also be referred to 'annual cost' on

Table 2.1 which are basically calculated by cost factors, based on specific maintenance necessities. It must also be emphasised that both major and minor critical factors can make a system go wrong. Strict maintenance is necessary, especially in earth moving operations, water distribution work and crust breaking since the surface zone of the soil itself represents the irrigation system. Mostly, the maintenance cannot be done on time because of availability of labour, and/or the quantity and quality of particular machinery for earth moving and cultivation work.

For pressure irrigation methods, the critical points of maintenance are based on the availability of spare parts as well as on the know-how for operation and repair.

The influence of different maintenance requirements on the design of field irrigation systems will be discussed in Chapter 3.7.

2.4 LABOUR AND WATER ECONOMICS

The economics of the labour input needed to operate an irrigation system can be determined according to:

i labour demand at periodic intervals and in units of time per m^3 irrigation water distributed over the field.

ii production capacity per m^3 irrigation water in relation to the input of labour per ha and total growth period under irrigation.

This includes the labour requirements for irrigation, maintenance of the field ditches, water distribution (flow control) and specific irrigation follow-up operations. Excluded from this figure are the labour requirements for water lifting, storage and conduction to the irrigated area.

(i) Labour demand:

As personally observed in Colombia (high plains of Bogotà) in 1965 to 1967 and in Spain (Murcia) in 1971 to 1974, the periodicity of labour demand for irrigation represents a serious problem for farm management. The irrigation season starts simultaneously with the growing season of the crops. Plant protection operations, weed control and the harvest of forage crops and vegetables have to be realized parallel with the irrigation labour.

For example, in the high plains of Bogotà, a mobile sprinkler irrigation unit of 15 sprinklers had been used as a device for supplemental irrigation for 50 ha cereals and 50 ha maize and forage crops. With three skilled labourers available, who were also trained as tractor drivers, the farm management had to choose between the continuation of the regular farm work and irrigation. As there were no skilled casual workers available to move the equipment the irrigation work could not be done.

In Spain, the vegetable growers had to employ day-labourers for surface (furrow) irrigation, even on small farms with a size of about 10 ha, to master the labour peak during the irrigation season. The periodically mobilized casual workers specialized in irrigation, got about the double of the wages than permanent employed farm workers. Their employment is based on the indispensability of both, irrigation and other farm work.

The required labour demand in units of time per m^3 irrigation water is related to the

- kind of irrigation system
- layout and operating conditions of the irrigation system
- size of the irrigated plots
- availability of the amount of water per unit of time
- level of mechanization or automatization
- level of knowledge of the labourer

In surface irrigation systems the amount of water delivered in an unit of time depends on the flow capacity of the canals and ditches, and/or on their feeding capacity. The allowed maximum flow velocity on the soil surface compared with the ratio of water absorption to avoid erosion, as well as the physical labour capacity for controlling and guiding the water stream over the irrigated plot must be considered. Intermittent application of water is characteristic of flooding systems in which the soil-water balance fluctuates over time. As we shall see later in Chapters 3 and 4, the periodicity of maximum and minimum water holding in the root zone is very largely determined by specific biological, soil and climatic conditions. However, the direct labour demand by irrigation is governed by the cycle during which soil moisture is built up by water application, depleted by demand and then replenished.

In such systems, the control of flow is carried out mainly by manual labour.

On well established surface irrigation schemes, for example in the South East of Spain (Huerta de Murcia), the flow capacity of most irrigation ditches had been standardized during the Roman and Arab Empire at 144 m^3/h, respectively 40 l/s.[2.5] This amount of water can be handled by one skilled labourer, controlling the flow into basins or furrows as well as the distribution over the plot. Considering the typical amount of 1,200 m^3/ha irrigation water per irrigation interval on orchards, one labourer will be able to irrigate one ha in 1,200 $m^3 \div 144\ m^3 = 8$ hours.

On other irrigation schemes, with less adequate levelling and layout, for example in Haradh, Saudi Arabia, one man can hardly handle a flow of more than 30 l/s.[2.6] Personal observations were made on newly established irrigation schemes in Morocco having nearly the same environmental conditions as found in the South East of Spain. However, there was different and relatively unfavourable layout of irrigated plots, both in levelling and size, and these were handled by farmers who were not yet familiarized with irrigation practices. Here, the estimated average capacity to control the water flow into basins or furrows was in the range of 80 m^3/h, respectively 22 l/s. Considering again a water amount of 1,200 m^3/ha and irrigation interval, one labourer will be able to irrigate one ha in 1,200 $m^3 \div 80\ m^3 = 15$ hours or, in other words, two days.

On pressure irrigation systems the labour demand required per m^3 irrigation water depends on the

- type, layout and extension of the system
- flow rate through the system.

The cycle of depletion and replenishment of soil moisture is closly related to the kind of irrigation equipment used. Ideally, the root zone water budget is maintained at a desired level by the almost continous addition of small increments of water. Labour demand therefore is determined by the operation and controlling of each period of continous water application. If we take as a standard for comparison a watering cycle by surface flooding and sprinkler irrigation an interval of some 15 days (e.g. in Iran[2.7] and Egypt[2.8]), we can assess the labour demand for different pressure irrigation systems as follows.

A fixed sprinkler irrigation system on average requires 0.5 man hours per ha per 15 day cycle. Semi fixed and mobile sprinkler systems obviously have higher demands averaging some 4 hours/ha per cycle since equipment has to be moved at various time frequencies.[2.4]

Drip irrigation systems, mostly permanently installed, have the characteristics of low water output per unit of time but very frequent irrigation applications in very short cycles. Therefore the labour time spent cannot as easily be calculated or related to the cycles. In relation to the fixed installed sprinkler irrigation system noted above, operated at 15 days intervals by a labour demand of 0.5 h/ha, drip irrigation requires, during the same period, about 0.5 to 1 man hour expenditure per ha for control and maintenance work.

In other words, during the same 15 days period a smaller volume of water would be applied, in a series of short cycles of near continuous application and the total labour demand would be similar or only slightly greater.

(ii) Production capacity:

As stated in Figure 2.1, the amount of irrigation water used by the plants varies between 30% and 90%, depending on the water losses (efficiency of irrigation = $e_{3/3}$).

As operated in the South East of Spain, to produce a harvest of, for example, 35 tons of tomatoes per ha with a total growth period of 150 days, the water and labour requirement for irrigation water were:

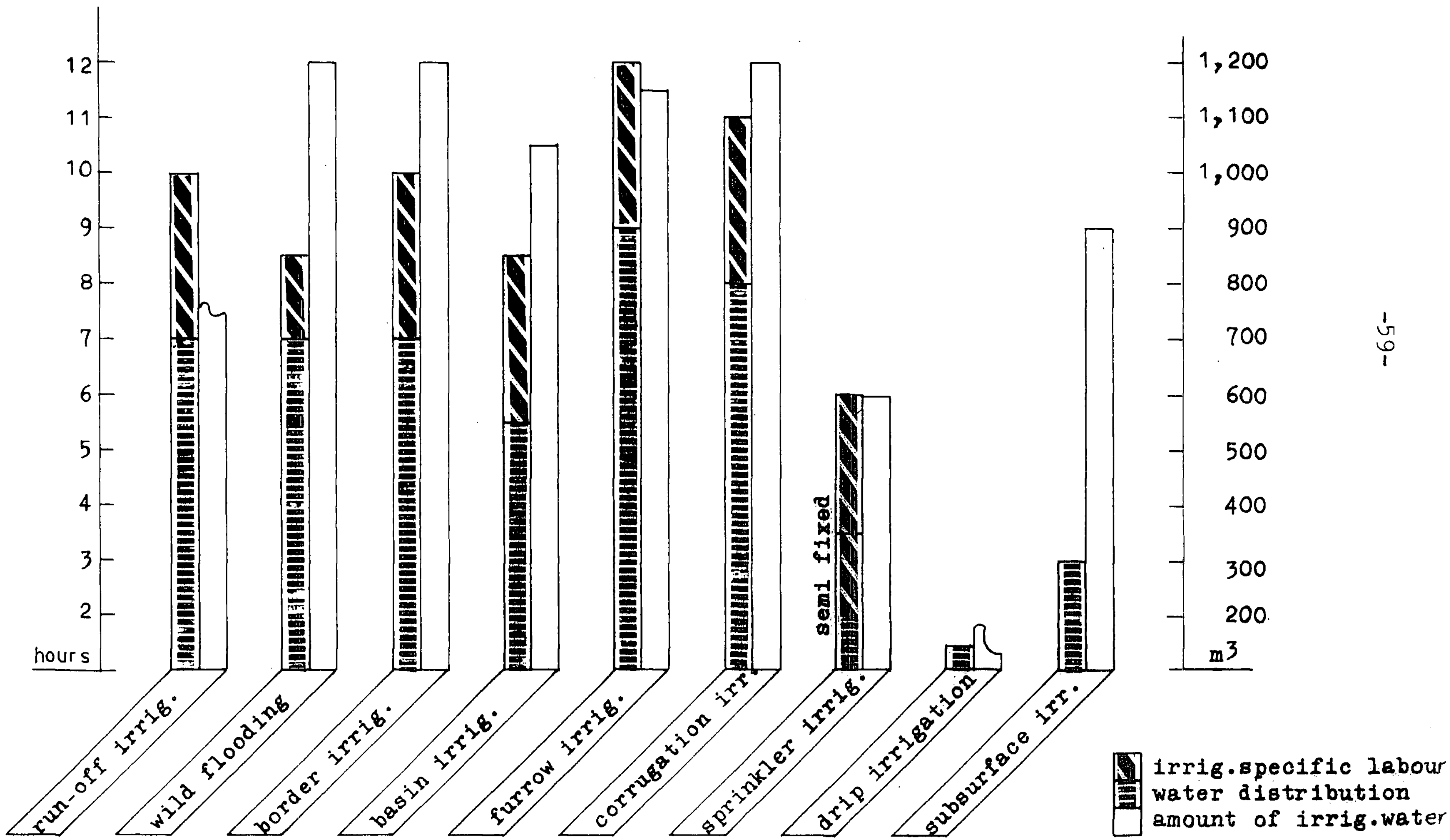
- by drip irrigation 4,000 m^3/ha water and 10 man hours
- by furrow irrigation 8,000 m^3/ha water and 56 man hours.

The difference in the production capacity per m^3 irrigation water and man hours can be calculated as follows:

- Drip irrigation, 35,000 kg ÷ 4,000 m^3 = 8.8 kg tomatoes per m^3 irrigation water by a labour input of 35,000 kg ÷ 10 h = 3,500 kg per man hour.
- Furrow irrigation, 35,000 kg ÷ 8,000 m^3 = 4.4 kg tomatoes per m^3 irrigation water by a labour input of 35,000 kg ÷ 56 h = 625 kg per man hour.

Figure 2.3 shows relative data of labour demand for irrigation specific operations in man hours per ha and irrigation cycle (e.g. crust breaking, maintenance of ridges and ditches, movement of irrigation equipment) as well as for water distribution (e.g. flow control over the irrigated plot, control and maintenance of irrigation equipment).These Figures are in relation to the corresponding amount of the irrigation water usually applied. In run-off irrigation, the amount of water depends on the intensity of precipitation and therefore cannot be predeterminated. As drip irrigation has short intervals between the cycles the corresponding amount of water cannot be related to one irrigation cycle in this Figure. In surface irrigation, the highest labour demand per amount of water applied can be observed in furrow irrigation. This demand is mainly based on the relatively high labour required both for flow control by furrows and for crust breaking. In subsurface irrigation, no specific irrigation follow-up labour is required; as the soil surface will be kept dry by irrigation, crust formation or puddling of the upper soil layer is prevented.

Figure 2.3 : Labour demand in hours per hectare and irrigation cycle for water distribution and directly related irrigation specific cultivation work.



2.5 ECONOMY - BALANCE OF INPUT FOR THREE ROW CROPS UNDER SURFACE AND PRESSURE IRRIGATION

Most of the following data of input for irrigation were obtained in 1974 in Murcia. In this area surface irrigation had been introduced by the Greeks and Romans during their imperial epochs and is still practiced.

The soil of the observed irrigated area can be described as a sandy loam, poor in organic matter with an infiltration rate of about 1.5 cm per hour. The depth of the topsoil is around 3 m with a pH value of 8.0 to 8.5.

The irrigation water in this case, rised from a well 150 m deep, had an electrical conductivity of 3,937 millimhos/cm, containing 990 mg NaCl per l and a SAR (sodium adsorption ratio) of 4.1. According to the classification diagram for irrigation water, from the US Salinity Laboratory, the water could be classified into L4/N2 (L4 = high salinity, N2 = moderate Na^+ content). Despite the high salt content, artificial drainage operations were not necessary in most cases. This was because of the deep topsoil and absence of obstructive soil layers.

The carbonate hardness of the water was in the range of 64 degrees (1 degree = 1 grain $CaCO_3$ per gallon of water). This relatively high carbonate content which would cause incrustations in the emitters made drip irrigation difficult.

The climatic data, given in Table 2.2, shows a dry season from February till September, and a wet one from October till January.

The data of initial investment and costs of surface irrigation, shown in Table 2.3, were collected on a 60 ha farm in this area. As mentioned before, the water is pumped from a well 150 m deep. In order to have a water reserve, for example, if the pump unit has to be repaired, a storage reservoir of 70,000 m^3 capacity had been constructed beside the well. Table 2.4 shows the corresponding data of input for irrigation and irrigation specific cultivation work for 50 ha of citrus fruits (plant distance 5 x 4 m), 9 ha of melons and 1 ha of tomato/aubergine, cultivated in a greenhouse in 2 to 2.5 crop rotations/year. Here, the citrus fruits are irrigated by basins and border irrigation; the vegetables (melons, tomatoes and aubergines) by furrow irrigation.

For the basis of the comparison made below the water used in this system is assumed to equal the actual water requirements.

For a semi-fixed sprinkler irrigation system, the data is given in Tables 2.5 and 2.6. It was collected on different farms in the same region and is extrapolated to standard areas. It may be noted that sprinkler irrigation would not be successful with this kind of water because of the high salt content which caused scorching of the fruit trees leaves.

Tables 2.7 and 2.8 give an example of the costs for drip irrigation. Data was obtained from existing drip irrigation systems on farms as well as from results from several trials in the same area.

To correlate the fixed costs to the input requirements of the different crops, i.e. how much one has to invest to be able to irrigate a certain crop, the sum of fixed costs has been distributed in relation to the ratio of water required by each crop.

It may be explained, that the percentages of depreciation allocated in Tables 2.3, 2.5 and 2.7 , are calculated on the base of the farmers expectation of the useful life of the corresponding items, supported by other evidence (see Ref. 2.9 and 2.10). Calculating the percentage of depreciation the formula is:

$$\frac{100\%}{\text{useful life of corresponding item/year}} = \text{depreciation \%/year}$$

Average annual interest costs marked in Tables 2.3, 2.5 and 2.7 are calculated on the assumed interest rate of 8 percent. This Figure was arrived through conversations with IRYDA in Sevilla, Spain, in 1979.[2.11] Here it should be noted that of the general actual interest rate of about 12 percent/year, the government meets 4 percent as a grant. The formula used for calculating the average annual interest cost of the investment is estimated by multiplying the rate of interest times the average investment.

$$\text{Annual interest cost} = \frac{\text{new cost of item}}{2} \times \text{interest rate}$$

Table 2.2 : Climatic data of the region of Murcia, Spain
(average of the years 1954 - 1964)

month	hours of sunshine / month units of 12 hours	average temp./ month ^{o}C	average precipitations / month mm	rate of evapotranspiration (Thornwaite) mm
January	25.5	11.01	24.33	22.95
February	25.2	12.50	14.93	35.28
March	30.9	14.86	16.15	67.98
April	30.0	16.83	19.62	95.70
May	36.9	20.82	26.62	173.43
June	37.2	23.70	20.04	200.88
July	37.5	27.08	0.28	225.00
August	35.1	27.42	2.86	210.60
September	31.2	24.54	17.75	174.72
October	28.8	19.69	40.37	109.44
November	25.2	14.63	28.24	42.84
December	24.9	11.77	26.18	22.41
Total			237.37	1,381.23

After ref.:2.5

Table 2.3 : Initial investment and costs of surface irrigation of 60 ha farmland (1974)

item	new cost £	useful life years	depreciation/ amortisation %	depreciation/ amortisation £	interest on new cost + 2 %	interest on new cost + 2 £	fixed costs £
- pump station 77 kWh, 132 m^3/h pump unit	28,000.-	12	8	2,240.-	8	1,120.-	3,360.-
- well drilling 150 m	12,000.-	50	2	240.-	8	480.-	720.-
- reservoir 70,000 m^3 earthen, plastic membrane	67,000.-	20	5	3,350.-	8	2,680.-	6,030.-
- field canals plastic membrane	23,000.-	20	5	1,150.-	8	920.-	2,070.-
- land levelling	30,000.-	--	4*	1,200.-	8	1,200.-	2,400.-
subtotal	160,000.-			8,180.-		6,400.-	14,580.-

Distribution of fixed costs to the irrigated area per ha and year in relation to the water requirement:

Fixed costs £ 14,580.- + 392,000 m^3 total water requirement = £ 0.037 per m^3 irrigation water

= for citrus fruits 6,000 m^3 x 0.037 = £ 222.- per ha and year
= for melons 8,000 m^3 x 0.037 = £ 296.- per ha and year
= for green house 20,000 m^3 x 0.037 = £ 740.- per ha and year

* 4 % write off instead of depreciation/ amortisation

Source: fieldwork

Table 2.4 : Variable costs including labour input for surface irrigation per ha / year

item	citrus fruits specification	citrus fruits value £	melons specification	melons value £	greenhouse specification	greenhouse value £
water lifting, 0.58 kWh/m^3, 1 kWh 0.05 £ = 0.03 £ per m^3	6,000 m^3	180.-	8,000 m^3	240.-	20,000 m^3	600.-
man hours for irrigation, 1 man hour £ 3.5 (1 irrigation cycle = 7 man hours)	42 h (6 cycles)	147.-	56 h (8 cycles)	196.-	168 h (24 cycles during 3 growing periods)	588.-
man hours for irrigation specific cultivation work, £ 3.5 per hour and	18 h	63.-	24 h	84.-	72 h	252.-
estimated machinery expenses, £ 5 per hour	9 h	45.-	10 h	50.-	30 h	150.-
estimated repair expenses		10.-		20.-		40.-
subtotal		445.-		590.-		1,630.-

Source: fieldwork

Table 2.5 : Initial investment and costs of semi-fixed sprinkler irrigation of 60 ha farmland (1974)

item	new cost £	useful life years	depreciation/ amortisation %	depreciation/ amortisation £	interest on new cost + 2 %	interest on new cost + 2 £	fixed costs £
- pump station 77 kWh, 132 m^3/h pump unit	28,000.-	12	8	2,240.-	8	1,120	3,360.-
- well drilling 150 m	12,000.-	50	2	240.-	8	480.-	720.-
- reservoir 70,000 m^3 earthen, plastic membrane	67,000.-	20	5	3,350.-	8	2,680.-	6,030.-
- pump unit 70 m^3/h	5,000.-	10	10	500.-	8	200.-	700.-
- fixed main pipes with 150 mobile sprinklers (£ 1,000.- ha)	60,000.-	10	10	6,000.-	8	2,400.-	8,400.-
subtotal	172,000.-			12,330.-		6,880.-	19,210.-

Distribution of the fixed costs to the irrigated area per ha and year in relation to the water requirement - 20 % lower than by surface irrigation - :

Fixed costs £ 19,210.- + 313,600 m^3 total water requirement = £ 0.061 per m^3 irrigation water

= for citrus fruits 4,800 m^3 x 0.061 = £ 293 per ha and year
= for melons 6,400 m^3 x 0.061 = £ 390 per ha and year
= for greenhouse 16,000 m^3 x 0.061 = £ 976 per ha and year

Source: fieldwork

Table 2.6 : Variable costs including labour input on semi-fixed sprinkler irrigation per ha / year

item	citrus fruits specification	citrus fruits value £	melons specification	melons value £	greenhouse specification	greenhouse value £
water lifting 0.58 kWh/m^3, 1 kWh 0.05 £ = 0.03 £/m^3	4,800 m^3	144.-	6,400 m^3	192.-	16,000 m^3	480.-
water distribution 0.4 kWh/m^3, 1 kWh 0.05 £ = 0.02 £ per m^3	4,800 m^3	96.-	6,400 m^3	128.-	16,300 m^3	326.-
man hours for irrig. (displacement of the sprinklers), 4 h per cycle, 1 man hour £ 3.5	28 h (7 cycles)	98.-	40 h (10 cycles)	140.-	40 h (X cycles, fixed system)	140.-
man hours for specific cultivation work for irrigation, £ 3.5 per man hour and	18 h	63.-	24 h	84.-	72 h	252.-
estimated machinery expenses, £ 5 per hour	9 h	45.-	10 h	50.-	30 h	150.-
estimated repair expenses		20.-		30.-		50.-
subtotal		466.-		624.-		1.398.-

Source: fieldwork

Table 2.7 : Initial investment and costs of drip irrigation of 60 ha farmland (1974)

item	new cost £	useful life years	depreciation/ amortisation %	depreciation/ amortisation £	interest on new cost + 2 %	interest on new cost + 2 £	fixed costs £
- pump station 57 kWh, 90 m^3/h pump unit	17,000.-	12	8	1,360.-	8	680.-	2,040.-
- well drilling 150 m	12,000.-	50	2	240.-	8	480.-	720.-
- reservoir 30,000 m^3 earthen, plastic membrane	28,000.-	20	5	1,400.-	8	1,120.-	2,520.-
- head unit of drip irrigation, 50 m^3/h pump unit	8,000.-	10	10	800.-	8	320.-	1,120.-
- distribution pipes, fitting material, lateral pipes and emitters, £ 800.-/ha in trees (50 ha)	40,000.-	10	10	4,000.-	8	1,600.-	5,600.-
£ 3,000.-/ha in vegetables (10 ha)	30,000.-	10	10	3,000.-	8	1,200.-	4,200.-
subtotal	135,000.-			10,800.-		5,400.-	16,200.-

Distribution of the fixed costs to the irrigated area per ha and year in relation to the water requirement - 50 % lower than by surface irrigation - :

Fixed costs £ 16,200.- ÷ 196,000 m^3 water requirement = £ 0.083 per m^3 irrigation water

= for citrus fruits 3,000 m^3 x 0.083 = £ 249 per ha and year

= for melons 4,000 m^3 x 0.083 = £ 332 per ha and year

= for greenhouse 10,000 m^3 x 0.083 = £ 830 per ha and year

(Source: fieldwork)

Table 2.8 : Variable cost including labour input on drip irrigation per ha / year

item	citrus fruits specification	citrus fruits value £	melons specification	melons value £	greenhouse specification	greenhouse value £
water lifting, 0.58 kWh/m^3, 1 kWh 0.05 £ = 0.03 £/m^3	3,000 m^3	90.-	4,000 m^3	120.-	10,000 m^3	300.-
water distribution, 0.2 kWh/m^3, 1 kWh 0.05 £ = 0.01 £/m^3	3,000 m^3	30.-	4,000 m^3	40.-	10,000 m^3	100.-
man hours for irrig. skilled labourer, £ 5/h	7 h	35.-	10 h	50.-	20 h	100.-
man hours for displacement of the emitter lines	-	--	16 h	80.-	40 h	200.-
estimated repair expenses		20.-		100.-		300.-
subtotal		175.-		390.-		1,000.-

Source: fieldwork

On the basis of this example analysis the conclusion can be summarised thus: low demand on initial investment costs generally requires a high demand in running expenses, mainly in terms of labour, because of the poor efficiency of the method of irrigation. In particular, by surface flooding (furrow and basin irrigation) a relative low initial capital investment with a high demand on labour, associated with a low effectivity of irrigation water is given. Here, the fixed costs are about 50% lower than the variable costs for running expenses.

With semi fixed sprinkler irrigation, no significant difference in terms of demand on running expenses in comparison to surface flooding can be observed. The savings of man hours, at highest in the greenhouse, had to be substituted by higher initial investment for the irrigation equipment. The effectivity of irrigation water is slightly higher than by surface irrigation, e.g. furrow or border irrigation.

With drip irrigation, the demand on initial investment capital on average is slightly higher than for surface irrigation, but lower than by semi fixed sprinkler irrigation. Here, the main difference in comparison with surface and semi fixed sprinkler irrigation consists in the low demand on labour and running expenses as well as on the high effectivity in terms of irrigation water.

Figure 2.4 represents an overview of the fixed and variable costs required by surface irrigation (basin or furrow irrigation), semi fixed sprinkler and drip irrigation. Here the following main characteristics can be observed:

- the fixed costs are lower than the variable costs by surface and sprinkler irrigation and vice versa; by drip irrigation the contrary cost relation can be observed in the case of citrus and an equal ratio with vegetables.
- the fixed costs are at the lowest level with surface irrigation; however, those costs are only about 20% higher (with drip irrigation) than with surface irrigation. If we compare the level of fixed costs, sprinkler irrigation is the most expensive.
- the variable costs are at their lowest level in drip irrigation, about 50% lower than with surface irrigation. With sprinkler irrigation, the variable costs are, except the greenhouse, nearly at the same level as surface irrigation.

It can be summarised, that the demand on total inputs are nearly equal for surface and sprinkler irrigation. By using drip irrigation, the comparatively lowest demand on total inputs can be achieved. Some qualifications have to be added to this generalisation.

First, in many cases where the technologically simpler methods of irrigation are used, e.g. basin flooding, we find that labour inputs are not costed in monetary terms. Thus, high inputs of manual family labour in flow regulation, earth movement in terracing etc. may be acceptable in subsistence orientated farming. Therefore, in many parts of Africa small farms will utilize basin irrigation methods.

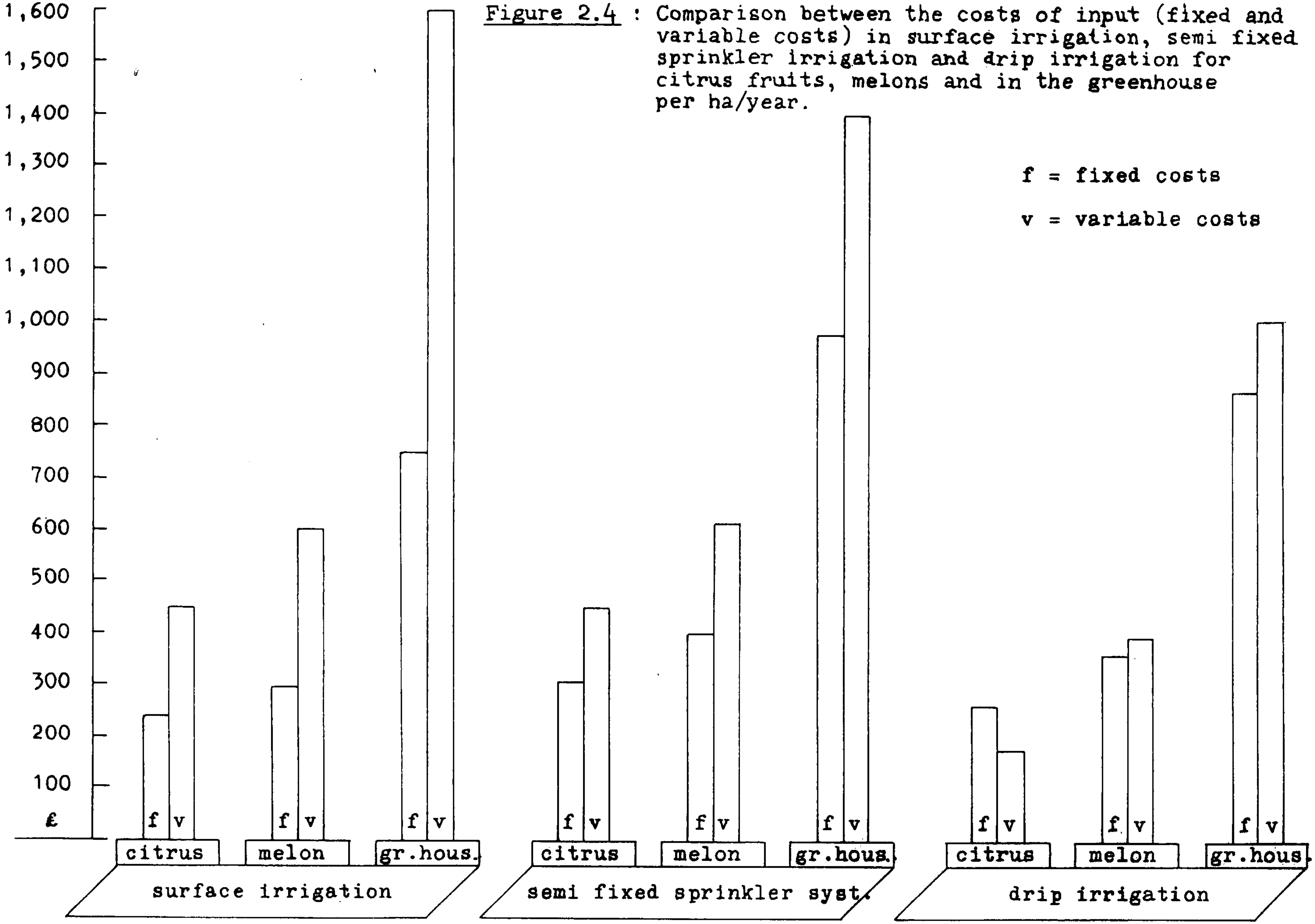
Secondly, the cost of material equipment inputs will vary regionally with accessibility of supplies, transport facilities etc., as for example in Oman.[2.12]

Thirdly, imported high technology equipment represents for many less developed countries a demand on scarce foreign exchange - important for example in Mali or the Sahel region. Even so, this economic analysis may only be utilized as one of many criteria, which have to be considered as pro and contra in the comparison of field irrigation systems.

Figure 2.4 : Comparison between the costs of input (fixed and variable costs) in surface irrigation, semi fixed sprinkler irrigation and drip irrigation for citrus fruits, melons and in the greenhouse per ha/year.

f = fixed costs

v = variable costs



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CHAPTER THREE

3. FACTORS INFLUENCING THE DESIGN OF FIELD IRRIGATION SYSTEMS

Introduction

In order to get optimum production capacity in designing irrigation units for presently unirrigated land as well as the improvement of existing irrigation systems, the layout has to be orientated around local environmental, economic and human characteristics. In this thesis the main emphasis will be an approach through the consideration of the technical aspects of irrigation. In many irrigation schemes, general aims are formulated without sufficient appreciation of the limitation of freedom of manoeuvre imposed by technical factors. In practice it can be observed that the decisions in selecting a specific irrigation system are basically affected by the following factors:

- On the regional or governmental level the motivation in deciding between various irrigation methods or systems is mainly based on results of scientific calculations or trials obtained in other analogous areas; the politico-economic benefit of crop production in relation to the financial possibilities and national prestige. Here, the farmers attitude and their knowledge are seldom respected.
- At farm level, the main arguments in selecting an irrigation system are mainly based on the farmers traditional experience perceived economic possibilities, credit facilities, possible return on capital, labour economy and the practices of the neighbouring farm areas.

A close co-ordination between these two groups of interest is seldom realized. However, where the farmer himself has selected 'his' irrigation method, fewer breakdowns can be observed than on irrigated areas where he has to follow orders given by a water and irrigation authority.

From the following short examples, some planning failures may be observed.

Since time immemorial irrigation water represents for the Egyptian farmer the essential medium to realise a harvest (personal observation in 1977). With the construction of the Assuan Dam, water is now limitless and free. Consequently, the farmers are inclined to water the land as much as possible. This has resulted, via capillarity, in the rising of the ground water table to the soil surface, causing a heavy salt concentration in the upper soil.

- On a farm in South East of Spain using surface irrigation, the amount of water delivered by a deep well, was often insufficient a few weeks before harvest time. This was because of the well's limited capacity. Consequently, nearly every third harvest was lost, although the total water capacity available over the irrigation period would have been sufficient; had a more effective method, e.g. pressure irrigation, be used.
- The levelling costs on moderate to steep slopes are, even when machinery is used, extremly high. It can be noted, that were levelling not necessary, that this expenditure would have covered the cost of the entire installation of the irrigation system, e.g. in Khuzistan, Iran, the estimated costs for land levelling and land

preparation for surface irrigation were calculated by 500 to 600 U.S. $/ha. In reality, those costs rose by some 100% to about 1.200 U.S. $/ha.[3.1]

3.1 CLIMATIC CONDITIONS

The expression 'climate' stands for the meteorological conditions, consisting of the main factors of precipitation, temperature of the air and earth's surface, air humidity and evaporation, hours of sunshine and radiation of sun and sky, wind direction and velocity and frost incidence over a given area within a specified period of time. The climatic conditions on small areas of the earth's surface, for example in a crop field, is called micro-climate. The climate over a very large area, such as desert or ocean, is called macro-climate.

Irrigation is essential in arid climates which are characterized by very low precipitation and high rates of potential evaporation.

Due to lack of sufficient moisture,agriculture without irrigation is not possible. In semi-arid areas, by definition, crops can be grown without irrigation but irrigation facilities may be necessary to rise better crops or yields.

The macro-climate consists of existing meteorological conditions and their change or rectification is not possible. However, by irrigating, micro-climatic changes are induced, and the following relationships between the climate factors, irrigation methods applied, and crop responses may be observed:

- Precipitation
  This climatic factor can be artificially substituted or supplemented in order to rectify the growing conditions of the plants. Precipitation represents the sole climatic factor which can be artificially replaced under field conditions.
- Temperature of the air and earth's surface
  When the entire earth surface of the field is irrigated, the temperature of the air and earth's surface becomes lower than the dry area. This is due to loss of heat energy through evaporation. Even using irrigation water with a moderately lower temperature than that of the earth's surface, an adverse effect to plant growth can be caused. This is particularly marked in overhead irrigation where the water causes cold shocks which depress growth. However, with very high surface temperature conditions even if relatively cool water is used, favourable growth effects are achieved. This is due to temperature regulation in the root zone.

  In drip or subsurface irrigation, the temperature of the irrigation water is adapted to the environmental temperature because the water has to move slowly by capillarity through a pipe system from the subsoil to the root zone. With cold sensitive crops using surface or sprinkler irrigation, the temperature of the water should be adapted to the air temperature by exposing it in a storage basin to the sun.

- Air humidity and evaporation

  Changes in the plant environment, micro-climate, by raising humidity in the soil and in the surrounding air an increase in fungus diseases and insect problems may result. The amount of evaporation loss (the passage of water from the liquid and solid phase to the vapour phase) depends on the saturation pressure of the air as well as on the extent of the wetted soil surface. Evaporation losses by surface and sprinkler irrigation are therefore much higher than by drip or subsurface irrigation where only small spots of the soil surface are wetted.
- Hours of sunshine and radiation of sun and sky

  These are important as data for the theoretical calculations of the crop water requirements. Day length responding plants are particularly strongly affected by temperature since they are species which are naturally subject to fairly wide day length variations. Subtropical and tropical plant species are less sensitive. Nevertheless, to get an optimal use of the radiation, the row direction of the plants is normally situated to face the main sun radiation direction, this can affect and be affected by irrigation layout.
- Wind direction and velocity

  Wind represents a physical force which can produce soil erosions and physical damages to the crops. Wind protection measures, usually living fences of trees, are extremely common in subtropical areas. In cultivations where the soil surface has to be kept uncovered, to avoid water losses by evapo- transpiration, wind erosion very often represents a serious problem. The row direction of trees are normally parallel to the main wind direction to prevent wind damage. Wind can also increase the rate of evapo-transpiration. The transpiration peak rates can reach a critical stress point during periods of high wind and radiation intensity.

Hence, in most plantations there must be a compromise between the directive effects of wind and sun direction, as well as irrigation layout.

- Frost

Nightfrost damages to crops may occur during growing seasons in all but low-latitude lowland. It is characterized meteorlogically by calm weather and clear sky. The re-radiation into Outer Space has to be considerably higher than the return radiation to the earth's surface. The air close to the ground will be cooled by conduction to temperatures frequently below zero ^{o}C. Low lying areas in hilly regions are particularly vulnerable to cold air pooling.

Protection against nightfrost damage can be provided by sprinkler irrigation. The waterdrops in their trajectory through the air settle on the ground surface and the leaves. The drop will transmit heat to the surrounding cold air, and the humidity will increase the dry cold air, thus changing the micro-climate near the ground. The water on the cold ground surface and leaves will then freeze and release heat so that the temperature of the leaves may stay around 0 ^{o}C.

However, surface irrigation has also a mitigating effect against nightfrost damage. If the soil surface is wet, distillation (evaporation of moisture from warm areas and its condensation on cool areas), can occur freely, as mentioned above in sprinkler irrigation.

These two processes can provide adequate energy and maintain a sufficiently high temperature on plant surfaces.

Table 3.1 schematically shows the possibilities for and intensities to which the different climatic conditions in a hypothetical arid region can be rectified through different irrigation methods in terms of improving the growing conditions. The negative side-effect of irrigation under open air conditions and in greenhouses is also shown.

It can be observed that the climate factor 'precipitation' can be improved by all irrigation methods, except by subsurface irrigation, where the upper soil layer very often cannot be sufficiently wetted (see Chapter 1.3). Mainly in greenhouses, but also under open air conditions, surface flooding and sprinkler irrigation have unfavourable side-effects in terms of raising the air humidity and evaporation. These effects are caused by wetting the whole or large parts of the earth's surface, including the plants, where sprinkler irrigation is used. Therefore, in greenhouses an irrigation system should be used, which keeps the earth's surface as well as the plant's surface dry. This dry environmental condition can be reached by the use of subsurface and drip irrigation.

As stated in Chapter 1, high air moisture content can cause in plants, diseases, such as fungus attacks. A soaked soil surface can cause high water losses by evaporation.

Table 3.1 : Climatic factors and their alteration through the influence of different irrigation methods in an arid region under open air conditions and in green-houses.

	irrigation method	precipitation	temperature (air and earth's surface)	air humidity and evaporation	hours of sunshine and radiation	wind	frost
open air cond.	surface irrigation	XXX	cold water YY XX temp. water	Y	0	0	(0)
	pressure systems:						
	- sprinkler	XXX	cold water YY XX temp. water	YY	0	0	XX
	- drip	XXX	(0)	(0)	0	0	0
	subsurface irrig.	XX	0	0	0	0	0
greenhouses	surface irrigation	XXX	cold water YY XX temp. water	YY	0	protected by the green-. house	protected by the green-house
	pressure systems:						
	- sprinkler	XXX	cold water YY XX temp. water	YYY	0		
	- drip	XXX	(0)	(0)	0		
	subsurface irrigat.	XX	0	0	0		

alteration intensity of the climatic factors with the effect of

	positive:		negative:
X	low	Y	low
XX	moderate	YY	moderate
XXX	high	YYY	high

(0) negligible) influence of growing conditions
0 no influence) of most of the plants

3.2 WATER QUANTITY AND QUALITY

Water for irrigation can be obtained from surface run-off as river or spring water and/or by the raising of ground-water. In hilly terrain direct run-off from precipitation can be conveyed to irrigate fields, run-off irrigation. In the future a potential source of water might be the desalinization of brackish or seawater.

The quantity of surface water and ground-water depends on the amount of the precipitation (intake ratio) on the corresponding catchment area. Therefore, the water quantity often varies from year to year in relation to the intensity of the precipitation. For developing a new irrigation area, one of the first steps consists in determining the amount of water available. If this data is obtained, the theoretical crop water requirement can be calculated by formula or by using data of real water consumption in similar areas.

The possible extension of the area to be irrigated depends on the amount of water available. Water losses through percolation in storage basins, canals and on the irrigated field as well as evaporation reduces the extent of the area to be irrigated. For example, if water losses can be cut from 50% to 20% through better management or by alterating the irrigation method, 10 ha irrigated land could be extended by as much as 6 ha or 60%.

The expression 'water quality' stands firstly for the amount and kind of dissolved minerals in the water and secondly for the amount of suspended solids. The water quality for irrigation water based on the amount and kind of dissolved minerals (chemical impurities) is closely related to the different crop response and sensitivity of the plants to these minerals as well as to the chemical reactions with the minerals or colloids in the soil.

The total dissolved minerals are sometimes expressed in parts per million (p.p.m. = mg/l^{-1}). More common is the measurement by electrical conductivity in micromhos per cm at 25 ^oC.

The U.S. Department of Agriculture classified the irrigation water, modified by Thorne and Peterson,1954, as follows: (Source ref. 3.2)

low salinity	= $<$ 250	micromhos/cm at 25 ^oC
moderate salinity	= 250 - 750	" " " " "
medium salinity	= 750 - 2,250	" " " " "
high salinity	= 2,250 - 4,000	" " " " "
very high salinity	= 4,000 - 6,000	" " " " "
excessively high salinity	= $>$ 6,000	" " " " "

Salts are the most common chemical impurities which inhibit the plant growth. Neutral salts, carried with the irrigation water to the field, are normally transported by osmotic movement to the upper soil layer where they concentrate in a salt crust. To prevent high salt concentrations in the soil, the salts have to be dissolved and transported away from the irrigated field by an application of excessive water, called leaching. The salt affect in the soil water on the plants consists of a reduction in the osmotic pressure difference between the roots and the soil by a limitation of the water absorbtion. Furthermore, an inbalance of ions in the plant may develop, thus disturbing the metabolic processes. The different ions are listed according to their toxidity, diminishing from left to right:

$NaCl$ - $CaCl_2$ - KCL - $MgCl_2$ - KNO_3 - $Mg(NO_3)_2$ - Na_2SO_4 - $MgSO_4$

For plant growth, the important factor consists of the salt concentration in the soil water at the root zone. This concentration rises according to the water reduction in the soil, for example between irrigation cycles, up to a plant toxic concentration.[3.3] Thus ideally irrigation management consists in stabilisation of the soil moisture and the salt concentration in the soil water by the application of small amounts of water in very frequent irrigation cycles. This is best met by pressure irrigation systems, mainly drip irrigation.

Further attention must be given to the amount of sodium Na^+ in the irrigation water. The interchangeability of the cations by the soil colloids should be the same as the ions in the soil water. If the sodium ions in the water increase the soil colloids adsorb more of them. This results in an accumulation of the pH value >8.5, also called alkalisation. By this process, adsorbed Ca^{++} will be changed against Na^+ according to the formula:[1.4]

$$2\,Na^+ + Ca\,[clay] \rightleftharpoons Na\,[clay]\,Na + Ca^{++}$$

The soil structure may be destroyed and the soil become nearly impermeable in wet conditions. This process is also influenced by the degree to which the sodium is interchangeable as defined by the sodium adsorption ratio (SAR)

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{++} + Mg^{++})/2}}$$

If the amount of Na^{+}, Ca^{++} and Mg^{++} in millival per l solution is known, the SAR value can also be determined by nomograms, which are published in most of the irrigation publications, for example source ref. 3.2.

Hence, the content of bicarbonate in the irrigation water tends, if calcium and magnesium is present, to precipitate out as carbonates (HCO_3 may react with Ca^{++} or Mg^{++} and precipitate out as $CaCO_3$). Thus, in reducing the soluble calcium and magnesium and inreasing the sodium adsorption ratio in the water, the SAR, value will be larger than originally determined.

With drip irrigation, bicarbonates precipitate in the emitters as $CaCO_3$ thus blocking the water outlets. Prevention of emitter blockages by carbonates can be realized by the incorporation of additives like nitric, or hydrochloric acid into the irrigation water. Iron content in the irrigation water also forms precipitations in the emitters resulting in blockages. The iron impurity in the water can be eliminated by precipitating and filtering the iron before entering the pipe system by using an oxygen iron-remove plant. Personal trials have shown that iron precipitations in the pipe system can also be prevented if the pH value of the water can be brought below pH 3 by an acid incorporation. More than 0.1 mg/l iron, e.g. iron bicarbonate and/or more than 200 mg/l carbonates e.g. CaO, can be considered as a moderate to high impurity content.

Suspended solids in the irrigation water such as algae, clay, silt and sand may cause damages in pressure irrigation systems and wear out the water pumps and produce in drip irrigation blockages of the emitter. The type and concentration of the solids determines the type and size of the required water filters. Solids, smaller than 0.002 mm are difficult to filter and represents a factor which can cause blockages of the emitters.

3.3 TOPOGRAPHY AND SOIL

For surface irrigation systems, the required slope to control the water flow is between 0.2% and 8% (see Chapter 1). As the soil itself represents an integral part of the irrigation system, the soil surface has to be adapted to the irrigation system to be used. On uneven land, the soil surface has to be levelled in the two dimensions, width and height, by earth moving work. To intensify the sun radiation or because of shortage of land, earth moving operations are carried out even on steep hills. The construction expenses for surface irrigation methods are closelyrelated to the topographic conditions. These are based on the amount of earth or rocks to be removed. The displacement of the upper soil layer by surface levelling will produce yield depressions in the first years until the soil structure is reconstructed by biological regenerations.

Pressure irrigation methods as three dimensional irrigation systems can be adapted to different topographic conditions. The irrigation water can be conducted uphill by artificial overpressure in closed pipes; land levelling is not then necessary. On steep sloped land, as the installation of pressure irrigation can be adapted to the soil surface it is less expensive than the earth moving work for surface irrigation.

If in pressure irrigation on steep slopes the earths surface is kept uncovered there will be an increase in soil erosion. Strips of vegetation such as grass should be planted along the hillside to prevent erosion by heavy precipitation.

On light or shallow soils with characteristically low water storage capacity, irrigation practices with frequent intervals of small amounts of water are essential to prevent water losses by seepage and to avoid soil drying between the irrigation cycles.

The reduction by leaching of the salt content in the soil due to primary or secondary salination (see Chapter 1.4) is necessary to control salt accumulation which can affect crop growth. Leaching can be defined as a heavy overirrigation so that the water, enriched by soluble salts, percolates and leaves the irrigated plot by natural or artificial drainage facilities. Because of the relatively large amount of water required, leaching should be carried out during the season or seasons of lowest plant-water demand.

Leaching efficiency depends on the quantity and quality of water percolating through the soil, pore sizes in the soil, thickness of the soil layer, soil moisture and the vertical salt distribution through the soil layer.

With drip irrigation, the amount of water which can be delivered per unit of time is not sufficient to cover the soil surface as would be required for leaching. As the salts are accumulated in the transition zone from the soil wetted by the emitters to the dry part of the soil, a continuous surface watering over a period of few days will normally be sufficient for dissolving and leaching these salts.

Care has also to be taken for the effect of precipitation during growth period. Water derived from precipitation distributes the salts from the transition zone around the emitter into the root zone of the plants with resultant salinisation. This effect can only be avoided by (as absurd as it may seem) , irrigating during the time of precipitation.

In the case of subsurface irrigation, leaching has to be arranged either by surface overflooding or by sprinkler irrigation.

On saline-sodic soils which contain a large amount of exchangeable sodium with a low amount of calcium, the leaching process promotes an alkalisation by washing away the soluble components (see Chapter 3.2). To avoid such a soil degradation associated with a collapse of the soil structure, a distribution of sulphurous compounds, gypsum ($CaSO_4$) or limestone ($CaCO_3$) is required. This restores the soil structure or prevents structural deterioration in parallel with leaching.

It can be stated that soil salinity represents the most critical factor for irrigated plant growth. In particular the exchangeable sodium level determines the possible decline of soil structure.

Table 3.2 shows the interrelationship between different saline soils as well as specific measures for their reclamation.

Figure 3.1 shows the interdependance of topographic and soil conditions for the design of different irrigation systems as well as the relevant restrictive factors. It illustrates that surface flooding irrigation methods are strongly affected in their layout (width and length of the irrigated plots) by topographic and soil conditions. In topography, a transvers slope is not considered but has to be taken into account assuming an even gradient as illustrated. By pressure irrigation, different soil and topographic conditions do not represent restrictive factors in terms of the layout of those systems. However, these irrigation systems have to be adapted to topography by pressure control devices as well as to the transmissability in the soil, e.g. in drip irrigation, water outflow quantity per unit of time by the emitter so that the formation of water puddles is avoided.

Subsurface irrigation has to be considered, as one can see in Chapter 1.3, as a modified gravity system of surface irrigation or as a subsurface use of a pressure system. As a buried pressure system it can be subsumed under the buried drip irrigation system. Subsurface irrigation systems are now very rarely installed and therefore, they are not considered seperately in this thesis.

Table 3.2 : Inter-relationship between different saline soils and the possibilities of their reclamation. (After reference 1.4)

Salinisation

- by minerals of weathered rocks,
- capillary rise of saline groundwater,
- saline irrigation water

Alkalisation

- by destroying the soil structure through a replacement of exchangeable Ca-ions by Na-ions

SALINE SOILS

affecting crop growth if
- EC_e higher than 4 mmhos/cm at 25 °C
- ESP lower than 15
- pH below 8.5

soil structure is not affected

SALINE-SODIC SOILS

affecting crop growth if
- EC_e higher than 4 mmhos/cm at 25 °C
- ESP higher than 15
- pH seldom higher than 8.5

soil structure usually fair

by leaching, soil may become strongly alkaline; permeability will diminish markedly

R E C L A M A T I O N

l e a c h i n g

leaching combined with the addition of sulphur, gypsum or limestone

amelioration by lowering the groundwatertable, breaking impermeable layers and drainage.

NON-SALINE SODIC SOILS

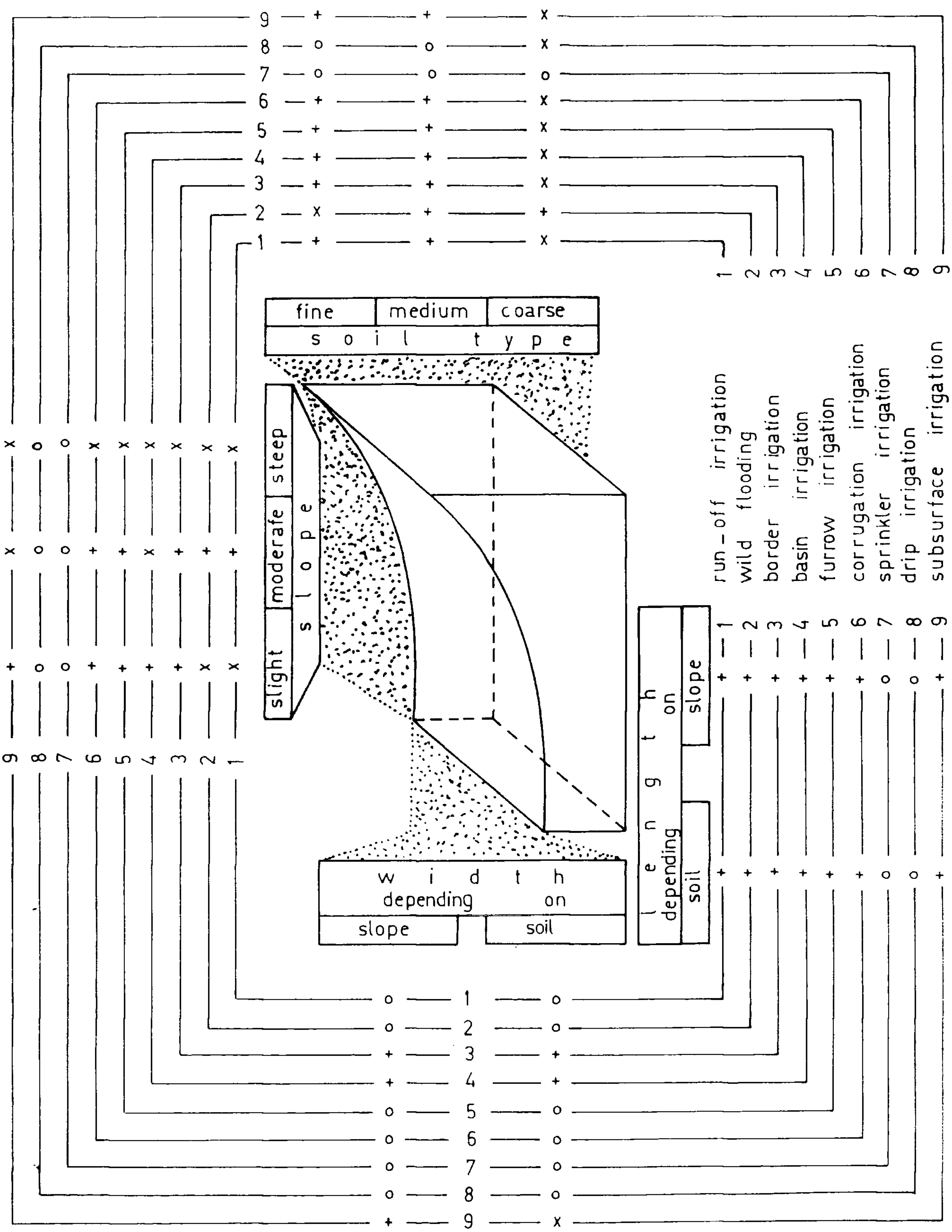
crop growth is impeded if
- EC_e lower than 4 mmhos/cm at 25 °C
- ESP higher than 15
- pH between 8.5 and 10 (on lime free soils lower than 6)

R E C L A M A T I O N

- chemicals (sulphur, gypsum, limestone) have to be mixed into the soil.
- having replaced the sodium by this measure, sodium must be removed from the field by leaching.

EC_e = electrical conductivity of the soil saturation extract in mmhos
ESP=exchangeable sodium percentage
pH=log of the reciprocal of the gram ionic hydrogen equivalents per l

Figure 3.1: The interdependence of topographic and soil conditions with field irrigation systems and their design.



\+ = required / dependence
x = restricted
o = not relevant

3.4 WATER REQUIREMENT OF PLANTS

The question 'how much water does the plant need for optimal growth' can be interpreted as follows:

i Development of water resources or
how many hectares of a certain crop can be irrigated with the quantity of water available?

ii Amount of water necessary at farm level during the period of maximum plant water requirement;

iii Irrigation practices or
when and how much to irrigate?

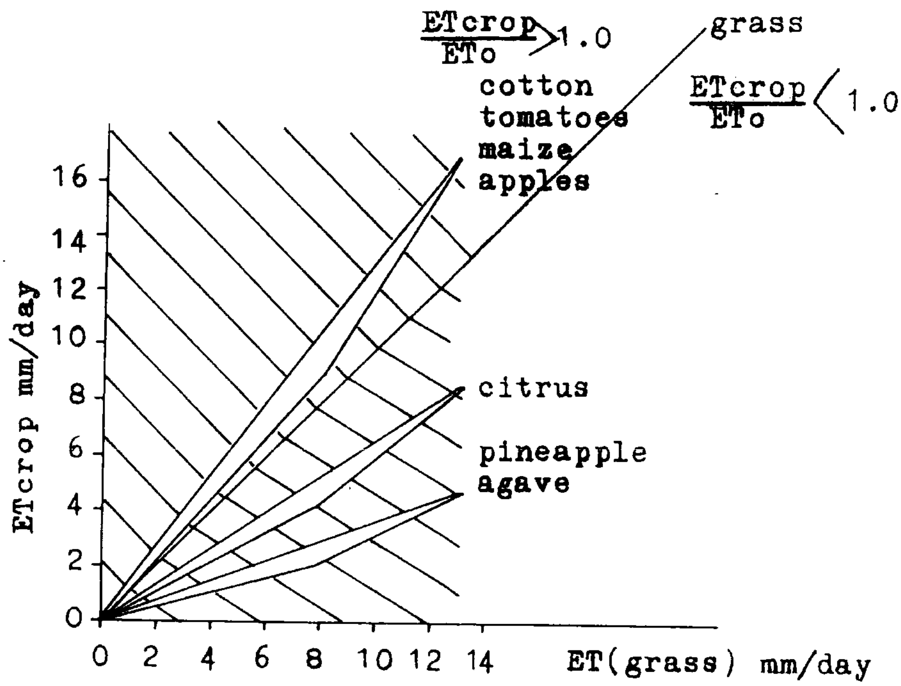
(i) Different calculation methods based on empirical data of environmental conditions are used to determine the theoretical water requirement of different crops under different climatic conditions. The crop water requirement is influenced by climate, crop characteristics, local conditions and agricultural practices.

The effect of climate is based on the water losses through evapo-transpiration affected mainly by the factors:-

- temperature
- wind
- air humidity
- sunshine and radiation.

The effect of crop characteristics on crop water requirement is influenced by their specific resistance to transpiration, stage of growth and length of growing season. These conditions are expressed as crop co-efficients. The reference crop on which evapo-transpiration under different climatic conditions is based, can be defined as a green grass, 8 cm to 15 cm tall, actively growing, no shortage of water and providing complete ground cover. Figure 3.2 shows the crop evapo-transpiration (ETcrop) as compared to reference crop evapo-transpiration (ETo)

Figure 3.2 : ETcrop as compared to ETo (After ref. 3.4)



Local conditions effect the crop water requirement by variations in climate over a period of time, quality of irrigation water, water availability in the soil, soil structure and soil texture.

The main effects of agricultural practices on crop water requirement are, the method of irrigation, cultivation methods such as space of planting, groundcover and size of the fields.

The main methods of predicting the crop water requirement are:

- Thornthwaite Method

  consisting of an empirical formula for the estimation of potential evaporation, based on temperature.

- Blaney - Criddle Method

  This method is suggested for areas for which only the data of air temperature and day length is available.

- Olivier's Method

  For the utilization of this method, data of temperature, air humidity and wind must be available.

- Radiation Method

  This method can be used for areas where climatic data of air temperature, duration of sunshine, cloudiness or radiation are available.

- Penman Method

  This method may be used if data of temperature, air humidity, wind and duration of sunshine or radiation are available.

- Pan Evaporation Method

  Evaporation pans provide a measurement of evaporation from a specific open water surface. This measurement integrates the effect of radiation, wind temperature and air humidity.

Detailed descriptions of the methods and guidelines presented above are published in most of the literature of irrigation (for example Sources ref.: 1.5, 3.4, 3.5). The possible errors when using these methods under different climatic and agronomic conditions from those for which they were originally developed, range from 10% to 25%.

Table 3.3 shows different data, required for calculating the theoretical water demand of crops using the different calculation methods. The methods developed by Thornthwaite and Blaney-Criddle, requires less data than developed by Olivier and Penman or by the Radiation method. The Thornthwaite and Blaney-Criddle methods can therefore be utilized to give a theoretical overviéw of the water demand of crops in these regions where only data of temperature and day length are available. Pan evaporation measurements have to be recorded in situ; the measured data of evaporation have to be adapted to the specific crop water demand by using conversion factors.

(ii) For the plant, different amounts of water are required at different stages of its growth, and also because of the different environmental conditions. Water consumption increases gradually with the temperature, wind, sunshine, radiation intensity and the development of the plant growth stages.

Many irrigation schemes have been designed on the basis of an assumed water duty in terms of the number of hectares which can be irrigated by an unit volume of water during the year. Hence, water shortage may be observed on many irrigated areas during the maturation stage of the crops which consequently reduces the yields. Therefore, the estimated water consumption per ha must also be calculated on the basis of the highest water requirement per unit of time, e.g. August in mid-latitude northern hemisphere, and the amount of water available during this critical period.

Table 3.3 : Climatic data needed for the different most important methods of determining theoretical crop water requirement. (After ref. 3.4)

method	temperature	sunshine/ day length	humidity	wind	radiation	evaporation
Thornthwaite	+	0	–	–	–	–
Blaney-Criddle	+	0	0	0	–	–
Olivier's	+	–	+	+	–	–
Radiation	+	+	0	0	(+)	–
Penman	+	+	+	+	(+)	–
Pan evaporation	–	–	0	0	–	+

+ = measured data
(+)= if available, but not essential
0 = estimated data
– = not necessary

(iii) Irrigation practice must be made as efficient as possible. This means retaining soil moisture by regulating the irrigation intervals as well as the corresponding amounts of irrigation water, according to optimal conditions for the plant's specific water requirement. The results of theoretical calculations of plant water requirement can be utilized as a guideline to the amount of water required by the plant during a certain period of time. This data can be used for irrigation methods which do not allow precise control of irrigation water needs in specific detailed conditions. With surface irrigation practices like furrow, basin, border or corrugation irrigation, a minimum amount of water is always required in order to keep the water moving from the water intake to the end of the field.

With pressure irrigation systems (sprinkler or drip irrigation), the conduction of small amounts of water to the plant is possible. However, mainly with drip irrigation, where the soil moisture is limited to small wetted areas produced by the emitters, the determination of the optimum water, e.g. moisture content in the soil, is not possible without micro-instrumentation. Given the possibility of adding a precise amount of water by having the technology for absolute control of the irrigation water, application to the plant through permanent watering, the essential problem is to know the actual moisture conditions in the soil around the plant roots. With sophisticated technology for precise water application the following devices for measuring of the actual soil moisture to determine the quantity of irrigation water and the irrigation cycles are used by laboratories or at farm level.

Soil moisture determination:

- Pan evaporation

  As stated earlier, pan evaporation may be used to predict the crop water requirement. However, to determine the correlation between evaporation from crop and pan, experimental values called 'crop co-efficients' (ratio of crop water use to pan evaporation) have to be used. These values are published in the literature (for example see references 1.5 and 3.4). Pan evaporation operations (estimation of the water losses in the soil by evapo-transpiration) may therefore not only be used to predict crop water requirement for a total growth period but also as an operate of determining the water quantity per irrigation cycle as well as the irrigation intervals. It may also give reasonable quality data about the amount of irrigation water which should be replaced. Pan evaporation operations may be used to provide reference data for all irrigation methods. However, specific conversion factors must be adapted according to the growing stage and type of crop and to the irrigation method used.

- Atometer

  The atometer contains a porous surface connected to unlimited water supply from which evaporation occurs. This instrument may be used as standard of reference for evapo-transpiration like the pan evaporation method.

- Lysimeter

  The lysimeter is a large container of soil, set in a natural surrounding with the least possible discontinuity between the crop on the lysimeter and the surrounding field. This method of measuring the components of the water balance is one of the most direct ways.

Lysimeters are constructed in three forms:

- 'weighing' lysimeter, where the water losses by evapo-transpiration are found in weight between water applications.
- The 'non-weighing' lysimeter determines the soil moisture storage capacity by measuring the difference of the water intake and outflow.
- 'water table' lysimeter, where the crop water use is measured by maintaining a water table at a constant depth below soil surface.

The weighing lysimeter can be used where a short term measurement of evapo-transpiration is required, e.g. for monitoring pressure irrigation systems.

The use of non-weighing or water table lysimeters allows weekly measurements. They can be used to give data for surface irrigation practices.

The construction of lysimeters is expensive and their handling and maintenance very complicated. Therefore, lysimeters are mainly used for laboratory or research works.

- Gravimetric analysis

The moisture content of the soil can be determined by weighing a soil sample, drying it in an oven at 105 ^{o}C and weighing it again. This method is laborious and liable to errors if non representative samples are taken. The use of this analysis is mostly practiced by laboratories.

- Tensiometer

The instrument consists of a ceramic cup, a body tube, a vacuum gauge, and a reservoir. Movement of moisture in and out of the ceramic cup causes tension on the column of water in the tube which is shown on the dial of the gauge. The tensiometer measures the soil moisture condition and not the quantity of the water in the soil. Measurements from 0 to 80 centibars of vacuum are reliable. If soil suction exeeds 80 centibars, air enters through the pores of the cup into the system. The roots of the plant have to develop the same vacuum tension to absorb water as measured by the tensiometer. Because of this function, the tensiometer can also be defined as an 'artificial root'.

With pressure irrigation methods, and especially with drip irrigation, where the soil around the emitters should be kept wet, the tensiometer represents an ideal instrument for irrigation control. Equipped with electrical contacts, the quantity of irrigation water as well as the irrigation intervals can be controlled automatically.

- Porous resistance block

A porous block of gypsum, glass fibre or nylon is moulded around a pair of electrodes which are connected to electrical leads. The moisture content of the block and the variations of the moisture are indicated by the electrical conductivity of the liquid between the electrodes. Installed in the ground, there is an equilibrium between the moisture content in the block and that in the surrounding soil. The range of useful measurement compared with the tensiometer, is from 10 to 150 centibars. The conductivity between the electrodes is also influenced by the mineral (salt) content of the water. As the salt content or concentration increases, the soil water decreases through evapo-transpiration losses, thus measured results can be very inaccurate.

Porous resistance blocks are very useful for measuring the soil moisture, where the chemical impurities in the soil and therefore irrigation water are fairly low.

- Neutron-scattering

With this method, the collision of neutrons from a fast neutron source with nuclei of low atomic weight (hydrogen in the soil moisture) is measured by a detector. Because of the variation of hydrogen contents of salts in the soil moisture, the instrument must be calibrated. Because of variations in salt concentration, the measurement is as inaccurate as by the determination of conductivity in the porous resistance blocks.

Because the equipment is very expensive and the potential human health hazard, this method is almost exclusively practiced by research institutes.

Table 3.4 summarises the different methods of measurement to determine the moisture in the soil, their accuracy, suitability and handling. As shown in the Table, it can be noted that all methods of soil moisture measurement are especially suited for all irrigation methods, with the exception of the tensiometer. As far as field irrigation is concerned the value of the soil moisture represents one of the important basic data. In order to determine the amount of water to be applied as well as for the frequency of irrigation, the farmer should have for his disposal such methods or instruments, which are easy to handle, accurate in measurement with low investment costs and without the need for mathematical conversions of the measured data. As one can see in Table 3.4, the porous resistance block as well as the tensiometer are, even though not ideal, the most suitable to be used by farmers; these are followed by pan evaporation and atometer.

The gravimetric analysis, lysimeter and neutron-scattering are essentially methods, suitable for handling by specialized staff on large irrigation schemes or laboratories.

Table 3.4 : Comparison between the different direct and indirect methods for the determination of the actual soil moisture.

method	accuracy	suitability for	handling	remarks
pan evaporation and atometer	moderate	all irrigation methods	easy	indirect method; measurement must be converted; low investment
lysimeter	high	all irrigation methods	compli-cated	direct method; high investment and complicated maintenance
gravimetric analysis	high	all irrigation methods	laborious	direct method; requires high accuracy
tensiometer	high	all irrigation methods where the soil can be kept wet	easy to moderate complicat.	direct method; low investment; requires frequent maintenance
porous resistance block	moderate	all irrigation methods	easy	direct method; salt sensitive measurement; low investment; negligible maintenance
neutron-scattering	high	all irrigation methods	compli-cate	direct method; health hazard; salt sensitive; very high investment; high maintenance required

Data for different water consumption by furrow, basin and drip irrigation in relation to theoretical water requirements, calculated according to the 'Blaney-Criddle' formula in the cultivation of apple trees, globe artichokes and in a vineyard were obtained by the author in 1973 in Murcia, South East of Spain. The corresponding climatic data are shown in Table 2.2. Soil and water characteristics of the trial area are explained in Chapter 2.5. The results of the trials are presented in Figures 3.3, 3.4 and 3.5 which can be explained as follows:

Figure 3.3; The irrigation period of globe artichokes is limited from July to October. The cultivated area is kept dry till July. The growing season starts with irrigation in July and stops during the harvest time between November and January. Because of winter precipitation, irrigation during the harvest time is not necessary.

Figure 3.4; The period of irrigation (basin) in vineyards starts in January to produce a reservoir of moisture in the soil for flowering and ends in September before harvesting.

Figure 3.5; Because of the high salt sensitivity of apple trees, irrigation by border strips, as mentioned before, was not possible as 1 l of irrigation water contained nearly 1 gram CaCl. Irrigation under these conditions was only possible by maintaining a constant soil moisture by drip irrigation, thus stabilizing the salt concentrate in the soil water.

The drip irrigation system used in these trials was monitored automatically by tensiometers whereby the soil moisture around the emitters never fell below 90% field capacity at a soil suction pressure of 15 to 20 centibars of vacuum.

Because of scorching of the plant leaves by precipitation of salts by evaporation, sprinkler irrigation could not be used. Since by sprinkler irrigation the entire soil surface will be wetted, the level of the water consumption can be estimated as the same or even higher than used by the furrow and basin irrigation method.

Even at this stage, some preliminary evaluation conclusion can be drawn although comparison between irrigation methods on the basis of other than water requirements and supply is deferred to Chapter 4. First, the sprinkler method was disqualified under these climatic and water quality conditions because of leaf scorching. Secondly, since apples are a salt sensitive crop, basin irrigation with its tendency to concentrate surface-salinity had to be avoided. Thirdly, the 'Blaney-Criddle' formula in each case indicated the main water requirement seasonal regime. Lastly, in the vineyard and with the globe artichokes, drip irrigation represented a considerable saving of utilized water over alternate methods and gave similar yields. However, as we shall see later, other factors than soil water demand and supply also have to be considered.

Figure 3.3 : Water consumption of globe artichokes under furrow and drip irrigation in relation to theoretical water requirement.

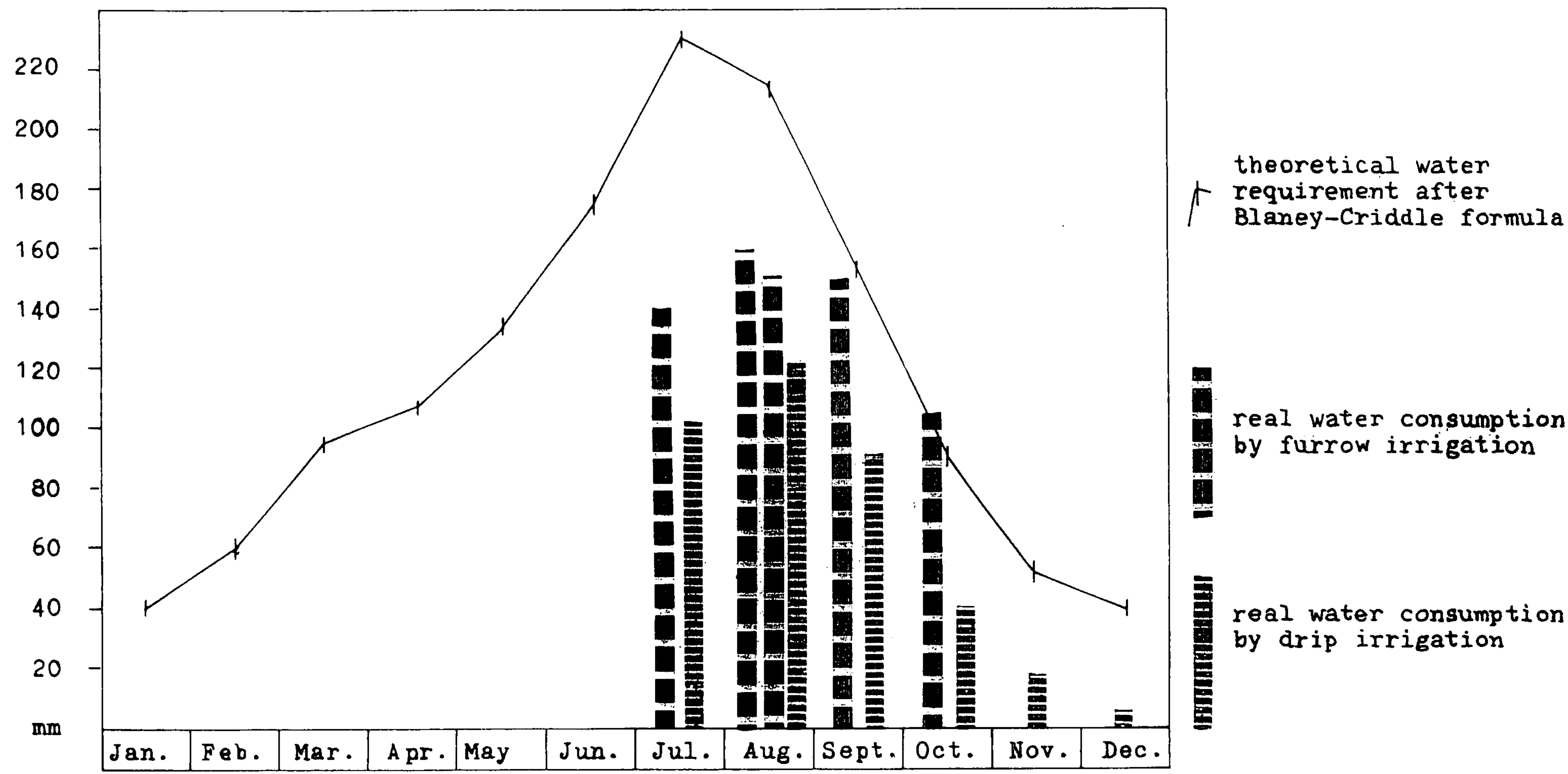


Figure 3.4 : Water consumption of a vine-yard, 8 years old, under basin and drip irrigation in relation to theoretical water requirement.

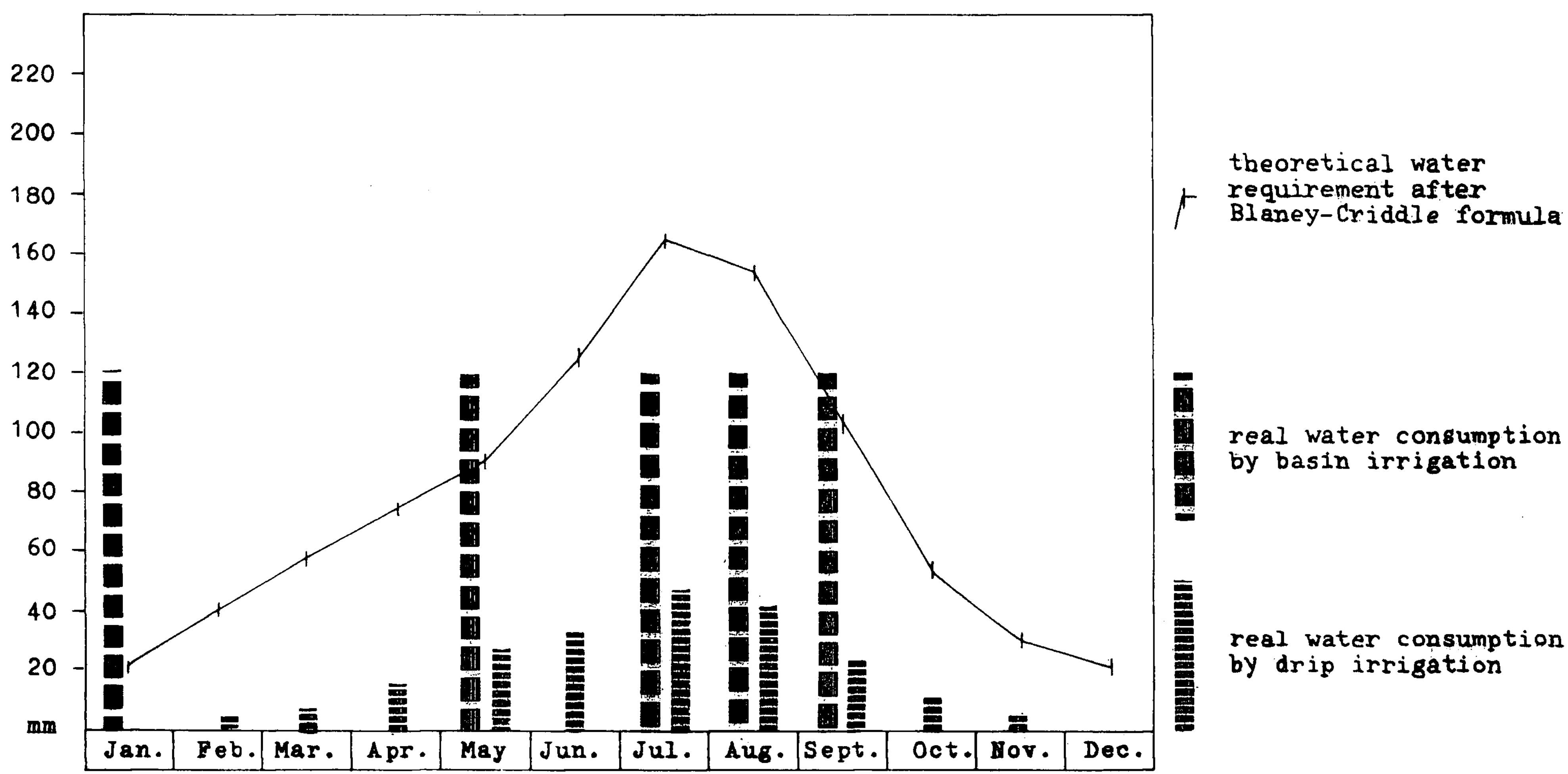
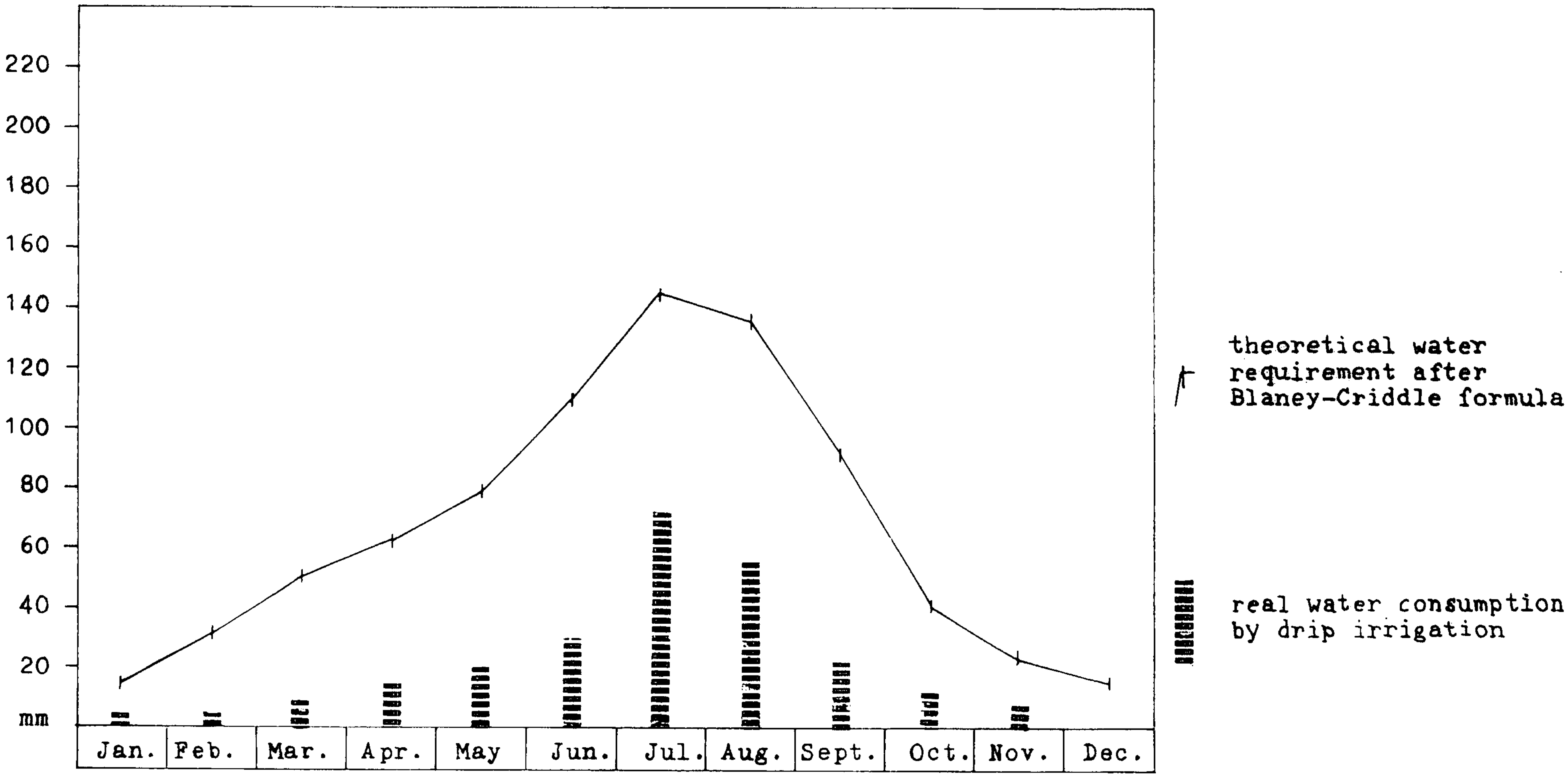


Figure 3.5 : Water consumption of apple trees, 3 years old, under drip irrigation in relation to theoretical water requirement.



3.5 ENERGY

For irrigation, energy other than gravity is required for:

- water lifting from
  - the ground-water table to the earths surface
  - any water sources into canals
  - canals to the level of the irrigated plots
- water distribution over the irrigated area by
  - sprinkler irrigation
  - drip irrigation
- monitoring of irrigation systems by
  - tensiometer
  - porous resistance block
  - other electrical devices such as electric sensors

In most cases of surface and subsurface irrigation, the irrigation water has to be artificially elevated from the natural water table to a level wherefrom the intake into the irrigated plot is possible. Exceptions appear if the water sources are located higher than the irrigated areas. The water elevation can only be realized by an input of power, the sources of which can be classified as:

- human power
- animal power
- electricity
- solid fuel powered machines
- wind
- water
- sun

The use of human and animal power for water elevation is common in traditional irrigated areas, e.g. in Africa and Asia on small irrigation extensions of about 3 ha per family involving a water elevation of between 2 m and 10 m in height. Water elevations in large quantities and over considerable heights is only possible with the use of fuels or electrical energy. Irrigation schemes are therefore dependent on the availability of power sources.

Because of the increased costs of fuel and electrical energy the use of water pumps driven by wind or sun are making a comeback. The practical utilization of this power sources is still limited because of the small outputs.

By surface irrigation, the water distribution over the field is realized by gravity using the characteristic slope of the soil surface.

For water distribution by pressure irrigation systems the water has to be delivered through pipes by an overpressure of about 1 atm by drip irrigation, between 3 to 10 atm by sprinkler irrigation. In the absence of fuel or electric energy, except in conditions where geodetic gravity can be utilized, these pressures cannot be reached by other power sources such as human, animal, wind or solar power. However, as a result of the low pressure requirement of 1 atm by drip irrigation and, in relation to other irrigation methods, its high irrigation efficiency, drip irrigation represents the most energy economic irrigation method.

The monitoring of irrigation of soil moisture by, e.g. tensiometers or porous resistance blocks, connected to selenoid valves, requires electrical energy in the field, but in this case, also batteries can be used. Irrigation systems, controlled by water metric valves usually use the flow volume and the pressure energy of the irrigation water itself. Here, the requirement amount of water flow has to be pre-selected by hand.

Table 3.5 shows the different main sources of energy and their application for irrigation. Further, it can be observed that for water lifting by human and animal power, a quite number of different traditional devices exist. They are exclusively used for irrigating small individual extensions of a size of seldom more than 5 ha per family, as has been personally observed in Egypt and Morocco. In pressure irrigation, the energy demanded for water lifting as well as for producing overpressure for the water distribution through pipe systems, has to be met by fuel or electricity. The utilization of the so called renewable energies like sun, wind and water are until now mainly in the stages of technical probation (except the transformation of water power to electricity).

Table 3.5 : Different sources of energy and their application for irrigation.

source of energy	field of application		
	water lifting	water distribution	irrigation control
human power	scoop, doon, swing bascet counterpoise lift, archimedean screw, paddle well, chain pump	conducting the water flow over the field	-
animal power	rope- and bucket lift, persian wheel, sakia, zawafa, baldeo, balti	-	-
electricity	all pump types	by sprinkler or drip irrigation	by electrical sensors or devices
fuel	all pump types	by sprinkler or drip irrigation	-
wind	windmill, wind motor	-	-
water	water wheel, hydraulic ram	-	-
sun	solar driven pumps		

3.6 ECONOMIC ASPECTS

The output of an irrigated area consists in the quantity of the produced crops and their marketable value. This output has to be set against the different factors of input as stated in Chapter 2. As far as economic viability is concerned, the cost of input has to be kept as low as possible, whilst, the costs of output as high as possible.

Because of continuous shifts in the costs of inputs as well as in the market prices, the maintenance of a margin of rentability depends on the flexibility of adaptation to changing price levels of input and output factors by the use of adapted methods of production technologies. Assuming static conditions of natural production factors like soil fertility, availability of irrigation water and climate, the main factors causing a decrease of rentability are:

- lack of labour with the consequence of exploding labour costs
- increase of energy costs such as fuel and electricity
- decrease of market prices for the produced goods with consequential need to alterate the kind of crop,

  or,

  to reach higher yields,

  or,

  to extend the irrigated area.

These circumstances may require alterations in the irrigation techniques used on existing irrigated areas and have to be taken into account in the planning of new irrigated areas.

By increasing the labour costs, one has to calculate the costs required to substitute labour by technical devices such as sprinkler or drip irrigation. As one example in Table 3.6, a calculation of labour substitution of surface irrigation by sprinkler and drip irrigation is based on data given in Tables 2.3 to 2.8. Table 3.6 shows that, in comparison with surface irrigation, sprinkler irrigation results as more expensive than drip irrigation in this aspect of labour substitution by technical devices.

According to Tables 2.6 and 2.8, the expenses for electrical energy required for water distribution per ha and year are, for drip irrigation about 60% lower than for sprinkler irrigation. This difference is based on the lower water pressure required by drip irrigation and on the difference of 15% to 20% less water required than for sprinkler irrigation.[3.6]

As a consequence of the differences in the water effectivities between the irrigation methods, different areas can be irrigated using the same amount of water. As shown in Figure 2.1, the water effectivity on the irrigated area ($e_{3/3}$) for surface irrigation can be assessed at 50%; for sprinkler irrigation by 75% and for drip and subsurface irrigation by 90%, e.g. with the same amount of water as required for one ha of surface irrigation, one can irrigate 1.5 ha by sprinkler irrigation and 1.8 ha by drip or subsurface irrigation.

Table 3.6 indicates the choice between irrigation systems on these economic grounds alone. Nevertheless,

Table 3.6 : Fixed and variable costs, and man hour substitution cost per ha and year for sprinkler and drip irrigation, in comparison with surface irrigation for different crops.

c r o p	fixed and variable costs £ per year		difference (a)	man hours for irrigat.and irrig. specific cult.work		difference (b)	substitution cost per man hour/year (a + b) £
	surface irrigation	sprinkler irrigation		surface irrigation	sprinkler irrigation		
citrus fruits	667.-	759.-	- 92	60	46	+ 14	- 6.6
melons	886.-	1,014.-	-128	80	64	+ 16	- 8.0
greenhouse	2,370.-	2,374.-	- 4	240	112	+ 128	- 0.03
	surface irrigation	drip irrigation		surface irrigation	drip irrigation		
citrus fruits	667.-	424.-	+ 243	60	7	+ 53	+ 4.6
melons	886.-	722.-	+ 164	80	26	+ 54	+ 3.0
greenhouse	2,370.-	1,830.-	+ 540	240	60	+ 180	+ 3.0

Data source: Tables 2.3 to 2.8

there is also dependence on factors mentioned earlier, availability of capital, opportunity costs, relationship between theoretical returns realistically in terms of technology and organisational requirements.

3.7 MANAGEMENT, LABOUR AND AGROTECHNOLOGICAL REQUIREMENTS

Each irrigation method applied requires, for its successful operation and maintenance, a specific know-how in terms of skilled management and labour as well as agrotechnologies adapted to the specific irrigation methods.

The management necessary to establish and maintain an irrigated area can be classified as follows:

Management organization of large sized irrigation schemes ranging from government operated irrigation schemes to private farmer co-operatives with the duty to administer the available water sources including their distribution and quantification up to field level and to advise farmers in the construction and maintenance of irrigation and drainage systems. Furthermore, the duties of such a management may include advisory work in agrotechnology, for example in applying fertilizer and weed/pest control. Also, the establishment of credits to farmers and marketing organisations may be supervised by such managements. Last but not least, in most of the cases, 'on the job' training and practical demonstrations for farmers and personnel has to be arranged by the administrative organisations. As great as are the advantages of such centralized organisation and administration bodies in terms of applying modern know-how, economic power and maintaining policy objectives are, equally great, are the risks for the farmers if wrong decisions or failures by the responsible organisations, inevitably associated with political interests, occur.

On the other hand we find the particular management of private controlled farms, where the farmer himself has to implement his own decisions. Here, less sophisticated know-how can be observed. Nevertheless, because working for himself and at his own loss, the decisions are mostly well based on experience and on specific known economic possibilities. The demand for information and technical know-how in such cases has to be supplied in most countries by the agricultural extension services.

Generally, the management of irrigated agriculture has to be able to co-ordinate the irrigation practices with the crop production techniques to minimise the inputs and to optimise the returns. This includes not only optimising the effectivity of the plant production factor 'water' but also the relevant production factors, as for example improvement of crop rotation, use of selected seed, pest and weed control, use of machinery as well as the marketing of the produced goods. In other words, returns on investment in the relatively expensive irrigation constructions and equipment can only be assured by optimising all production factors to get optimum yields in terms of quality and quantity. Here, the engineering operations have to be integrated with agricultural practices. For example, with basin irrigation the use of machinery for soil preparation, cultivation operations and harvesting is restricted by ridges which surround the irrigation plot. Most of the work has to be realized by hand, animal or by small powered machinery. If two or three crop rotations per year are required, field preparation which use small powered machinery or animals normally take too much time. In corrugation irrigation, all cultivation and harvesting operations can be fully mechanized, including the construction of the corrugation rills. In furrow irrigations, as the length of the furrows depends on the topography and soil conditions (see Chapter 1.1.5), the effectivity of machinery is often restricted by wasted time for turn round if the length of the furrows cannot be extended over 100 m. In sprinkler irrigation, usually no restrictions in terms of cultivation techniques are given because mobile and semi-fixed systems are moved from the irrigated plot after use. Fixed systems, mostly installed in orchards and vegetables, are installed about 2 m over the earth's surface. In drip irrigation, applied in orchards, soil preparation, for example by rotavators, is only possible parallel to the emitter pipes because the pipes cannot be crossed. Weeds, growing around the emitters must be controlled by hand or by herbicides. In this connection, personal trials found that these weeds can be replaced by growing leguminosa in the area wetted by the emitters with the side effect of nitrogen production and improvement of the soil structure. Applying drip irrigation in vegetables, no furrows (usually needed for growing vegetables) should be constructed. By 'even earth' cultivation, one emitter line can normally be used to irrigate a double row.

The labour situation in terms of quantity of personnel available represent a dominant factor in maintaining all kinds of surface irrigation methods. Here, labour is usually required for water distributing over the field and for earth moving work. In pressure irrigation, the quality and the technical know-how of the operators is essential for operating and maintaining the systems. If pressure irrigation equipments are operated by untrained personnel, as seen in Egypt, the break down occurs of the whole system in a short period of time.

The availability of spare parts for the irrigation equipment represents, besides the above mentioned operations and maintenances, a critical factor for nearly all irrigation systems. In surface irrigation systems (except run-off irrigation) the water usually has to be elevated by fuel or electric powered pumps from the water source up to the field level. Spare parts for the water pumps should be available to guarantee a quick repair in the irrigation season.

With pressure irrigation systems, the equipment for water distribution is connected to the pumps. In this case, spare parts for the distribution equipment as well as for the water pumps should be at the virtually immediate disposal of the farmer. If continuous watering is practised, for example in drip irrigation, repairs must be realized in two or three days. As in drip irrigation the water in the soil is only concentrated around the emitters, the absolute amount of water in the soil available for the plants is very limited and therefore consumed by the plants in about two or three days or less. In addition, by the use of saline water or in saline soil conditions, the salt concentration in the water around the root zone will rise to plant toxic concentration level if the delivery of water stops over a long time period, whilst, respectively the moisture concentration in the root zone of the soil decreases (see also Chapter 3.2). Since in surface irrigation as well as in mobile and semi-fixed sprinkler irrigation, the time between the irrigation cycles are 8 to 15 days, a longer time period needed for repair work can be tolerated than with drip irrigation where a daily watering is practised. Therefore, spare parts for drip irrigation should be stored in advance by the users; including the water pump which feeds the systems. Countries where the irrigation equipment has to be imported, spare parts shortages can produce serious operation problems.

The following Figures 3.6 to 3.13 give a simplified overview of the interrelationship of various conditions with specific irrigation methods, as treated in this thesis, including some which have not been previously considered. The status of these conditions in relation to requirements is judged by their suitability for construction and maintenance and demonstrated as matrixes.

That is:

- − = no influence
- / = not required or normally not existing
- + = required/typical or favourable condition
- (+) = critical condition
- Y = high demand of investment for the given condition
- X = restrictive condition/impeding the construction or operation of the respective irrigation method
- ∅ = other irrigation method normally used
- 0 = not direct interrelated

Referring Fig. 3.9 (basin irrigation), an example is given below for each case:

- The condition 'water impurity' has no influence '-' to the different requirements of basin irrigation.
- The condition 'advanced agrotechnology' is even 'not required' or in this case 'normally not existing' in connection with the requirement 'low level management', therefore '/'
- 'Required/typical or favourable conditions' for basin irrigation are, e.g. 'arid climate' together with the requirement 'unlimited water quantity', therefore '+'
- The condition 'moderate agrotechnology' compared with 'limited water quantity' represents '(+)' as indicating a critical condition.
- If 'drainage' of the soil is inhibited, 'Y' stands for high demand of investment in this case melioration operation.

- 'X' stands for restrictive conditions which are impeding the construction or operation of the irrigation method, such as the condition 'limited water quantity' compared with the requirement of 'high plant water demand'.
- By the condition 'humid climate', compared with 'limited or moderate water quantity', where supplementary irrigation is required, basin irrigation will normally not be applied. Therefore, 'Ø' stands to indicate that in this case other irrigation methods with less investment costs in construction and maintenance should be utilized.
- As the condition 'water salinity' cannot directly interrelated to the requirement 'topography', therefore 'O'

Figure 3.14 also shows as a summation of the Figures 3.6 to 3.13, the interdependance of the various field irrigation methods with the different main conditions, as treated in this Chapter as well as in the introduction. This Figure may be utilized later in the thesis as basic data for the comparison of different irrigation methods, where they will be used as generalised Figures displaying the principles which can be established from the absolute data given earlier.

Figure 3.6 :

Run-off irrigation

(Ref.:Nomenclature)

CONDITION		REQUIREMENT: Climate arid semi arid humid	Water quantity limited moderate unlimited	Water salinity low moderate high	Water impurity low moderate high	Topography - slope - even slight moderate steep	Soil fine medium coarse	Drainage -permeability- high moderate inhibited	Plant water demand high moderate low	Energy for water distribut. available limited restricted	Capital available limited restricted	Management trained moderate low level	Labour available restricted	Labour trained moderate low level	Agro-technology advanced moderate low level	Spare parts available limited restricted
Climate	arid semi arid humid		+ØØ +ØØ ØØØ	/	–	X+++ X+++ ØØØØ	++(+) ++(+) ØØØ	(+)++ (+)++ ØØØ	X(+)+ X(+)+ ØØØ	–	O	++(+) +++ ///	+(+) +(+) //	++(+) ++(+) ///	++(+) ++(+) ///	O
Water quantity	limited moderate unlimited	O		/	–	X+++ X+++ ////	+(+)X +(+)X ///	X(+)+ X(+)+ ///	XX+ X(+)+ ///	–	O	++X ++X ///	+(+) +(+) //	++X ++(+) ///	+++ +++ ///	O
Water salinity	low moderate high	/	/		/	/	/	/	/	/	/	/	/	/	/	/
Water impurity	low moderate high	–	–	/		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	O	XØØ +ØØ +ØØ +ØØ	/	–		ØØØ +(+)X ++X ++X	ØØØ X(+)+ X++ X++	O	–	ØØØ +++ +++ +++	ØØØ ++(+) +++ ++(+)	// +(+) ++ ++	/// ++(+) +++ ++(+)	+++ +++ ++(+)	O
Soil	fine medium coarse	O	++Ø (+)+Ø X(+)Ø	/	–	X+++ X(+)++ XX(+)(+)		(+)++ X(+)+ X(+)+	X(+)+ XX+ XX(+)	–	O	+++ +(+)X ///	O	O	++(+) ++X	O
Drainage -permeability-	high moderate inhibited	O	O	/	–	XXX(+) X(+)(+)+ X+++	(+)XX +++ ++(+)		O	–	O	+(+)X ++(+) +++	+X +(+) +X	+(+)X ++(+) +++	+(+)X ++(+) +++	O
Plant water demand	high moderate low	O	X// (+)// +//	/	–	O	ØØØ (+)XX ++X	XXX X(+)(+) (+)++		–	O	+XX ++(+) +++	+X +(+) ++	+XX +(+)(+) +++	+(+)X +(+)X ++(+)	O
Energy for water distribut.	available limited restricted	–	–	/	–	–	–	–	–		–	–	–	–	O	O
Capital	available limited restricted	O	O	/	–	O	O	O	O	–		+++ ++(+) (+)(+)X	++ +(+) +X	+++ +++ (+)(+)X	+++ ++(+) (+)(+)(+)	O
Management	trained moderate low level	O	+// +// (+)//	/	–	X+++ X(+)++ XX(+)+	++(+) +(+)X +(+)X	(+)++ (+)++ X(+)(+)	(+)++ X(+)+ XX+	–	O		++ ++ +(+)	+++ +++ +(+)(+)	+++ ++(+) (+)(+)(+)	O
Labour	available restricted	–	–	/	–	X+++ X+++	–	–	/++ /(+)+	–	O	O		O	O	O
	trained moderate low level	O	O	/	–	X+++ X(+)++ X(+)++	O	O	/++ /(+)+ /(+)(+)	O	O	O			+++ (+)++ X(+)+	O
Agro-technology	advanced moderate low level	O	+// +// (+)//	/	–	X+++ X(+)++ X(+)++	O	X(+)+ X(+)+ XX+	X++ X(+)+ X(+)+	–	O	+// ++/ //(+)	++ +(+) +X	++(+) ++(+) ++(+)		O
Spare parts	available limited restricted	–	O	/	–	–	–	–	–	–	O	O	–	–	O	

Figure 3.7 : Wild flooding irrigation
(Ref.:Nomenclature)

CONDITION \ REQUIREMENT		Climate	Water quantity	Water salinity	Water impurity	Topography - slope -	Soil	Drainage -permeability-	Plant water demand	Energy for water distribut.	Capital	Management	Labour		Agro-technology	Spare parts
		arid semi arid humid	limited moderate unlimited	low moderate high	low moderate high	even slight moderate steep	fine medium coarse	high moderate inhibited	high moderate low	available limited restricted	available limited restricted	trained moderate low level	available restricted	trained moderate low level	advanced moderate low level	available limited restricted
Climate	arid semi arid humid		X(+)+ X(+)+ X++	+(+)X ++X + //	–	X+++ X+++ X+++	(+)++ (+)++ (+)++	++X ++X ++X	X(+)+ X(+)+ X++	–	0	++(+) +++ +++	+(+) +(+) +(+)	++(+) +++ +++	++(+) +++ +++	0
Water quantity	limited moderate unlimited	0		+(+)X +(+)X ++X	–	X(+)++ X(+)++ X+++	X(+)+ (+)++ (+)++	++(+) ++(+) ++(+)	X(+)+ X(+)+ (+)++	–	0	+(+)X +(+)X +++	0	++(+) +++ +++	+(+)(+) ++(+) +++	0
Water salinity	low moderate high	0	+++ (+)++ X(+)+		–	0	0	++(+) +(+)(+) +XX	+++ (+)(+)+ XX+	–	0	+++ +(+)X +(+)X	0	+++ ++(+) +(+)X	+++ +(+)(+) +XX	0
Water impurity	low moderate high	–	–	–		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	0	(+)(+)+ +++ +++ (+)++	0	–		ØØØ ++(+) +++ (+)++	ØØØ ++(+) ++X +(+)X	0	–	ØØØ +++ +++ +++	ØØØ +++ +++ ++(+)	ØX +(+) ++ ++	Ø(+)X ++(+) +++ ++(+)	Ø(+)X ++(+) +++ +++	0
Soil	fine medium coarse	0	+++ (+)++ X(+)+	0	–	X++(+) X++(+) X(+)++		++(+) ++(+) ++(+)	X++ X(+)+ X(+)+	–	0	++(+) +++ +++	0	0	++(+) +++ +++	0
Drainage -permeabi-lity-	high moderate inhibited	0	(+)++ (+)++ (+)(+)(+)	+++ +(+)X (+)XX	–	X(+)++ (+)+(+)(+) ++(+)X	+++ (+)++ X(+)(+)		0	–	+++ ++(+) +(+)X	+++ ++(+) +(+)X	0	0	+++ ++(+) +(+)X	0
Plant water demand	high moderate low	0	X(+)+ X(+)+ +++	+(+)X +(+)X +(+)X	–	0	+(+)X ++(+) +++	0		–	0	+XX ++(+) +++	+(+) ++ ++	+(+)X ++(+) +++	+(+)X ++(+) +++	0
Energy for water distribut.	available limited restricted	–	–	–	–	–	–	–	–		–	–	–	–	0	0
Capital	available limited restricted	0	0	0	–	Ø+++ X+++ X+++	0	++(+) ++(+) ++X	0	–		+++ ++(+) (+)(+)X	++ +(+) +X	+++ +++ (+)(+)X	+++ (+)+(+) X(+)(+)	0
Management	trained moderate low level	0	+++ (+)(+)+ XX+	+++ ++(+) +(+)X	–	(+)+++ X+++ X++(+)	+++ (+)++ (+)++	++(+) ++(+) +(+)X	+++ (+)++ X(+)+	–	0		++ ++ +(+)	+++ +++ +(+)(+)	+++ ++(+) (+)(+)(+)	0
Labour	available restricted	–	–	–	–	(+)++ X++(+)	–	–	+++ (+)(+)+	–	0	0		0	0	0
	trained moderate low level	0	+++ (+)++ X(+)+	0	–	X+++ X+++ X++(+)	0	0	+++ (+)++ (+)(+)+	0	0	0	0		+++ (+)++ X(+)(+)	0
Agro-technology	advanced moderate low level	0	+++ (+)++ X(+)+	+++ ++(+) +(+)X	–	X+++ X+++ X++(+)	0	++(+) ++(+) +(+)X	+++ (+)(+)+ X(+)+	–	0	+// +// //+	++ +(+) +X	++(+) ++(+) ++(+)		0
Spare parts	available limited restricted	–	0	–	–	–	–	–	–	–	0	0	–	–	0	

Figure 3.8 : Border irrigation

(Ref.:Nomenclature)

CONDITION	REQUIREMENT	Climate arid semi arid humid	Water quantity limited moderate unlimited	Water salinity low moderate high	Water impurity low moderate high	Topography - slope - even slight moderate steep	Soil fine medium coarse	Drainage -permeability- high moderate inhibited	Plant water demand high moderate low	Energy for water distribut. available limited restricted	Capital available limited restricted	Management trained moderate low level	Labour available restricted	Labour trained moderate low level	Agro-technology advanced moderate low level	Spare parts available limited restricted
Climate	arid semi arid humid		X (+) + (+) + + ø ø ø	+ (+) X + + (+) + / /	–	(+) + + y (+) + + y (+) + + y	+ + (+) + + (+) + + (+)	(+) + (+) + + (+) + + +	(+) + + (+) + + + + +	–	O	+ + (+) + + (+) + + +	+ (+) + (+) + +	+ (+) (+) + + (+) + + +	+ (+) (+) + + (+) + + +	+ + (+) + + (+) + + +
Water quantity	limited moderate unlimited	O		+ (+) X + + (+) + + +	–	(+) + + (+) (+) + + y + + + (+)	+ + (+) + + (+) + + +	(+) + (+) + + (+) + + y	X (+) + (+) + + + + +	–	O	+ (+) X + + (+) + + +	O	+ (+) X + + (+) + + +	+ (+) X + + (+) + + +	O
Water salinity	low moderate high	O	+ + + (+) + + X X (+)		–	O	O	+ + (+) + + (+) + (+) X	+ + + (+) + + X (+) +	–	O	+ + + + + (+) + (+) X	O	+ + + + + (+) + (+) X	+ + + + + (+) + (+) X	O
Water impurity	low moderate high	–	–	–		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	O	(+) (+) + + + + + + + (+) y y	O	–		+ (+) X + + (+) + + + (+) + +	(+) + (+) + + y + + y (+) (+) X	O	–	+ + (+) + + + + + (+) + (+) X	+ (+) (+) + + + + + + + (+) X	+ (+) + + + + + (+)	+ + (+) + + + + + + + (+) X	+ (+) X + + + + + + + (+) X	O
Soil	fine medium coarse	O	+ + + + + + X (+) +	O	–	+ + + y (+) + + (+) X + + (+)		+ + y + + (+) (+) + (+)	+ + + + + + (+) + +	–	O	+ + (+) + + + + + (+)	O	O	+ + (+) + + + + + (+)	O
Drainage -permeability-	high moderate inhibited	O	(+) + + + + + (+) (+) (+)	+ + + + (+) X (+) (+) X	–	(+) + + + + + + y (+) (+) (+) X	+ + (+) + + + y y y		O	–	+ + + + + + + (+) X	+ + (+) + + + + (+) X	O	O	+ + (+) + + + + (+) X	O
Plant water demand	high moderate low	O	X (+) + X + + + + +	+ (+) X + + (+) + + +	–	O	+ + (+) + + (+) + + +	O		–	O	+ (+) X + + (+) + + +	+ (+) + (+) + +	+ + (+) + + (+) + + +	+ (+) X + + (+) + + +	O
Energy for water distribut.	available limited restricted	–	–	–	–	–	–	–	–		–	–	–	–	O	O
Capital	available limited restricted	O	O	O	–	+ + + + (+) + + (+) X + + X	O	+ + + + + (+) (+) + X	O	–		+ + + + + (+) (+) (+) X	+ + + (+) + (+)	+ + + + + (+) + (+) X	+ + + + + + (+) X X	O
Management	trained moderate low level	O	+ + + (+) + + X (+) +	+ + + + + (+) + (+) X	–	+ + + + (+) + + (+) X + + X	+ + + + + (+) + + (+)	+ + + + + (+) (+) + X	+ + + (+) + + (+) (+) +	–	O		+ + + (+) + X	+ + + + + (+) + (+) X	+ + + + + (+) (+) (+) (+)	O
Labour	available restricted	–	–	–	–	+ + + + (+) + + (+)	–	–	+ + + X (+) +	–	O	O		O	O	O
	trained moderate low level	–	+ + + (+) + + X (+) +	O	–	+ + + (+) (+) + + (+) (+) + + X	O	O	+ + + (+) + + X (+) +	O	O	O	O		+ + + (+) + + X (+) (+)	O
Agro-technology	advanced moderate low level	O	+ + + (+) (+) + X (+) +	+ + + + + (+) + (+) X	–	+ + + + (+) + + (+) (+) + + X	O	+ + + (+) + (+) (+) + X	+ + + (+) + + X (+) +	–	O	+ / / + + / / / (+)	+ + + (+) + X	+ + X + + (+) + + (+)		O
Spare parts	available limited restricted	–	O	–	–	–	–	–	–	–	O	O	–	–	O	

Figure 3.9 :

Basin irrigation

(Ref.:Nomenclature)

CONDITION ↓ / REQUIREMENT →		Climate	Water quantity	Water salinity	Water impurity	Topography - slope -	Soil	Drainage -permeabi-lity-	Plant water demand	Energy for water distribut.	Capital	Management	Labour		Agro-technology	Spare parts
		arid semi arid humid	limited moderate unlimited	low moderate high	low moderate high	even slight moderate steep	fine medium coarse	high moderate inhibited	high moderate low	available limited restricted	available limited restricted	trained moderate low level	available restricted	trained moderate low level	advanced moderate low level	available limited restricted
Climate	arid semi arid humid		X(+)+ (+)++ ØØ+	+(+)X ++X +//	–	+(+)yy +(+)yy +(+)yy	+(+)Ø +(+)Ø ++Ø	(+)+(+) (+)+(+) (+)+(+)	+++ +++ +++	–	0	++(+) ++(+) +++	+(+) +(+) ++	+(+)X ++(+) +++	+(+)(+) ++(+) +++	++(+) ++(+) +++
Water quantity	limited moderate unlimited	0		+(+)X ++(+) ++(+)	–	+(+)yX ++(+)X ++(+)(+)	+(+)X ++Ø ++Ø	(+)+(+) ++(+) ++(+)	X(+)+ (+)++ +++	–	0	+(+)X ++(+) +++	0	+(+)X ++(+) +++	+(+)X ++(+) +++	0
Water salinity	low moderate high	0	+++ (+)++ XX(+)		–	0	0	++(+) ++(+) +(+)X	+++ X(+)+ XX(+)	–	0	+++ ++(+) +(+)X	0	+++ ++(+) +(+)X	+++ ++(+) +(+)X	0
Water impurity	low moderate high	–	–	–		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	0	+++ +++ X(+)+ Xyy	0	–		++(+) ++(+) +(+)X +XX	+++ (+)++ (+)+(+) X(+)(+)	0	–	++(+) +++ +(+)X +XX	+++ +++ ++(+) +(+)X	++ ++ +(+) +X	+++ +++ ++(+) +(+)X	+++ +++ ++(+) +(+)X	0
Soil	fine medium coarse	0	+++ (+)++ X(+)+	0	–	++yy ++yy (+)(+)XX		++(+) ++(+) (+)+(+)	+++ +++ (+)(+)+	–	0	+++ ++(+) +(+)X	0	0	+++ ++(+) +(+)X	0
Drainage -permeabi-lity-	high moderate inhibited	0	X(+)+ (+)++ (+)(+)+	+++ ++(+) +(+)X	–	(+)++X +++(+) ++(+)(+)	++X ++(+) yyy		0	–	++(+) +++ +(+)(+)	+(+)(+) +++ +(+)(+)	0	0	+(+)X +++ +(+)(+)	0
Plant water demand	high moderate low	0	X(+)+ (+)++ +++	+(+)X ++(+) +++	–	0	+(+)(+) ++(+) +++	0		–	0	+(+)X ++(+) +++	+(+) +(+) ++	++(+) ++(+) +++	+(+)X ++(+) +++	0
Energy for water distribut.	available limited restricted	–	–	–	–	–	–	–	–		–	–	–	–	0	0
Capital	available limited restricted	0	0	0	–	++++ ++(+)X ++XX	0	+++ (+)+(+) (+)+(+)	0	–		+++ ++(+) (+)(+)X	+(+) +(+) +X	+++ ++(+) (+)(+)X	+++ (+)+(+) (+)XX	0
Management	trained moderate low level	0	+++ (+)++ X(+)+	+++ ++(+) +(+)X	–	++++ +++(+) ++(+)X	+++ ++(+) (+)(+)X	+++ ++(+) (+)+(+)	+++ (+)++ X(+)+	–	0		++ +(+) +X	+++ ++(+) +(+)X	+++ ++(+) (+)(+)(+)	0
Labour	available restricted	–	–	–	–	++++ ++(+)X	–	–	+++ (+)++	–	0	0		0	0	0
	trained moderate low level	–	+++ (+)++ X(+)+	0	–	++++ +++(+) ++(+)X	0	0	+++ (+)++ X(+)+	0	0	0	0		+++ (+)++ X(+)(+)	0
Agro-technology	advanced moderate low level	0	+++ (+)(+)+ X(+)+	+++ ++(+) +(+)X	–	++++ +++(+) ++(+)X	0	+++ (+)++ X+(+)	+++ (+)++ X(+)+	–	0	+// ++/ //(+)	++ +(+) +X	+(+)X ++(+) ++(+)		0
Spare parts	available limited restricted	–	0	–	–	–	–	–	–	–	0	0	–	–	0	

Figure 3.10 :

Furrow irrigation

(Ref.:Nomenclature)

CONDITION \ REQUIREMENT		Climate arid semi arid humid	Water quantity limited moderate unlimited	Water salinity low moderate high	Water impurity low moderate high	Topography - slope - even slight moderate steep	Soil fine medium coarse	Drainage -permeabi-lity- high moderate inhibited	Plant water demand high moderate low	Energy for water distribut. available limited restricted	Capital available limited restricted	Management trained moderate low level	Labour available restricted	Labour trained moderate low level	Agro-technology advanced moderate low level	Spare parts available limited restricted
Climate	arid semi arid humid		(+) + + + + + ø ø ø	+ (+) X + +(+) + + /	–	(+) + +(+) (+) + +(+) (+) + +(+)	+ +(+) + +(+) + +(+)	+ +(+) + +(+) + + +	(+) + + + + + + + +	–	0	+ +(+) + +(+) + + +	+(+) +(+) + +	+(+)X + +(+) + + +	+(+)(+) + +(+) + + +	+ +(+) + +(+) + + +
Water quantity	limited moderate unlimited	0		+(+)X + +(+) + +(+)	–	(+) + + y (+) + + y + + +(+)	+ +(+) + +(+) + + +	(+) +(+) + +(+) + +(+)	X(+)+ (+) + + + + +	–	0	+(+)X + +(+) + + +	0	+(+)X + +(+) + + +	+(+)X + +(+) + + +	0
Water salinity	low moderate high	0	+ + + (+) + + X X (+)		–	0	0	+ +(+) + +(+) +(+)X	+ + + (+) + + X(+)+	–	0	+ + + + +(+) + (+)X	0	+ + + + +(+) +(+)X	+ + + + +(+) +(+)X	0
Water impurity	low moderate high	–	–	–		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	0	(+)(+) + + + + + + + (+)(+) +	0	–		+(+)X + +(+) (+) + + X(+)+	(+) + y + +(+) + + X +(+)X	0	–	+ +(+) + + + + +(+) +(+)x	+ +(+) + + + + +(+) + (+)X	+(+) + + + + +(+)	+ +(+) + + + + +(+) +(+)X	+(+)X + + + + + + + (+)X	0
Soil	fine medium coarse	0	+ + + + + + (+)(+)+	0	–	(+) + + y (+) + +(+) X + +(+)		+ + y + +(+) (+) +(+)	+ + + + + + (+)(+)+	–	0	+ +(+) + + + + +(+)	0	0	+ +(+) + + + +(+)(+)	0
Drainage -permeabi-lity-	high moderate inhibited	0	(+) + + + + + (+)(+)(+)	+ + + + +(+) (+) X X	–	+ + + + + + +(+) y(+)X X	+(+)X + + + y y y		0	–	+ + + + + + +(+)X	+ +(+) + + + +(+)X	0	0	+ +(+) + + + +(+)X	0
Plant water demand	high moderate low	0	X(+)+ (+) + + + + +	+(+)X + +(+) + + +	–	0	+ +(+) + +(+) + + +	0		–	0	+(+)X + +(+) + + +	+(+) +(+) + +	+(+)(+) + +(+) + + +	+(+)X + +(+) + + +	0
Energy for water distribut.	available limited restricted	–	–	–	–	–	–	–	–		–	–	–	–	0	0
Capital	available limited restricted	0	0	0	–	+ + + + + + +(+) (+) +(+)X	0	+ + + + +(+) +(+)X	0	–		+ + + + +(+) (+)(+) X	+ + +(+) + X	+ + + + +(+) (+)(+)X	+ + + (+)+(+) (+)X X	0
Management	trained moderate low level	0	+ + + + + + (+) + +	+ + + + +(+) +(+)X	–	+ + + + (+) + +(+) X + + X	+ + + + + + (+) +(+)	+ + + + +(+) (+) + X	+ + + (+) + + X(+)+	–	0		+ + +(+) + X	+ + + + +(+) (+)(+)X	+ + + + +(+) (+)(+)(+)	0
Labour	available restricted	–	–	–	–	+ + + + (+) + + X	–	–	+ + + X(+)+	–	0	0		0	0	0
	trained moderate low level	–	+ + + (+) + + X(+)+	0	–	+ + + + (+) + +(+) (+) + + X	0	0	+ + + (+) + + X(+)+	0	0	0			+ + + (+) + + X(+)(+)	0
Agro-technology	advanced moderate low level	0	+ + + (+) + + X(+)+	+ + + + +(+) +(+)X	–	+ + + + (+) + +(+) (+) + + X	0	+ + + (+) +(+) (+) + X	+ + + (+) + + X(+)+	–	0	+ / / + + / / /(+)	+ + +(+) + X	+(+)X + +(+) + +(+)		0
Spare parts	available limited restricted	–	0	–	–	–	–	–	–	–	0	0	–	–	0	

Figure 3.11 :

Corrugation irrigation

(Ref.:Nomenclature)

CONDITION		REQUIREMENT: Climate	Water quantity	Water salinity	Water impurity	Topography - slope -	Soil	Drainage -permeabi- lity-	Plant water demand	Energy for water distribut.	Capital	Management	Labour		Agro- technology	Spare parts
		arid semi arid humid	limited moderate unlimited	low moderate high	low moderate high	even slight moderate steep	fine medium coarse	high moderate inhibited	high moderate low	available limited restricted	available limited restricted	trained moderate low level	available restricted	trained moderate low level	advanced moderate low level	available limited restricted
Climate	arid semi arid humid		X (+) + (+) + + Ø Ø Ø	+ (+) X + + (+) + / /	-	(+) + + + (+) + + + (+) + + +	+ + (+) + + (+) + + (+)	(+) + (+) (+) + (+) + + +	(+) + + (+) + + + + +	-	0	+ + (+) + + (+) + + +	+ (+) + + + +	+ + (+) + + + + + +	+ + (+) + + (+) + + +	+ + (+) + + (+) + + +
Water quantity	limited moderate unlimited	0		+ (+) X + + (+) + + (+)	-	(+)(+) + + (+) + + + (+) + + +	+ + (+) + + (+) + + (+)	(+) + (+) (+) + (+) + + +	X (+) + (+) + + + + +	-	0	+ (+) X + + (+) + + +	0	+ (+) X + + (+) + + +	+ (+) X + + (+) + + +	0
Water salinity	low moderate high	0	+ + + (+) + + X X (+)		-	0	0	+ + (+) + + (+) + (+) X	+ + + (+) + + X (+) +	-	0	+ + + + + (+) + (+) X	0	+ + + + + (+) + + X	+ + + + + (+) + (+) X	0
Water impurity	low moderate high	-	-	-		-	-	-	-	-	-	-	-	-	-	-
Topography -slope-	even slight moderate steep	0	X (+)(+) (+) + + + + + + + +	0	-		+ (+) X + + (+) + + + (+) + +	(+) + (+) + + (+) + + X + (+) X	0	-	+ (+) X + + + + + + + + +	+ (+) X + + + + + + + + (+)	+ X + (+) + + + +	+ (+) X + + (+) + + + + + (+)	+ (+) X + + (+) + + + + + (+)	0
Soil	fine medium coarse	0	+ + + + + + (+) (+) +	0	-	+ + + (+) (+) + + + (+) + + +		+ + y (+) + (+) (+) + (+)	+ + + (+) + + (+) + +	-	0	+ + + + + + + (+)(+)	0	0	+ + (+) + + + + (+)(+)	0
Drainage -permeabi- lity-	high moderate inhibited	0	X (+) + (+) + + (+) X (+) X (+)	+ + + + + (+) (+) X X	-	+ + + + + + + (+) (+)(+)(+) X	+ + (+) + + + y y y		0	-	+ + (+) + + + + (+) X	+ + (+) + + + + (+) X	0	0	+ + (+) + + + + (+) X	0
Plant water demand	high moderate low	0	X (+) + X + + + + +	+ (+) X + + (+) + + (+)	-	0	+ + (+) + + (+) + + +	0		-	0	+ (+) X + + (+) + + +	+ (+) + (+) + +	+ + (+) + + (+) + + +	+ (+) X + + (+) + + +	0
Energy for water distribut.	available limited restricted	-	-	-	-	-	-	-	-		-	-	-	-	0	0
Capital	available limited restricted	0	0	0	-	Ø + + + X + + + X + + (+)	0	+ + + + + (+) (+) + X	0	-		+ + + + + (+) (+)(+) X	+ + + (+) + X	+ + + + + (+) (+)(+) X	+ + + (+) + (+) (+) X X	0
Management	trained moderate low level	0	+ + + (+) + + X (+) +	+ + + + + (+) + (+) X	-	+ + + + (+) + + (+) X + + (+)	+ + + + + (+) (+) + (+)	+ + (+) + + (+) (+) + X	+ + + (+) + + X (+) +	-	0		+ + + + + (+)	+ + + + + (+) (+) X (+)(+)	+ + + + + (+) (+)(+) (+)	0
Labour	available restricted	-	-	-	-	+ + + + (+) + + (+)	-	-	+ + + (+) + +	-	0	0		0	0	0
	trained moderate low level	-	+ + + (+) + + X (+) +	0	-	+ + + + (+) + + (+) X + + (+)	0	0	+ + + + + + X (+) +	0	0	0	0		+ + + (+) + + X (+)(+)	0
Agro- technology	advanced moderate low level	0	+ + + (+)(+) + X X +	+ + + + + (+) + (+) X	-	+ + + + (+) + + + X + + (+)	0	+ + (+) + + X + (+) X	+ + + (+) + + X (+) +	-	0	+ / / + + / / / (+)	+ + + (+) + (+)	+ + X + + (+) + + (+)		0
Spare parts	available limited restricted	-	0	-	-	-	-	-	-	-	0	0	-	-	0	

Figure 3.12 :

Sprinkler irrigation
-semi-fixed-
(Ref.:Nomenclature)

REQUIREMENT		Climate	Water quantity	Water salinity	Water impurity	Topography - slope -	Soil	Drainage -permeabi-lity-	Plant water demand	Energy for water distribut.	Capital	Management	Labour		Agro-technology	Spare parts
CONDITION		arid semi arid humid	limited moderate unlimited	low moderate high	low moderate high	even slight moderate steep	fine medium coarse	high moderate inhibited	high moderate low	available limited restricted	available limited restricted	trained moderate low level	available restricted	trained moderate low level	advanced low level	available limited restricted
Climate	arid semi arid humid		(+)++ (+)++ ++/	++(+) ++(+) +++	–	++++ ++++ ++++	(+)++ (+)++ +++	++(+) ++(+) +++	+++ +++ +++	+(+)X +(+)X +(+)X	++X ++X ++X	+(+)X +(+)X ++X	+(+) +(+) +(+)	++(+) ++(+) ++(+)	+(+)(+) +(+)(+) ++(+)	+(+)X +(+)X +(+)X
Water quantity	limited moderate unlimited	0		+(+)X ++(+) ++(+)	–	0	++(+) +++ +++	(+)++ +++ +++	X(+)+ (+)++ +++	0	0	+(+)X ++(+) +++	0	0	+(+)X ++(+) +++	0
Water salinity	low moderate high	0	+++ (+)++ XX(+)		–	0	0	++(+) ++(+) +(+)X	+++ (+)++ X(+)+	++(+) ++(+) +(+)X	0	+++ ++(+) +(+)X	0	0	+++ ++(+) +(+)X	++(+) ++(+) +(+)X
Water impurity	low moderate high	–	–	–		–	–	–	–	–	–	–	–	–	–	–
Topography -slope-	even slight moderate steep	0	0	0	–		0	0	0	++(+) ++(+) ++(+) ++(+)	0	+++ +++ ++(+) ++(+)	++ ++ +(+) +(+)	+++ +++ +++ ++(+)	+++ +++ ++(+) +(+)X	0
Soil	fine medium coarse	0	+++ +++ (+)++	0	–	++(+)(+) +++(+) ++++		++X ++(+) ++y	+++ +++ (+)++	–	0	++(+) +++ ++(+)	0	0	++(+) +++ +++	0
Drainage -permeabi-lity-	high moderate inhibited	0	X++ +++ (+)(+)+	+++ ++(+) (+)(+)X	–	0	+++ +++ yyy		0	–	+++ +++ +(+)X	+++ ++(+) +(+)X	0	0	+++ ++(+) +(+)X	0
Plant water demand	high moderate low	0	X(+)+ (+)++ +++	+(+)X ++(+) +++	–	0	++(+) +++ +++	0		+(+)X ++(+) +++	0	+(+)X ++(+) +++	+(+) ++ ++	++(+) ++(+) +++	+(+)X ++(+) +++	+(+)X ++(+) ++(+)
Energy for water distribut.	available limited restricted	0	0	0	–	++++ +++(+) (+)(+)(+)(+)	0	0	+++ (+)++ X(+)+		0	0	0	0	0	–
Capital	available limited restricted	0	0	0	–	0	0	+++ ++(+) +(+)X	0	+++ ++(+) +(+)X		+++ ++(+) (+)(+)X	++ +(+) +X	+++ ++(+) (+)(+)X	+++ (+)+(+) (+)XX	++(+) ++(+) +(+)X
Management	trained moderate low level	0	+++ (+)++ X(+)+	+++ ++(+) (+)XX	–	++++ +++(+) ++(+)X	+++ +++ (+)++	++(+) ++(+) +(+)X	+++ (+)++ X(+)+	+++ ++(+) +(+)X	0		++ ++ +(+)	+++ ++(+) (+)XX	+++ ++(+) (+)(+)X	+++ ++(+) +(+)X
Labour	available restricted	–	–	–	–	++++ ++(+)X	–	–	+++ (+)++	–	0	0		0	0	0
	trained moderate low level	–	0	0	–	++++ +++(+) ++(+)X	0	0	+++ (+)++ X(+)+	0	0	0	0		+++ +++ X(+)(+)	+++ ++X +(+)X
Agro-technology	advanced moderate low level	0	+++ (+)++ X(+)+	+++ ++(+) +(+)X	–	++++ +++(+) +++(+)	0	++(+) ++(+) +(+)X	+++ (+)++ X(+)+	0	0	+// ++/ //(+)	++ +(+) +X	++X ++(+) ++(+)		+(+)X ++X ++(+)
Spare parts	available limited restricted	0	+++ (+)++ X(+)(+)	+++ ++(+) (+)(+)X	–	–	–	–	+++ X(+)+ X(+)(+)	0	0	+++ ++(+) +(+)X	0	++(+) +(+)X (+)(+)X	0	

Figure 3.13 : Drip irrigation

(Ref.:Nomenclature)

CONDITION \ REQUIREMENT		Climate	Water quantity	Water salinity	Water impurity	Topography - slope -	Soil	Drainage -permeability-	Plant water demand	Energy for water distribut.	Capital	Management	Labour		Agro-technology	Spare parts
		arid semi arid humid	limited moderate unlimited	low moderate high	low moderate high	even slight moderate steep	fine medium coarse	high moderate inhibited	high moderate low	available limited restricted	available limited restricted	trained moderate low level	available restricted	trained moderate low level	advanced moderate low level	available limited restricted
Climate	arid semi arid humid		+ + + + + + + + /	+ + (+) + + + + + +	+ + y + + y + + y	+ + + + + + + + + + + +	+ + (+) + + (+) + + (+)	+ + (+) + + (+) + + +	+ + + + + + + + +	+ + (+) + + (+) + + (+)	+ + X + + X + + X	+ (+) X + (+) X + + X	+ + + + + +	+ (+) X + (+) X + (+) X	+ (+) (+) + (+) (+) + + (+)	+ (+) X + (+) X + + X
Water quantity	limited moderate unlimited	0		+ + (+) + + + + + +	0	0	0	0	(+) + + + + + + + +	0	0	+ (+) X + + (+) + + +	–	–	+ + (+) + + (+) + + +	0
Water salinity	low moderate high	0	+ + + + + + (+) + +		0	–	0	+ + + + + (+) + (+) (+)	0	+ + (+) + (+) X + (+) X	0	+ + + + + (+) + (+) X	0	+ + + + + (+) + (+) X	+ + (+) + + X + (+) X	+ + (+) + (+) X + (+) X
Water impurity	low moderate high	–	–	–		–	–	–	–	–	+ + + + + (+) + (+) X	+ + + + + (+) + (+) X	0	+ + + + + (+) + (+) X	0	+ + + + + (+) + (+) X
Topography -slope-	even slight moderate steep	0	0	0	0		0	0	0	+ + (+) + + (+) + + (+) + + (+)	0	+ + + + + + + + (+) + (+) X	0	0	+ + + + + + + + (+) + (+) X	0
Soil	fine medium coarse	0	+ + + + + + (+) (+) +	0	–	0		+ + (+) + + (+) + + y	+ + + + + + (+) + +	–	0	+ + + + + + + + (+)	0	0	+ + + + + + + (+) (+)	0
Drainage -permeability-	high moderate inhibited	0	0	+ + + + + + + (+) (+)	–	0	+ + + + + + y y y		0	–	+ + + + + + + (+) X	+ + + + + + + (+) X	0	0	+ + + + + + + (+) X	0
Plant water demand	high moderate low	0	(+) + + + + + + + +	0	–	–	0	0		+ (+) X + + (+) + + +	0	+ (+) X + + (+) + + +	0	+ (+) X + + (+) + + +	+ (+) X + + (+) + + +	+ (+) X + + (+) + + (+)
Energy for water distribut.	available limited restricted	0	0	0	–	+ + + + + + + + (+) (+) (+) (+)	0	0	+ + + (+) + + X (+) +		0	0	0	0	0	–
Capital	available limited restricted	0	0	0	+ + + + + (+) + (+) X	0	0	+ + + + + (+) + + (+)	0	+ + + + + (+) + (+) X		+ + + + + (+) (+) X X	+ + + + + +	+ + + + + (+) (+) (+) X	+ + + + + (+) (+) X X	+ + (+) + + (+) + (+) X
Management	trained moderate low level	0	+ + + + + + (+) + +	+ + + + + (+) + (+) X	+ + + + + (+) + X X	+ + + + + + + (+) + + (+) X	+ + + + + (+) + + X	+ + + + + (+) + + (+)	+ + + + + + (+) + +	+ + + + + (+) + (+) X	0		+ + + + + +	+ + + + (+) X (+) X X	+ + + + + (+) (+) (+) X	+ + + + + (+) + (+) X
Labour	available restricted	–	–	–	–	0	–	–	0	–	0	0		0	0	0
	trained moderate low level	–	0	0	+ + + + + (+) + (+) X	+ + + + + + + + + + + (+)	0	0	+ + + (+) + + (+) (+) +	0	0	0	0		+ + + + + (+) (+) (+) X	+ + (+) + (+) X + (+) X
Agro-technology	advanced moderate low level	0	+ + + (+) + + X (+) +	+ + + + + (+) + (+) X	0	0	0	+ + + + + (+) + (+) X	+ + + (+) + + (+) + +	0	0	+ / / + + (+) / / X	+ + + + + X	+ + + + + (+) (+) (+) X		+ + X + (+) X + (+) X
Spare parts	available limited restricted	0	+ + + (+) + + X X (+)	+ + + + + (+) (+) X X	+ + + + + (+) + (+) X	–	–	–	+ + + (+) + + X (+) +	0	0	+ + + + + (+) + (+) X	0	+ + (+) + + X + (+) X	0	

Figure 3.14 : Dependence of field irrigation design on different conditions (Ref.: Nomenclature)

conditions		run-off irrig.	wild flooding	border irrig.	basin irrig.	furrow irrig.	corrugation	sprinkler irr.	drip irrigat.
Climate	arid	+	Ø	+	+	+	+	+	+
	semi arid	+	+	+	+	+	+	+	+
	humid	Ø	+	Ø	+	+	+	+	+
Water quantity	limited	+	X	X	X	X	X	X	+
	moderate	+	X	(+)	(+)	+	+	(+)	+
	unlimited	Ø	+	+	+	+	+	+	+
Water salinity	low	+	+	+	+	+	+	+	+
	moderate	(+)	(+)	(+)	+	(+)	+	(+)	+
	high	X	X	(+)	(+)	X	X	X	(+)
Water impurity	low	–	–	–	–	–	–	–	+
	moderate	–	–	–	–	–	–	–	+
	high	–	–	–	–	–	–	–	Y
Topography - slope -	even	X	X	(+)	+	(+)	(+)	+	+
	slight	+	+	+	+	+	+	+	+
	moderate	+	+	+	Y	+	+	+	+
	steep	(+)	(+)	Y	Y	Y	(+)	+	+
Soil	fine	+	(+)	+	+	+	+	(+)	+
	medium	(+)	+	+	(+)	+	+	+	+
	coarse	X	+	(+)	X	(+)	(+)	+	(+)
Drainage -permeability-	high	X	+	(+)	(+)	+	+	+	+
	moderate	(+)	+	+	+	+	+	+	+
	inhibited	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Plant water demand	high	X	X	(+)	+	+	(+)	+	+
	moderate	(+)	(+)	+	+	+	+	+	+
	low	+	+	+	Ø	+	+	+	+
Energy for water distribut.	available	/	/	/	/	/	/	+	+
	limited	/	/	/	/	/	/	(+)	+
	restricted	/	/	/	/	/	/	X	(+)
Capital	available	Ø	/	+	+	+	+	+	+
	limited	+	+	+	+	+	+	(+)	(+)
	restricted	(+)	+	(+)	(+)	(+)	(+)	X	X
Management	trained	+	/	+	+	+	+	+	+
	moderate	+	+	+	+	+	+	+	(+)
	low level	(+)	(+)	(+)	(+)	(+)	(+)	X	X
Labour	available	+	+	+	+	+	+	+	+
	restricted	(+)	+	(+)	(+)	(+)	(+)	(+)	+
	trained	/	/	+	+	+	+	+	+
	moderate	+	+	+	+	+	+	+	(+)
	low level	(+)	(+)	(+)	(+)	(+)	(+)	(+)	X
Agro-technology	advanced	+	/	+	+	+	+	+	+
	moderate	+	+	+	+	+	+	(+)	(+)
	low level	(+)	(+)	(+)	(+)	(+)	(+)	(+)	X
Spare parts	available	/	/	/	/	/	/	+	+
	limited	/	/	/	/	/	/	(+)	(+)
	restricted	/	/	/	/	/	/	X	X

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C H A P T E R F O U R

4. COMPARISON BETWEEN DRIP IRRIGATION AND OTHER IRRIGATION METHODS UNDER SAMPLE CONDITIONS (CASE STUDIES OF ROW CROP PRODUCTION)

In this Chapter, drip irrigation will be compared with some selected irrigation methods treated in earlier Chapters. Drip irrigation has recently assumed an important role as a field irrigation method, e.g. in 1974, 10,000 ha in Australia, 16,000 ha in U.S.A. and 3,400 ha in South Africa[4.1] were under drip irrigation; in 1981, the world-wide total is estimated at about 250,000 ha.[4.2] This trend in the use of drip irrigation is particularly reflected in the increase in application to intensive irrigated crops such as orchards, row crops and greenhouses. Since 1900, drip irrigation had been only used in small areas, mainly in greenhouses and nurseries. The expansion in field crops came in the 1950's with the reduced cost of small diameter plastic pipes.

This trend of expansion of drip irrigation in the industrialised countries did not stop, but was copied by other less developed countries, mainly those which are situated in arid regions. Precise studies of the effectivity under particular conditions or, in other words, criteria under which conditions drip irrigation can be preferred in comparison with other irrigation methods, have been few and therefore the subject of this thesis.

Drip irrigation will be compared with some representative irrigation methods treated in earlier Chapters such as sprinkler, furrow, basin and border irrigation in an arid region.

Run-off, wild flooding and corrugation irrigation are excluded from this comparison because

- run-off irrigation depends, as mentioned in Chapter 1.1.1 on very specific environmental conditions of topography, climate and soil. The water distribution over the irrigated plot is usually realized by the application of one surface irrigation method.
- wild flooding represents an irrigation method in which the irrigation efficiency results are extremly low. Particularly, because of the high water demand in relation to other irrigation methods, wild flooding cannot be considered as an alternative irrigation method in an arid region.
- corrugation irrigation, as mentioned in Chapter 1.1.6, is limited to the watering of closely growing crops such as cereals, forage and pasture. Furthermore, the main characteristics of soil and topography required are very similar to furrow and border irrigation; corrugation irrigation may therefore be excluded as a separate sample.

4.1 IRRIGATION AS A PRODUCTION FACTOR

The process of supplying water to the locations of the plants can economically be determined as the utilization of water as a production factor, such as fertilizer, labour or capital. Therefore, irrigation should be justified in the ratio of benefits and costs. As in any economic process, one or more of the production factors will usually limit the final revenue. The value of inputs for irrigation should be coordinated with the level and intensity of the other production factors which may determine a limit for the output. Therefore, irrigation must be integrated into the production process of a farm, having been adapted to the existing environmental, labour and economic conditions.

Assuming the conditions of an arid climate where crop growth without irrigation will be very restricted and poor, water supply by one irrigation method will not in itself guarantee in optimising farm income in spite of the maxim 'everything is made alive by water'. The inputs must be considered in relation to the output as well as the influence of the irrigation water on the fertility of the soil. It should be proven whether any particular existing limiting factors can be compensated for by economically acceptable expenditures; e.g. limited labour resources may be compensated for by the use of an irrigation method with a high production capacity per man hour.

A distinction can be made between the production capacity of irrigation water, usually expressed as 1 m^3, and of the production capacity of the labour input expressed in man hours, as well as the relation between monetary input and output. In cases where the amount of irrigation water is the main limiting factor, the planning orientation should be concentrated on the efficiency of irrigation in terms of water. On the other hand, where the availability of man hours in general, or skilled labour is restricted, the attention may be turned to this factor. Considering irrigation as a production factor with a demand of monetary input, there may be restrictions through the availability of capital for input as well as on the output through insecure marketing situations. In other words, high inputs into an irrigation system including high installation costs in order to get good results in water and labour effectivity may be invalidated if the output cannot be economically assured because of an inadequate market situation.

In addition, it must also be realized that for reaching a high output of produced crops, the other production factors, such as fertilizer, plant protection measures, tillage, etc., must be intensified in order to have, as far as possible, a balanced optimising of all production factors. Without this, even under the best moisture conditions created by watering, yields may be restricted by some other production factors being less than the minimum necessary. An analogy may be found in the use of high yield variety crops (HPY) the so called 'Green Revolution', where high potential results are only actually achieved if the associated inputs of the production factors noted above (and often also of appropriate irrigation) are <u>all</u> adequatly supplied.

The following sections develop in detail, this theme of balanced inputs appropriate to cultivation objections.

4.2 PLANNING OF IRRIGATION SYSTEMS AND RATIONAL CULTIVATION

In this Chapter, the planning criteria of field irrigation systems on farm level for irrigating row crops such as orchards, vegetables under open air condition and vegetables in greenhouses will be identified.

The planning of any irrigation system has to be orientated to the existing environmental, human and economic conditions. We can distinguish firstly between conditions which cannot fundamentally be altered or improved such as the following environmental conditions:

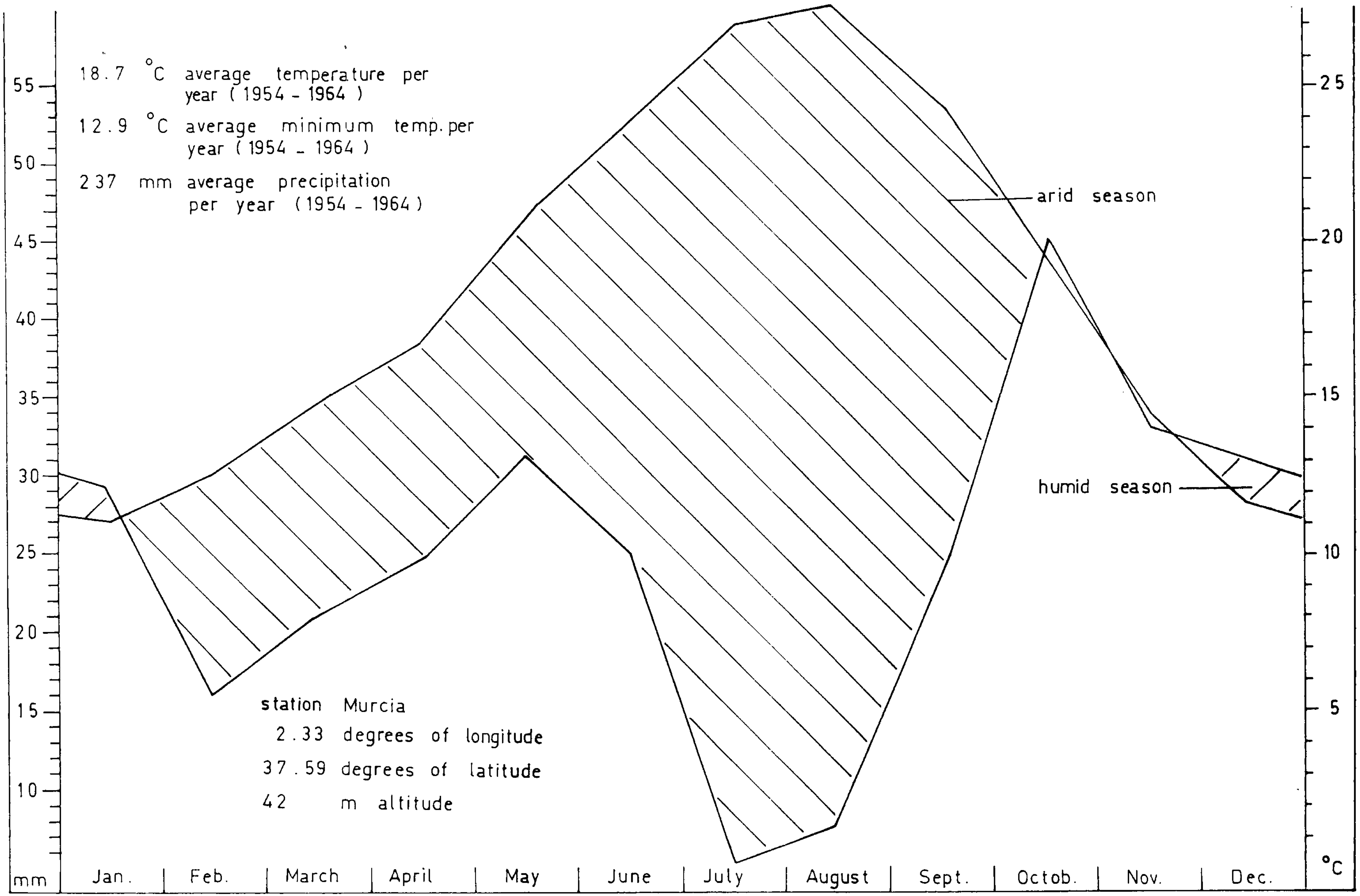
- climate (except in greenhouses)
- plant water demand
- water quantity and quality
- soil characteristics

and secondly, those environmental conditions which can be adapted to a particular irrigation system through an input of capital and labour:

- topography (by levelling)
- water impurity (by filtration)
- energy (by electricity or fuel)

and, thirdly, such conditions which are dependent on the education and training or supervision of the farmer

Figure 4.1: Climate diagram (After references 2.5 and 4.3)



as well as on credit and marketing policy:

- capital
- management
- labour
- agrotechnology
- spare part situation
- marketing

In the following example, based on conditions in Murcia, data of soil and water quality as well as the level of fixed and variable costs for labour and equipment, as stated in Chapter 2.5, will be utilized. In addition, Fig. 4.1 illustrates that, using climatic data given in Table 2.2, the year can be divided into a humid season during winter and an arid season during summer.

Let us assume a farm with a total area of 50 ha land, all suitable for irrigation, with the following land use:

- 10.0 ha orchards irrigated by border-stips
- 4.5 ha vegetables, open air, irrigated by furrows
- 0.5 ha vegetables in a greenhouse, irrigated by furrow and basin irrigation
- 10.0 ha forage crops, irrigated by border strips

= 25.0 ha crop production under irrigation and

- 25.0 ha cereals without irrigation during winter season.

For the purpose of obtaining a better farm income, an extension of the irrigated area by reclaiming the unirrigated cereal area is proposed, this 25.0 ha to be cultivated in 20.0 ha of orchards and 5.0 ha of vegetables. An analysis of this proposal would be as follows:

- The irrigation water, elevated by a deep well pump and deposited in a reservoir with 20,000 m^3 capacity, is limited in total availability to 265,000 m^3/year. According to average water consumption, as identified in Chapter 2.4 and 2.5, which is, per ha, 6,000 m^3/year in orchards (citrus), 8,000 m^3/year in vegetables under open air (melons) as well as forage crops and 20,000 m^3/year in the greenhouse, there can be subsumed a total water demand per year of:

10.0 ha orchards	x 6,000 m^3 =	60,000 m^3/year
14.5 ha vegetables and forage crops	x 8,000 m^3 =	116,000 m^3/year
0.5 ha greenhouse	x 20,000 m^3 =	10,000 m^3/year
	=	186,000 m^3/year

If we assume 30% water losses from storage and canals, through seepage, leakage and evaporation, of the total well capacity of 265,000 m^3 then,

$$265{,}000\ m^3 \times 70\% = 185{,}500\ m^3$$

water per year are available on the irrigated plots. In other words, the capacity of irrigation water is only sufficient for the farm area already irrigated.

We must now feed in other base data:

- The unirrigated land has slopes of between 2% and 5% which would require capital intensive levelling for the installation of surface irrigation.
- The irrigation water would need to be elevated by about 30 m to allow gravity distribution.

- The labour capacity consists of only four permanent labourers, including the farmer, without no possibility of increasing supply during the irrigation season since seasonal workers are hardly available during that period.

In favour of the reclamation of more land for irrigation are the following conditions:

- the market situation for vegetables and tree crop products (citrus)—expectation normally excellent.
- the structure and permeability of the soil now under cereals is suitable for irrigation.
- artificial drainage would not be necessary
- spare parts are available
- the farmer has a basic agricultural know-how as well as experience in irrigation
- the farm is equipped with machinery for soil preparation, weed and pest control and harvesting so that more land could be cultivated without the necessity of new machines.
- special credits at an interest rate of 4% can be obtained for the reclamation of irrigated land.

The planning problem in this situation consists of identifying an irrigation method by which the available amount of irrigation water, the labour capacity as well as the topography of the land can be utilized as economically as possible. The first solution could consist of optimising the present irrigation methods by reducing these water losses from the canals through seepage and leakage (about 20% of total water available) by improving the canals. Hereby, the water losses established in Figure 2.1

of some 20% (265,000 m^3 x 20% = 53,000 m^3) can be reduced to losses of the order of 5%. By this means, about 40,000 m^3 more irrigation water could be used for irrigating additionally about 7 ha of orchards. (6,000 m^3 per ha/year totalling 42,000 m^3 per year) <u>or</u> 5 ha of vegetables (8,000 m^3 per ha and year x 5 = 40,000 m^3 per year).

Another possibility for increasing the effectivity of the irrigation water consists of further reducing the water losses caused by evaporation and percolation on the irrigated plots. These losses, according to Figure 2.1 ($e_{3/3}$), are in the range of 30% to 50% of the water supplied up to the field header given the use of surface irrigation systems. If we assume the Figures of the proportional to total extraction (see Figure 2.1 ($e_{3/1}$)) are of the order of 50%:

10% by storage

15% by canals

<u>25%</u> by evaporation and percolation

50% total water losses can be considered.

This means, that of the total amount of 265,000 m^3 irrigation water extracted per year, 132,500 m^3 water are lost.

If we now apply the criteria shown in Figure 3.14, since the main restrictive condition for irrigation, in the case of this example, consists of a limitation in the quantity of irrigation water, there is no appropriate surface irrigation method which could be used to achieve the stated aim. Of the pressure irrigation systems only drip irrigation can be identified as the method where the particular constraint does not operate. Therefore, further calculations have to be made for the sample farm area to find out whether drip irrigation can be utilized to substitute for the existing surface irrigation methods as being a more favourable method of water distribution in terms of water management and economy.

If we consider drip irrigation to be a closed pipe system from the water reservoir to the orchards, vegetables and greenhouse (then it will not be suitable for forage crops which should be irrigated as previously stated by border strips, see Chapter 1.2.2) , the water balance for the given example, all under surface irrigation, can be calculated as follows:

10.0 ha orchards	x	3,000 m^3/ha	=	30,000 m^3/year
4.5 ha vegetables	x	4,000 m^3/ha	=	18,000 m^3/year
0.5 ha vegetables in the greenhouse	x	10,000 m^3/ha	=	5,000 m^3/year
10.0 ha forage crops	x	8,000 m^3/ha	=	80,000 m^3/year
				133,000 m^3/year

We must then add an estimate of forage canal loss of:	20,000 m^3/year
Total demand of irrigation water for the area already irrigated by surface irrigation:	153,000 m^3/year
The total well capacity of 265,000 m^3/year must be reduced by 10% for loss by evaporation from storage gives:	238,500 m^3/year
If we subtract from this the demand identified above:	153,000 m^3/year
then:	85,500 m^3/year

irrigation water are available for redeployment. This amount of water would be sufficient to irrigate the cereal area as intended under drip irrigation of

	20.0 ha orchards	x	3,000 m^3 =	60,000 m^3/year
and	5.0 ha vegetables	x	4,000 m^3 =	20,000 m^3/year
			thus	80,000 m^3/year

water is required by the use of drip irrigation.

After having calculated the technical conditions in distribution and application of the irrigation water, which determines the most limiting factor of irrigation in the given sample, the further planning steps consist in determining the specific economic conditions and labour situation before and after the proposed modification of watering most of the farm area by drip irrigation. Because of regional and annual variations in crop yields and market prices for the produced goods, the possible yields and their value cannot be calculated in actuality.

Table 4.1 shows the initial investments made for the already existing surface irrigation on the 25 ha of the mentioned sample. These data are extrapolated from the figures, stated in Table 2.3 to the corresponding 25 ha of the sample area.

Table 4.2 shows the man hours, necessary for irrigation as well as the irrigation specific variable costs of the 25 ha irrigated by surface irrigation per year.

Table 4.3 shows the value of initial investment and the fixed costs for the proposed installation of drip irrigation on 40 ha farmland. Items such as pump station, well drilling and reservoir are excluded from the total of new costs because they already exist on the farm. As these items are also used or required for watering the forage crops by surface irrigation, their corresponding fixed costs of £ 4,560.- per year cannot be associated totally with drip irrigation. Of the total amount of water of 238,000 m^3 available from the reservoir per year, 80,000 m^3 or about 34% are required by the forage crops. This 34% should be excluded from the fixed costs, which results in a value of £ 4,560.- - 34% = £ 1,550.- substracted from the fixed costs for drip irrigation.

Table 4.4 shows the required man hours per year as well as the variable costs, occuring after the installation of drip irrigation, these include the partial use of surface irrigation, but now on double the area which had been previously irrigated. Here, the work in laying out and removing of the emitter lines, necessary for vegetables and in the greenhouse, is added to the man hours alloted for irrigation.

Figure 4.2 gives a summarised overview of the results, calculated on Tables 4.1 to 4.4. Comparing the technical and economic situation of the sample farm before and after the installation of drip irrigation, then we see that with drip irrigation there is:

- lower demand for irrigation water
- lower demand in man hours
- lower demand in variable costs

  <u>but</u>

- higher demand in fixed costs.

It must be emphasised that, according to this balance and earlier analysis the implementation of a drip irrigation system requires for assured returns a stable market situation for the produced goods as well as the farmers ability to carry out rational crop production by means of obtaining high quality and yields by, e.g. weed and pest control, fertilising and harvesting.

The noted low demand in man hours can only be obtained by rational cultivation operations, as assumed in the calculation of man hours required given in Table 4.4. In the following Chapter 4.3, the associated detailed specific cultivation and irrigation operations necessary for profitable drip irrigation will be identified.

Table 4.1 : Estimated initial investment (new costs) extrapolated from the Figures in Table 2.3 as well as the corresponding depreciations and interests (fixed costs) of the 25 ha extension of the farm area, per year.

i t e m	new cost £	useful life years	depreciation/ amortisation %	depreciation/ amortisation £	interest on new cost ÷ 2 %	interest on new cost ÷ 2 £	fixed cost £
- pump station 90 m^3/h pump unit	17,000.-	12	8	1,360.-	8	680.-	2,040.-
- well drilling 150 m	12,000.-	50	2	240.-	8	480.-	720.-
- reservoir 20,000 m^3, earthen plastic membrane	20,000.-	20	5	1,000.-	8	800.-	1,800.-
- field canals earthen	8,000.-	20	5	400.-	8	320.-	720.-
- land levelling	12,500.-	—	4*	500.-	8	500.-	1,000.-
total	69,500.-			3,500.-		2,780.-	6,280.-

* 4 % write off instead depreciation/amortisation

Table 4.2 : Variable costs, (according to figures in Table 2.4) including labour input for surface irrigation for the 25 ha area already irrigated.
For the forage crops, the figures of inputs are intermediate between the values for orchards and vegetables.

i t e m	man hours	variable costs
- water lifting 265,000 m^3 x 0.58 kWh x £ 0.05		= £ 7,685.-
- man hours for irrigation		
.orchards (citrus) 42 h/ha x 10 ha	=420 h x £ 3.5/h	= £ 1,470.-
.vegetables (melons) 56 h/ha x 4.5 ha	=252 h x £ 3.5/h	= £ 882.-
.greenhouse 168 h/ha x 0.5 ha	= 84 h x £ 3.5/h	= £ 294.-
.forage crops 40 h/ha x 10 ha	=400 h x £ 3.5/h	= £ 1,400.-
- irrigation specific cultivation work		
. orchards (citrus) 18 h/ha x 10 ha	=180 h x £ 3.5/h	= £ 630.-
. vegetables 24 h/ha x 4.5 ha	=108 h x £ 3.5/h	= £ 378.-
. greenhouse 72 h/ha x 0.5 ha	= 36 h x £ 3.5/h	= £ 126.-
. forage crops 20 h/ha x 10 ha	=200 h x £ 3.5/h	= £ 700.-
- machinery expenses		
.orchards (citrus) £ 45/ha x 10 ha		= £ 450.-
.vegetables (melons) £ 50/ha x 4.5 ha		= £ 225.-
.greenhouse £ 150/ha x 0.5 ha		= £ 75.-
.forage crops £ 47/ha x 10 ha		= £ 470.-
- repair expenses		
. orchards (citrus) £ 10/ha x 10 ha		= £ 100.-
. vegetables (melons) £ 20/ha x 4.5 ha		= £ 90.-
. greenhouse £ 40/ha x 0.5 ha		= £ 20.-
. forage crops £ 15/ha x 10 ha		= £ 150.-
total	1.680 h	£15,145.-

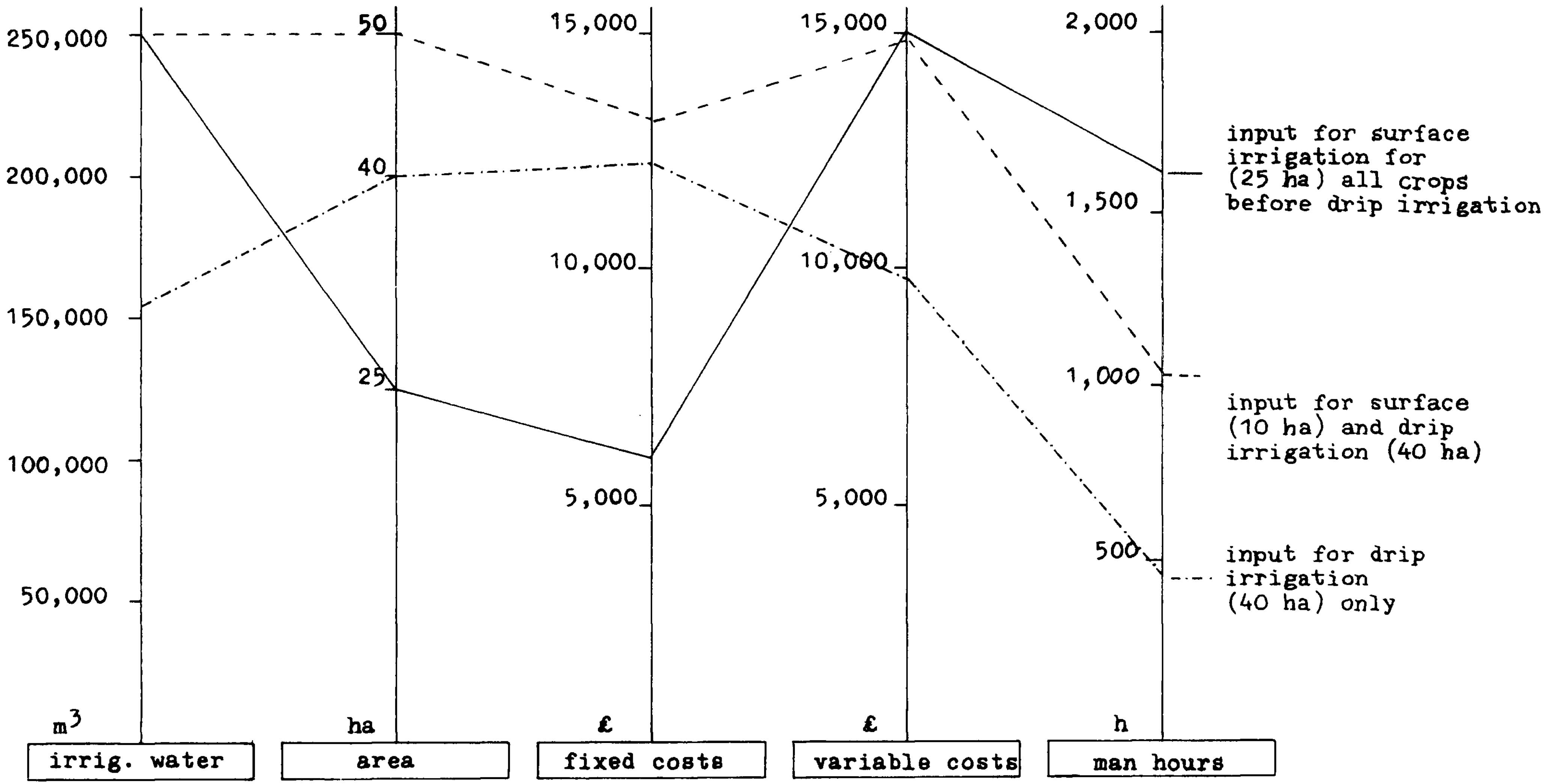
Table 4.3 : Initial investment (new costs) as well as depreciation and interest (fixed costs) necessary for the proposed installation of drip irrigation according to Table 2.7 (for total of 50 ha).

i t e m	new cost £	useful life years	depreciation/ amortisation %	depreciation/ amortisation £	interest on new cost + 2 %	interest on new cost + 2 £	fixed cost £
- pump station 90 m^3/h pump unit	17,000.-* (existing)	12	8	1,360.-	8	680.-	2,040.-
- well drilling 150 m	12,000.-* (existing)	50	2	240.-	8	480.-	720.-
- reservoir 20,000 m^3 earthen, plastic membrane	20,000.-* (existing) ==========	20	5	1,000.-	8	800.-	1,800.-
				2,600.-**		1,960.-**	4,560.-**
- head unit of drip irrigation 50 m^3/h pump unit	8,000.-	10	10	800.-	8	320.-	1,120.-
- distribution pipes fitting material lateral pipes and emitters							
. £ 800.-/ha in trees (orchards) 30 ha	24,000.-	10	10	2,400.-	8	960.-	3,360.-
. £ 3,000.-/ha in vegetables 10 ha	30,000.-	10	10	3,000.-	8	1,200.-	4,200.-
subtotal	62,000.-			8,800.-		4,440.-	13,240.-
* excluded subtotal of new cost ** of this subtotal, a contribution of 34 % for the forage crops is excluded which results:				- 884.-		- 666.4	- 1,550.4
total drip irrigation	62,000.-			7,916.-		3,773.6	11,689.6

Table 4.4 : Variable costs and labour input after installation of the proposed drip irrigation including the existing surface irrigation of the forage crops. The man hours for irrigation, based on Table 2.8 will be valued at £ 3.5 per hour as skilled labourer will not be employed.

item	man hours	variable costs
- water lifting 265,000 m^3 x 0.58 kWh x £ 0.05		=£ 7,685.-
- water distribution by drip irrig. .90,000 m^3/year in the orchard .38,000 m^3/year in the vegetables . 5,000 m^3/year in the greenhouse =133,000 m^3/year x 0.2 kWh x £0.05/kWh		=£ 1,330.-
- man hours for irrigation, lay out and moving of the emitter lines		
. orchards (citrus) 7 h/ha x 30 ha	= 210h x £ 3.5/h	=£ 735.-
. vegetables (melons) 26 h/ha x 9.5 h	= 247h x £ 3.5/h	=£ 864.5
. greenhouse 60 h/ha x 0.5 ha	= 30h x £ 3.5/h	=£ 105.-
*. forage crops 40 h/ha x 10 ha	= 400h x £ 3.5/h	=£ 1,400.-
- irrigation specific cultivation work		
.orchard (citrus)	nil	nil
.vegetables (melons)	nil	nil
.greenhouse	nil	nil
*.forage crops 20 h/ha x 10 ha	= 200h x £ 3.5/h	=£ 700.-
- machinery expenses for cultivation work on irrigation		
. orchards (citrus)	nil	nil
. vegetables (melons)	nil	nil
. greenhouse	nil	nil
*. forage crops £ 47/ha x 10 ha		=£ 470.-
- repair expenses		
.orchards (citrus) £ 20/ha x 30 ha		=£ 600.-
.vegetables (melons) £ 100/ha x 9.5 ha		=£ 950.-
.greenhouse £ 300/ha x 0.5 ha		=£ 150.-
*.forage crops £ 15/ha x 10 ha		=£ 150.-
total farm area	1,087 h	£ 15,139.5
* subtracting forage crops as being surface irrigated area as well as their part (34%) of water lifting costs (£ 7,685)	- 600 h	-£ 2,720.- -£ 2,613.-
total drip irrigated area	487 h	£ 9,806.5

Figure 4.2 : Relation between the amount of irrigation water (basic premiss) and the irrigated area on the sample farm as well as the different inputs before and after the installation of drip irrigation.



Finally, there will be given some examples of other conditions which could favour as well as restrict the utilization of drip irrigation. Here, the same basic conditions as stated before in the sample farm as well as in Figure 3.14 are assumed.

- If the farm area is limited because an additional area for irrigation is not available and a higher effectivity of the irrigation water is not required, the use of drip irrigation, mainly for vegetables, may be justified if:
  . land levelling can be avoided
  . there exists a serious shortage of labour
  . oversalting problems are occuring
  . better quality of crops should be realised
- if the water quality was low, the use of drip irrigation would represent the sole alternative to other irrigation methods (see Chapters 1.2.2 and 3.2).
- if spare parts availability cannot be guaranteed, the serviceability of the drip irrigation system cannot be assured. In these circumstances, the use of drip irrigation, as well as sprinkler irrigation, cannot be recommended
- if credit or credit at low interest rates are not available the high installation costs for drip irrigation may prohibit the realization of the proposed intention because of capital shortage at farm level.
- if there were no stable market for the produced crops, the returns on the relatively high fixed costs of the initial investment for drip irrigation could not be assured. Instable market situations are very serious

inhibitors of investment in high capital intensive irrigation systems because of the high risk of obtaining returns.

- if there is a low level of education and training, available for operations, for instance in preventing emitter blockages, as well as the precise observations of irrigation cycles, then totally rational crop production cannot be assured. The returns on the capital intensive investments, required by drip irrigation cannot be obtained if the equipment fails because of wrong use and maintenance; the equipment is far more delicate and sensitive than in other systems.
- if there is sufficient and cheap labour available, the relation of variable costs to the fixed costs, according to Figure 4.2, would be diminished because of the reduced input labour cost. In most of the developing countries ample and cheap labour is usually associated with low level of education which may prevent the use of a highly sophisticated irrigation method.

Further study of the different qualitative potentials of labour forces, for example in East Asia compared with inter-tropical Africa, in this context would be valuable but lie outside the scope of this thesis.

4.3 AGROTECHNOLOGY OF IRRIGATED CROPS

Here, we will initially review those relevant factors established earlier in this thesis of surface irrigation methods. The agrotechnology of crop production by irrigation can be defined as the resultant of two main groups of factors, the crop specific cultivation requirements and the layout of the irrigation system for conducting and distributing the water over the surface of the cultivated plot. Because of the fact that the plants are growing directly in the irrigation system, consisting of corrugations, furrows, border strips or basins, the technology of plant production has to be orientated around these conditions. Only with those crops, which should be cultivated in or on ridges, e.g. potatoes, does furrow irrigation represent a combination of both cultivation and irrigation techniques. As the minimum amount of irrigation water per irrigation cycle has to be associated with stream flow size, required to cover the irrigated plot, (see Chapter 1.1) and as post irrigation operations such as crust breaking may be necessary in most of the cases, the intervals between watering are planned to be as long as is consistent with refilling the field capacity before the wilting point of the plants is reached.

By sprinkler irrigation, the plants can be cultivated without depending on specific irrigation operations. As the whole earth surface is wetted by the sprinklers, individual plant watering (except by micro sprinklers) watering wide spaced crops such as trees, is not effective. Since that part of the irrigation water which wets the spaces between the tree rows is therefore mostly lost for the plant consumption. Except on sandy soils or with ground covering crops, crust has to removed after each watering, as well as the irrigation equipment of mobile and semi fixed sprinkler irrigation systems. As the plants are entirely wetted by each watering, temperature or fungus sensitive plants may suffer by high irrigation frequencies. Using irrigation water which contains a high content of salts, scorch damages on the plant leaves can be observed.[3.6] (see also Chapter 1.2.1) Although with sprinkler irrigation low amounts of irrigation water per irrigation cycle is possible, at field level, the cycles of watering are concentrated on replenishing soil moisture if the field capacity of the soil is exhausted near to the wilting point of the plants. Therefore, it can be stated that the practice of the utilization of sprinkler irrigation at field level, where it concerns the irrigation intervals and the amount of water per irrigation cycle does not significantly differ from that of surface irrigation.

By the use of drip irrigation, high irrigation frequencies can be practiced without the necessity of irrigation specific operations or pre-irrigation cultivation work. The main technological problems of crop production occuring by drip irrigation on field level can be defined as being the determination of the

i optimal soil moisture in the root zone of the plants

ii the layout of the emitter lines, to give the most rational cultivation technique

(i) Because of the visually small wetted area around the emitter, surrounded by dry earth surface, soil moisture content in the root zone cannot be estimated by eye or feel. The determination of the soil moisture with the use of drip irrigation has therefore be done by instruments. At farm level where the easy handling of apparatus is required, various methods, (see Table 3.4), pan evaporation and atometer, tensiometer and porous resistance block can be applied. By the use of pan evaporation and atometer, data has to be translated by plant specific conversion co-efficients (see Ref.: 3.4). The result is, that the measured data cannot be transferred immediately to irrigation impulses but at least is delayed by an average of one day.

Soil moisture measurements by tensiometer and porous resistance block can be transferred directly to give immediate indications for watering. For the unit operator, this mode of operation requires an understanding of the processes involved, rather than merely a blind carrying out of mechanical operations, a significant factor in the psychological demands made by the carrying out of the correct servicing and repair work.

The following data was obtained by personal research in the South East of Spain 1971 till 1974 under the same soil, water and climate conditions as stated in Chapter 2.5 and Figure 4.1. Here, tensiometers were used for controlling directly the irrigation cycles by electric connection to the head unit of drip irrigation. To find out the plant response to soil moisture, trials with aubergines irrigated by permanently adjusted vacuums of 10 and 25 centibars on the tensiometer, were done. The measuring point (ceramic cup of the tensiometer) was situated at a distance of 10 cm away of the emitter outlet and about 15 cm depth in the root zone. When the soil suction rose over the adjusted calibration, immediate watering was actuated and vice versa. This resulted to different developments of root extensions as shown by the following Fig. 4.3 and 4.4.

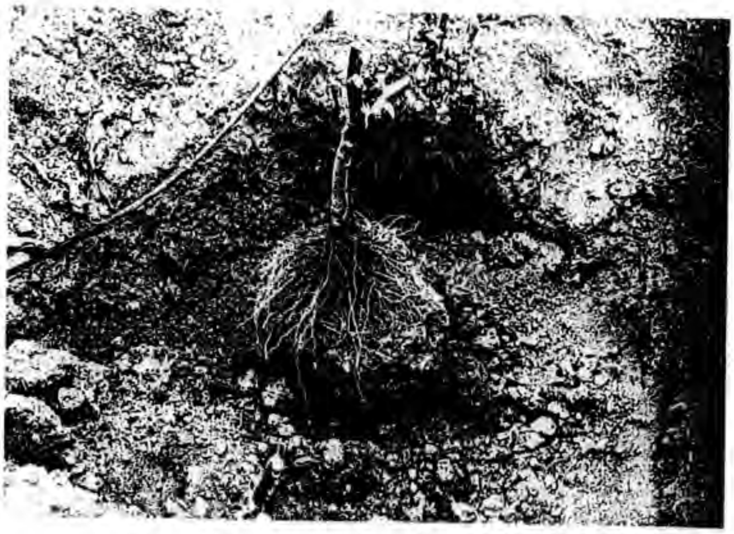


Figure 4.3 tensiometer adjustment of 10 centibars vacuum

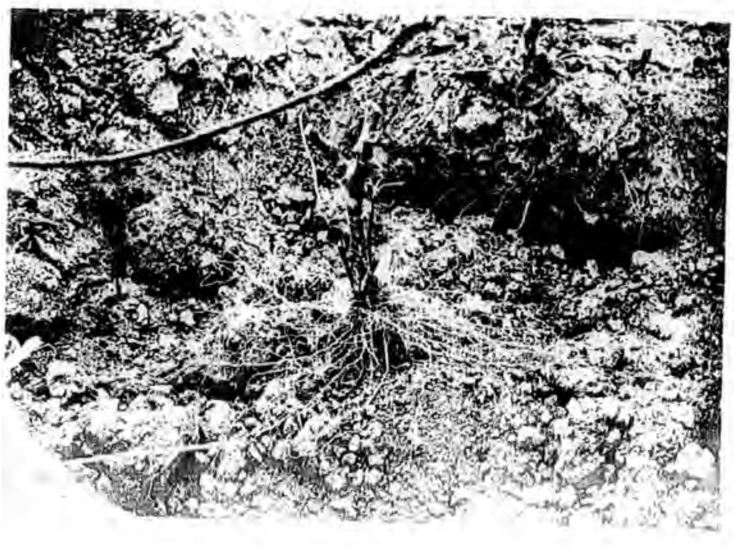


Figure 4.4 tensiometer adjustment of 25 centibars vacuum

It can be seen that with 10 centibars of vacuum, a more compact rootball without many horizontal extensions was produced than by 25 centibars vacuum, the above surface development of the plants in the trial with 10 centibars vacuum was markedly better than in trials with 25 centibars vacuum. Therefore, final tensiometer adjustments were set to 10 centibars vacuum for vegetables with similar results.

Figure 4.5 shows the sensitivity of the water consumption of tomato plants in relation to the temperature. This data was obtained via trials in a greenhouse where it was not possible to measure air humidity. It demonstrates the high differences in daily amounts of water, controlled by tensiometer. It also demonstrates, the impossibility of manual daily control of irrigation water achieving even approximately similar results. Further trials by tree crops found that soil moisture can be regulated by maintaining a constant soil suction of 20 centibars vacuum but by varying the distances between the emitter and the measuring point of the tensiometer. This distance variation allows the maintenance of the precise function of the tensiometer even though less attention as required for water refilling when it operates at over 30 centibars of vacuum.

Figure 4.6 shows the principle of tensiometer placement. Here, the water from the emitter has to reach the distance of line C to the ceramic cup of the tensiometer. Line A stands for the distance emitter to tensiometer and line B stands for the depth of the ceramic cup.

To establish guidelines for the different placements of the tensiometer to the emitter on different kinds of soils as well as for the required depth of wetting pattern, further trials were done. These results are shown in Figure 4.7 as guideline for use. Here, line A also stands for the distance emitter to tensiometer, line B stands for the depth of the ceramic cup and line C stands for the shortest distance of the emitter to the ceramic cup which the irrigation water has to reach.

Figure 4.8 shows the soil profile of measured moisture gradients expressed in volume percent by a permanently maintained 15 centibars vacuum around the ceramic cup of the tensiometer, as well as the distribution of salts. It can be observed, that by short frequency irrigation cycles, also called 'permanent watering' one emitter is able to produce a wetted radius of about 50 m on a sandy loam soil. For most kinds of tree crops, two emitters per tree may be sufficient under these conditions. Only on soils with less horizontal water movement capacity (light sandy soils) should the number of emitters per tree be doubled. As an important effect of the existence of permanent soil moisture around the emitter, the root density in this area will markedly increased.

Figure 4.5 : Water consumption of tomatoes by drip irrigation, controlled by tensiometer, in relation to the air temperature in a greenhouse (Source: Field work).

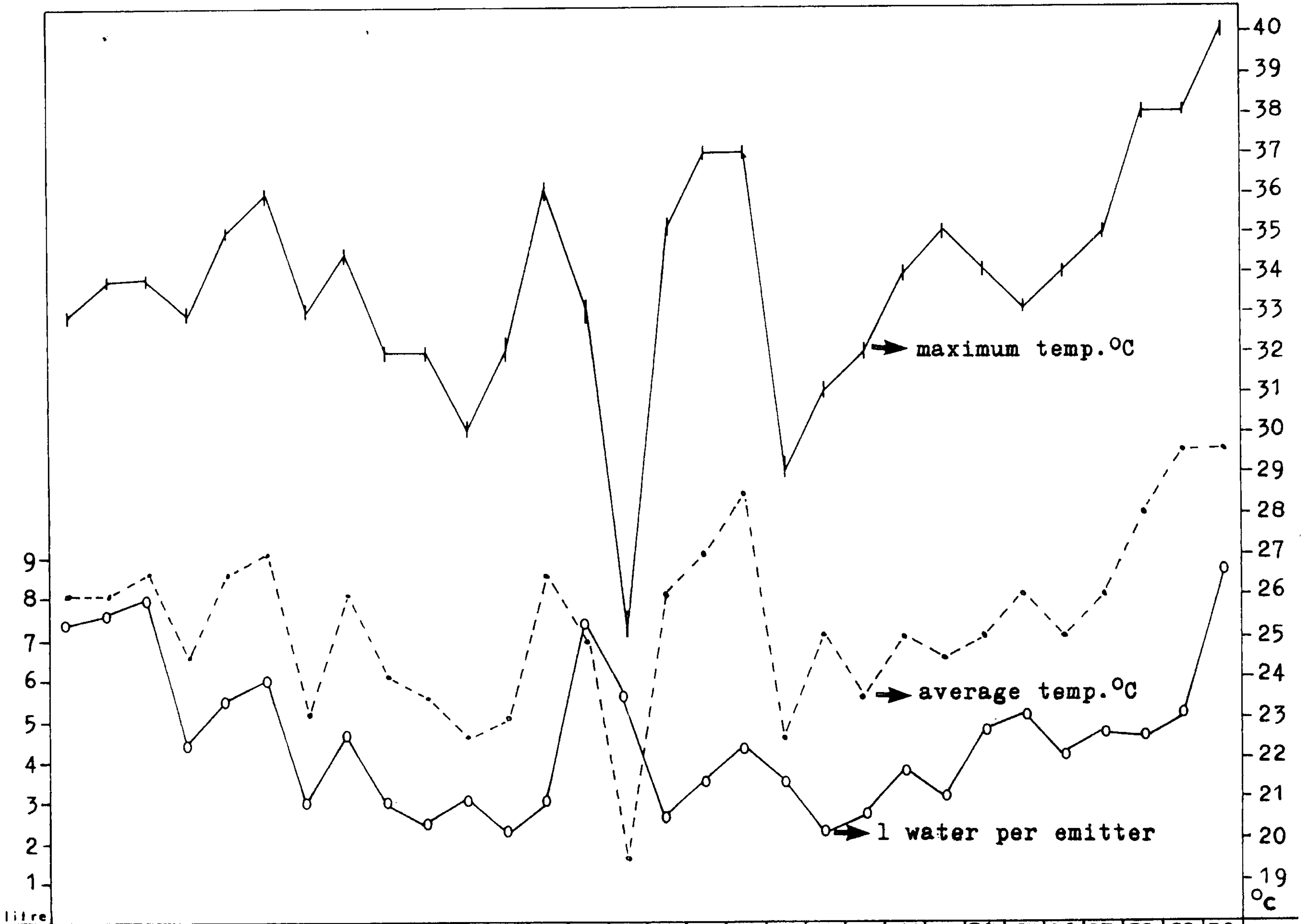
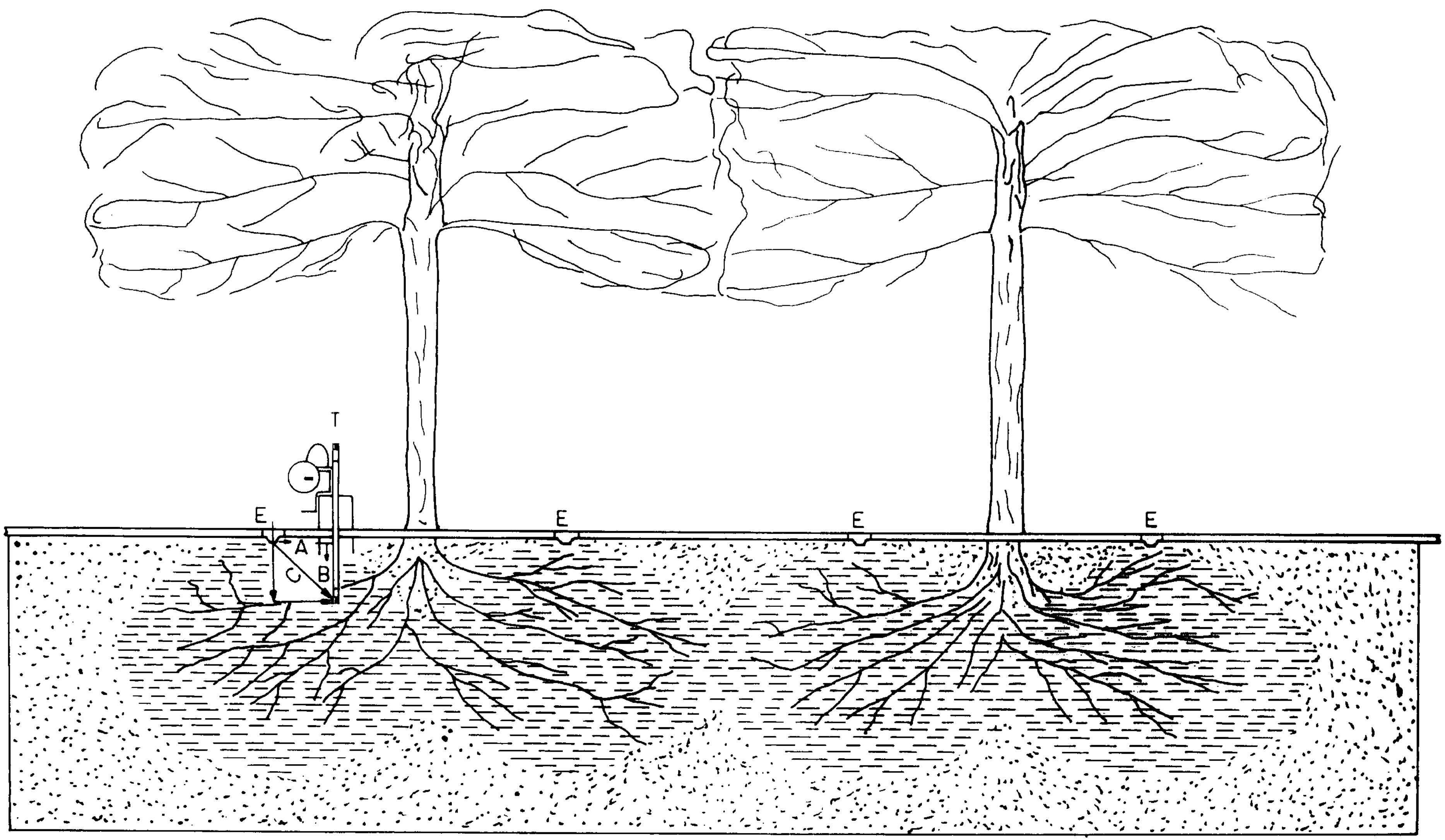


Figure 4.6: Principle of tensiometer placement



wet

dry

E = emitter

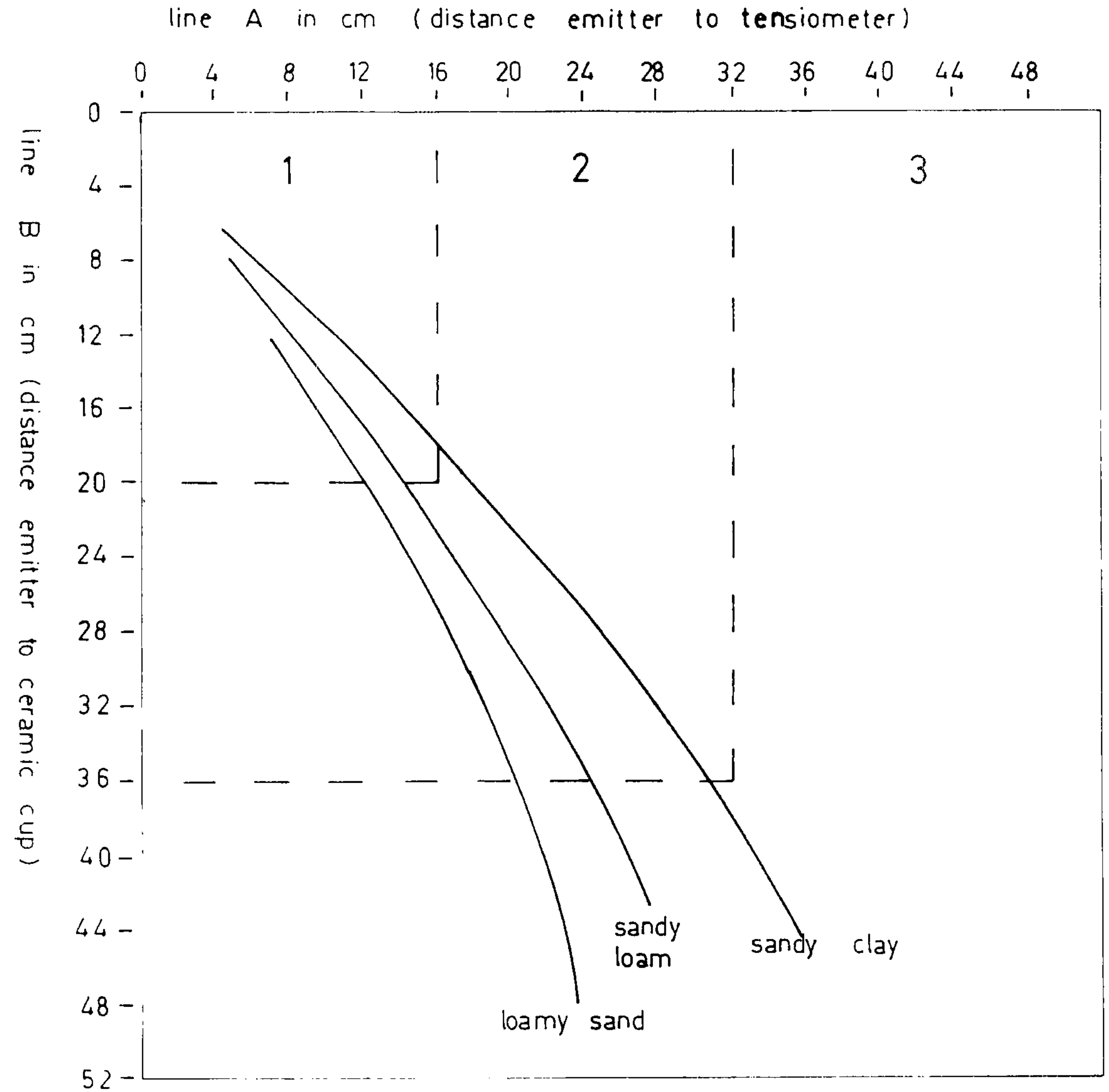
T = tensiometer

A distance emitter to tensiometer

B depth of the ceramic cup

C distance emitter to the ceramic cup

Figure 4.7: Guidelines for tensiometer placement for different kinds of soils and plants (Source: fieldwork)

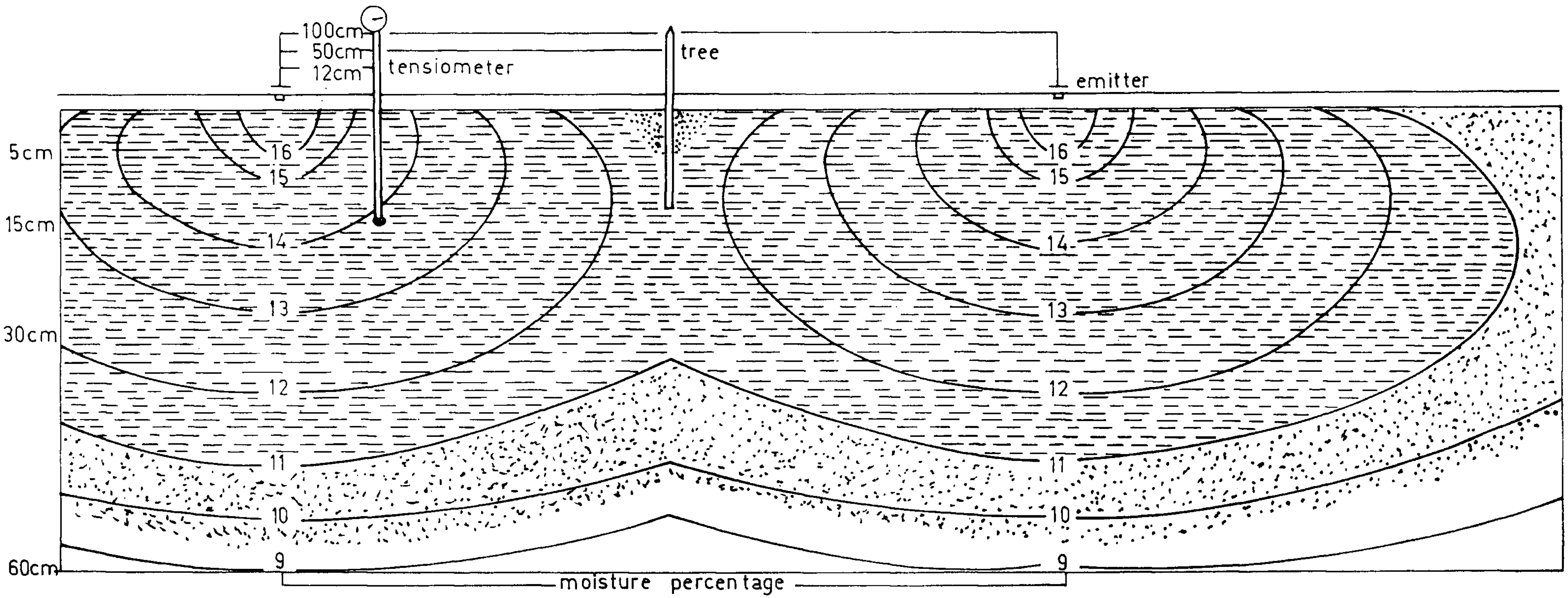


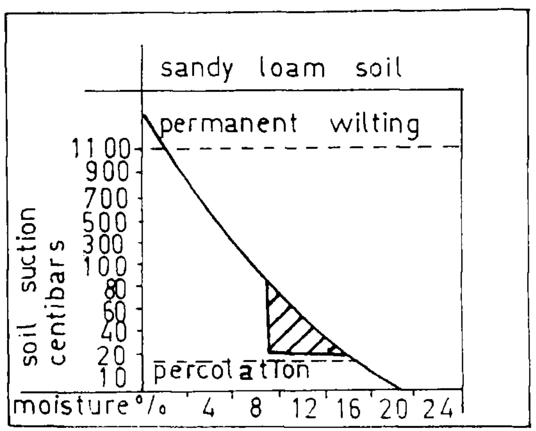
1 parameters for vegetables and new planted trees

2 parameters for perennial garden plants, shrubberries and young trees

3 parameters for mature trees

Figure 4.8: Moisture and salt gradients in a sandy loam soil produced by drip irrigation **controlled** by tensiometer





reference diagram of moisture percentage in relation to soil suction in a sandy loam soil.
(After ref. 4.6)

permanet moisture gradient by the given tensiometer position

samples taken on 9 . 7 . 1974
tensiometer adjustment at 20 centibars **vacuum**
emitter discharge rate 1.5 l/h
electrical cond. of irrigation water **3.2 millimhos/cm** at 25 °C

= 2.0 to 2.5 millimhos / cm at 25 °C soil water in the ratio 1 : 5

= 2.5 to 3.0 millimhos / cm at 25 °C soil water in the ratio 1 : 5

The minimum size of wetting pattern for irrigating trees or when converting mature trees to drip irrigation should be such that 25% to 30% of the total root system is supplied with water [4.4] and [4.5] the distribution of salts in the soil profile follows the general pattern of the water flow. Salt accumulations can be observed in the transmission zone area from wet to dry, up the 11% soil moisture gradient (see Chapter 3.3). To avoid an increase of salt concentration by a decrease of the soil moisture, precise soil moisture control in the wetted root zone is necessary (see Chapter 1.2.2).

The effectivity of permanently controlled soil moisture by using irrigation water with an electrical conductivity of 3.9 millimhos/cm at 25 °C could be demonstrated in the cultivation of apple trees in 1973, also in the South East of Spain. Leaves of trees in this three year old cultivation, irrigated by border strips, became chlorotic and branches stopped their growing because of salt stress. About six months after irrigating by tensiometer controlled drip irrigation, the leaves changed their colour to dark green and the branches showed marked development.

The following Figure 4.9 shows a young apple tree with healthy growth on the branch tips in contrast to the former leaf sizes and branch developments.

(ii) In cultivation of trees, the layout of the emitter lines consists normally of one emitter line per tree row, equipped with two emitters per tree. As with most kinds of trees, the area of root development is concentrated between the stem and the end of the lateral branches, the emitters should be placed in the middle of this zone. When starting drip irrigation of young trees, the placement of the emitters should be variably adapted to the tree's development.

Figure 4.10 shows above a possibility of the layout of the emitters in young trees. Here, a loop is fixed between the emitters on both sides of the stem. The arrows show the emitters can be placed along with tree growth, until their fixed position is reached; for this, flexible pipe material is required.

Weed control in tree crops can be done by machinery between rows along the emitter lines. Weed growth around the emitters normally must be controlled by hand or by herbicides. Another possibility of controlling weeds may consist in sowing legumes which need little of the irrigation water but which incorporate organic material and nitrogen into the soil. Furthermore, the wilting of these plants can indicate the possibility of emitter blockage. (see Chapter 3.7)

In vegetables, one emitter line can normally serve for irrigating two rows. Only in cultivations with a crop row distance of more than 1.5 m, is a separate emitter line required for each row. This is because of the limited horizontal water movement capacity of the soil. By hand planting, plant positioning in circles around the emitters is possible thus maximising the use of the soil surface. On dry soils, the soil should be wetted before or immediately after planting. Because of the emitter pipes, weed control by machinery is normally not possible so that this should be done by herbicides before planting. As furrows or rills for water conducting are not necessary in drip irrigation, nearly all kinds of plants may be cultivated on a flat surface. Because the soil surface is not wetted, crust breaking will not be required.

Figure 4.11 shows different possibilities of layout and plant positions of vegetables.

Mineral fertilizer can be dissolved and injected into the irrigation water but care has to be taken of possible adverse compound formations as a result of chemical reactions between injected fertilizer and chemical water impurities (see Chapter 1.2.2).

The design of drip irrigation in detail involving the calculating of pipe diameters, friction losses and possible lengths of the emitter lines will not be treated in this thesis as corresponding data are available in the literature, e.g. Ref. 4.7.

It can be stated that drip irrigation represents in comparison to surface flooding or sprinkler irrigation an active, dynamic process for determining soil and crop specific data and their control, whereas surface flooding and sprinkler irrigation are passive reaction processes in relation to this data.

Figure 4.10: Emitter layout possibility and displacement from young to mature trees by forming loops.

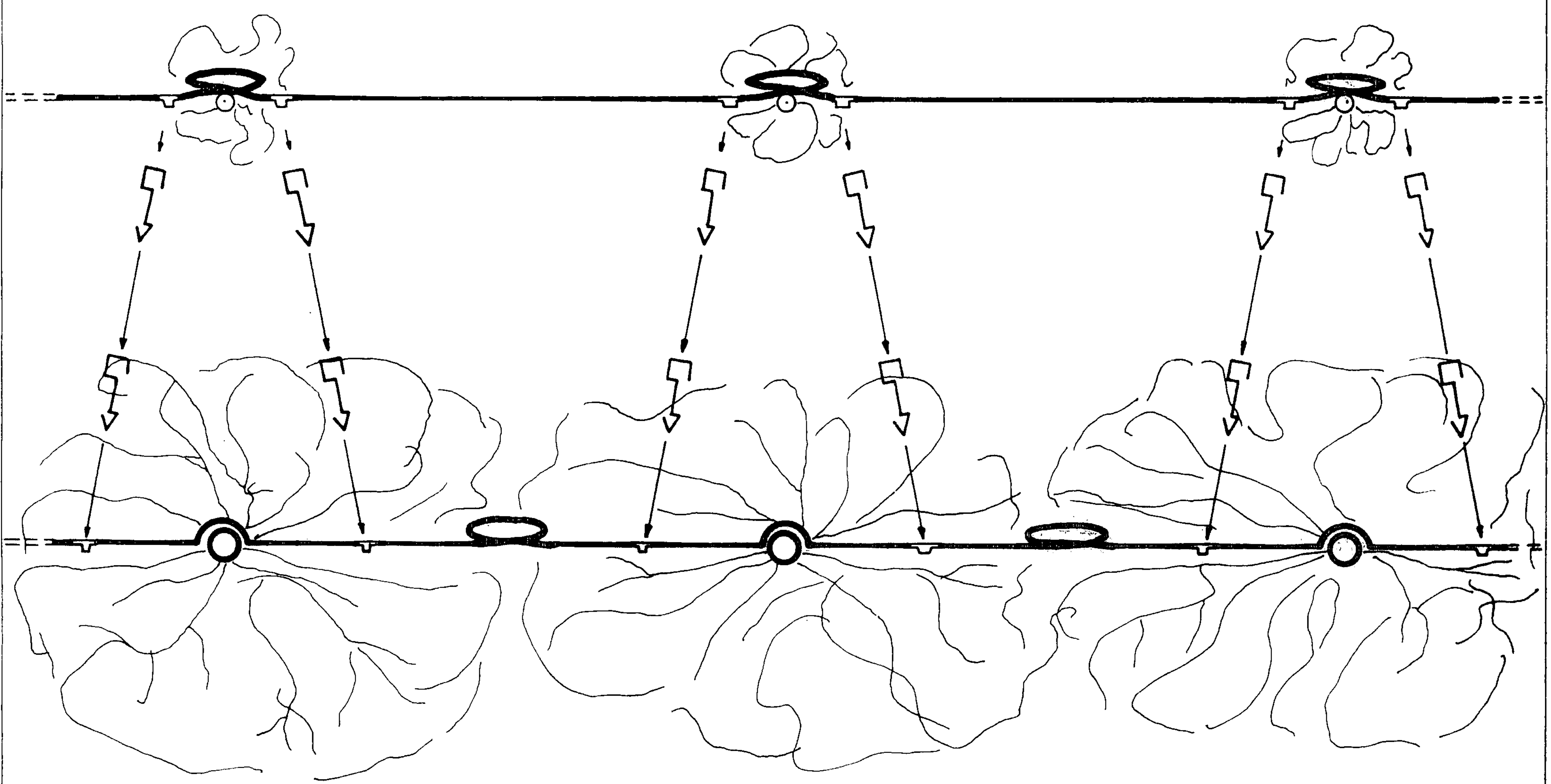
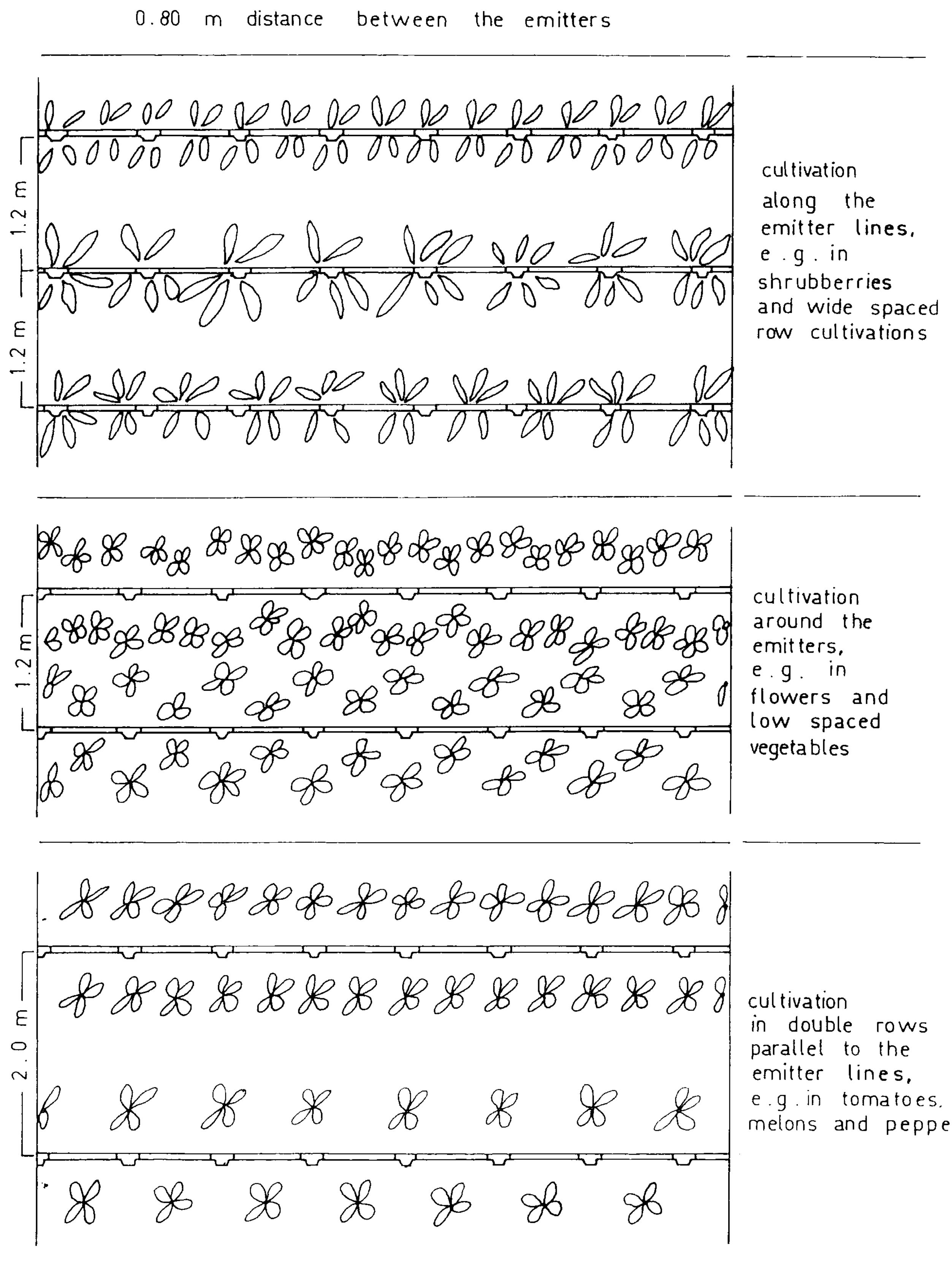


Figure 4.11: Emitter layout and different cultivation methods for vegetables



4.4 A TECHNICAL AND ECONOMIC COMPARISON BETWEEN DRIP IRRIGATION AND OTHER IRRIGATION SYSTEMS

In furrow, basin and border irrigation, as far as the main technical and economic characteristics are concerned, they are all very similar. As treated previously, these irrigation methods, therefore, will be subsumed under the single term 'surface irrigation' in the following comparison with sprinkler and drip irrigation.

According to the facts established in earlier Chapters, drip irrigation requires a high accuracy not only for determining the amount of irrigation water per irrigation cycle but also in the length of irrigation frequencies (see Chapters 1.2.2 and 3.2). This accuracy, which is necessary to produce optimum watering of the plants as well as an optimum efficiency of irrigation water used, can be obtained by automatic monitoring devices such as tensiometers or porous resistance blocks. As far as can be observed in the industry, the actual tendency is to use automatic control of the irrigation cycles for sprinkler irrigation systems by time switches, while for drip irrigation soil moisture detectors are used.
In surface irrigation systems, the automatisation of watering is limited to different systems of control gates, which regulate the water intake to the irrigated plots.

Since in drip irrigation only small parts of the soil surface are wetted, water losses by evaporation are nearly prevented. Also seepage losses can be diminished by the precise amount of irrigation water. Crust formation of the soil surface is avoided because the spaces between the plants are kept dry. However, this prevents the use of drip irrigation for watering closely growing crops such as forage, pasture and cereals. Also the germination of shallow seeds may be difficult by watering with drip irrigation.

As the monitoring devices around the emitters can maintain a constant soil moisture in the wetted area then water, with a higher salt content than is possible by sprinkler or surface irrigation, can be used. (Ref.: Chapters 1.2.1, 1.2.2, 3.2 and Fig. 4.5). This results because high frequency irrigation is easily possible by drip irrigation but cannot be obtained by, e.g. semi fixed sprinkler irrigation systems because of the high required labour demand for moving the equipment, or by surface irrigation because of the minimum water intake rate required per irrigation cycle. The salts accumulate in the transmission zone between the wet to the dry soil around the emitters. The salts can be leached, which is also possible by sprinkler and surface irrigation, by periodic overirrigation or even by seasonal rainfall.

In drip as well as in sprinkler irrigation, the water is delivered to the plants by overpressure through a closed pipe system. Since with sprinkler irrigation the water has to be spread through the air, the pressure demand is between two and ten times higher as for drip irrigation where the water leaves the pipes via the small outlets of the emitters. As a result of this, the energy demand and the associated running expenses are much lower in drip irrigation (Ref. Chapter 3.5).

Drip and sprinkler irrigation are both systems which do not require surface levelling which is usually necessary for most of the surface flooding irrigation systems.

As the name of the method implies, there is a drop by drop water delivery into the soil by drip irrigation and this must be paralleled with a horizontal water movement within the soil to obtain the requisite wetted area. In soils, where this movement is very limited, e.g. coarse sandy soils, the use of sprinkler irrigation may be relatively more favoured; mini sprinklers are utilized in such conditions, e.g. in Cyprus and South-Africa.[4.8]

With drip irrigation, neither the soil surface nor plant foliage will be moistured or wetted, so that air humidity is but slightly increased by irrigation. This may diminish the incidence of plant diseases, particularly fungal attacks. On the other hand, and for the same reason that micro-climate is little altered, drip irrigation cannot be used to prevent nightfrost damages as is found in sprinkler irrigation (see Chapter 3.1).

The small dimension water outlets in drip irrigation requires high quality maintenance of the system, not only in the filtration out of mechanical water impurities but also in several kinds of chemical treatments which may have to be applied, for example to avoid calcareous crust formation in the emitters as well as to prevent growth of bacteria and algae in the pipes. (Ref. Chapter 1.2.2). Therefore, the operators must be able to guarantee a high and constant level of maintenance. As well as this, the maintenance of the automatic monitoring devices should also be assured.

The possibility of high frequency irrigation (or in other words, permanent watering), requires as well as the above mentioned maintenance also a high level of agrotechnological know-how in the ability to determine the optimum soil moisture adapted to the water requirement of the plants.

As the emitter lines are placed on the soil surface, they may obstruct mechanized operations of soil preparations, weed control and harvest. Nevertheless, surface irrigation systems also, according to the size of the plots, water conducting canals as well as furrows, ridges and ditches, obstruct the use of machinery. In semi fixed sprinkler irrigation systems as well as by drip irrigation in, e.g.vegetables, the pipes and lines can be removed when not required. Whilst this requires a labour input,the demand is less than in earth moving of surface irrigation features.

Because of the possibility of high frequency watering by drip irrigation and the accompanying close control over the irrigation water, better crop response to irrigation and higher yields of better crop quality are possible than by the use of sprinkler or surface irrigation, see Ref. 3.6 and 4.9.

The initial investment expenses for drip irrigation equipment are as nearly as high as for fixed and semi-fixed sprinkler irrigation systems. For surface irrigation, the largest part of the initial investment consists in surface levelling and in the construction of canal systems. Because of the very different topographic conditions and the wide range of earth moving costs for levelling, initial investments for surface irrigation systems cannot be standardized but they are usually lower than for pressure irrigation systems (Ref.: Chapter 2.5). Because of the high initial investment costs of both, drip and sprinkler irrigation systems, to assure returns on the invested capital, a stable market situation for the products as well as a high agrotechnical and management level, is required. With surface irrigation, where the variable costs are usually higher than the fixed costs, instabilities in the market for production can be, to some extent, countered by the reduction of the current inputs.

The variable costs, in comparison with sprinkler and surface irrigation systems, are low in drip irrigation. This, besides the low energy demand for watering, results mainly from the comparatively low level of labour demand in drip irrigation. Also the costs, especially in labour, incurred for crust breaking and weed control which is obligatory in most orchard cultivations after each watering by sprinkler and surface irrigation are diminished in drip irrigation because of the permanently dry surface of the earth (Ref.: Chapter 2, Fig. 2.4).

Figure 4.12 in a simplified and schematic form compares the main characteristics as well as the fields of application of surface, semi-fixed sprinkler and drip irrigation. It can be observed that sprinkler irrigation takes an intermediate position between surface and drip irrigation. In terms of water delivery to the field through overpressure by a closed pipe system, sprinkler irrigation has the same characteristics as drip irrigation. These same characteristics of water delivery to the soil and plants have consequences for water efficiency (quantity required), water quality and requirements for energy, labour and running expenses, and here the position of sprinkler irrigation approximates closely to the characteristics of surface irrigation.

If we extract the relevant values from Fig. 4.12 the significant properties of drip irrigation can then be isolated as follows:

- advantages of drip irrigation:
  - high efficiency of irrigation watering,
  - low pressure demand for water distribution,
  - water application without levelling over uneven topography
  - control over the irrigation water is volumetrically assured with the additional advantage of:
  - salt control in the soil water,

    <u>and</u>
  - the possibility of continuous water application by high frequency irrigation cycles

<u>therefore</u>

- irrigation water with high content of dissolved salts can be applied without depressing growth,
- low water outlet rates per emitter and unit of time together with the possibility of high frequency irrigation cycles allow watering appropriate to a great range of soil types and of plant-water requirements,
- water losses by seepage can be easily avoided,
- uniform water applications along the line of flow by a closed pipe system,

<u>whereby</u>

- the plants are kept dry,
- air humidity will not be appreciably affected by watering,
- the soil surface between the plant spaces is kept dry,

<u>therefore</u>

- soil crust formation is avoided,

<u>and</u>

- water losses by evaporation are negligible,
- the possibility of automatic control,
- low labour demand,
- low demand in running expenses

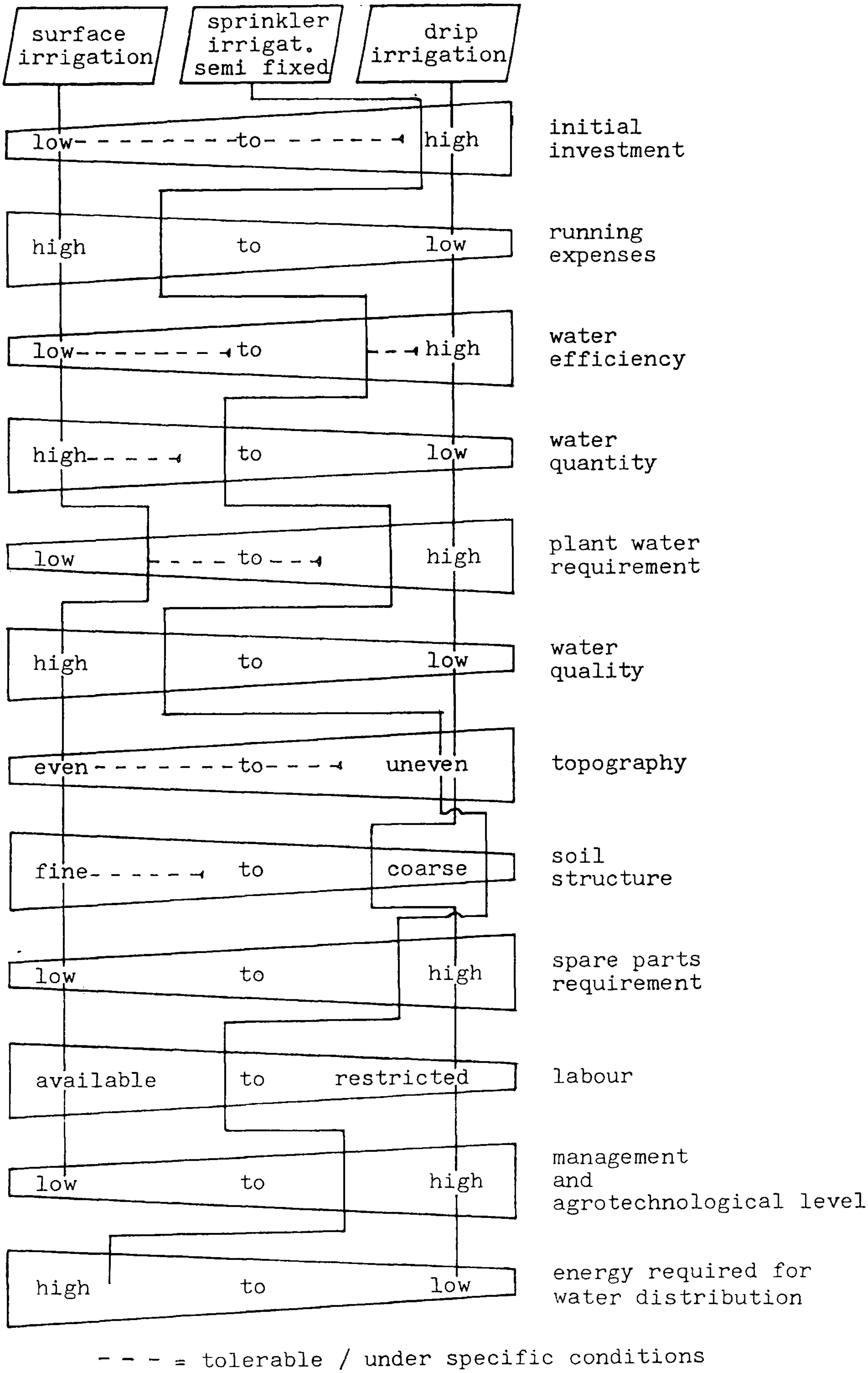
- disadvantages of drip irrigation
  - water filtration for solid impurities is obligatory,
  - chemical water treatment is necessary for specific dissolved chemical water impurities,
  - horizontal water movement capacity in the soil is required,

- pipe network of the emitters may obstruct mechanized cultivation or harvest operations,
- closely growing crops such as cereals, forage and pasture may not be irrigated by drip irrigation,
- crop protection against nightfrost damages cannot be obtained,
- spare parts should be available at short notice,

because

- during the growing season, stoppage of the system even for very short periods can injure crop growth,
- high initial cost of the equipment (almost the same as for sprinkler irrigation),
- economic and marketing situation should be assured for returns on capital,
- technical know-how of the operator is required,
- high technical and organisational background of the farmer and/or administrative organisation is necessary.

Figure 4.12 : Comparison of main characteristics and fields of application of different irrigation methods.



4.5 UTILIZATION OF DESIGN CRITERIA AND CHOICE OF IRRIGATION TECHNIQUES

The design criteria for any irrigation method, as stated in earlier chapters, consist of framework data, based on research or experimentation work which may be utilized as reference data appropriate to the specific local conditions. Therefore, in order to properly utilize the design criteria, data relating to local conditions, as shown in Figures 3.14 and 4.14 should be obtained and used in the identification of local suitabilities or constraints relevant to the installation or serviceability or specific irrigation methods. In the procedure of selecting one or more irrigation methods by using design criteria, a sequence of operational steps have to be taken consisting of e.g. data collecting, evaluating, preselection and selection of an irrigation method appropriate to the local conditions etc.. Figure 4.13 gives a summarized but systematic overview of such a sequence. As shown in Figure 4.13, the first step must consist in collecting data of the conditions which exist on a farm region, followed by their classification and comparison with requirements as shown in Figure 4.14. From Figure 4.14 we can identify consequencial restrictions on choice and/or certain critical demand requirements associated with one or more irrigation methods.

Step two is that of identifying those irrigation methods for which no restrictive or critical individual factor or combination of factors can be observed. There must also be proof of the applicability of such irrigation methods for watering the required crops. Here we can refer to the criteria illustrated in Figure 3.14. In the event that one or more restrictive, critical, or high investment demanding criteria can be identified at this level, further detailed evaluation criteria must be utilized. Such criteria have been considered in earlier Chapters and illustrated specifically in Figure 3.14 as well as in the Figures 3.6 to 3.13. Additionally, conditions, which in the first instance appear to militate against the use of a particular irrigation method, should be analysed in terms of the technical and economic feasibility of modifying them. The whole complex multi-variable situation cannot further be examined in this thesis and concentration is mainly on examining detailed individual or grouped problems. This can be justified by the already established fact of the critical importance of certain minimal inputs or satisfaction of specific requirements in local economic and environmental conditions. For example, if the water impurity is so high that usual standard filters may not be sufficient for drip irrigation, inquiries about other technical solutions and their costs should be carried out; or, if a shortage of labour is found where other conditions are suitable for sprinkler irrigation then investigations into sprinkler irrigation systems with less demand on man hours per ha should be realized (this would indicated in Table 4.14); or, if for drip irrigation which satisfies other requirements the human labour available is too low at trained level, the possibility of special training should be brought into consideration; or, if the topography for the otherwise suitable surface irrigation may be too accidented, one can select a surface irrigation method which may be tolerable under these condition, e.g. corrugation irrigation (see Figure 3.1 and/or Figure 3.14).

The third step consists in preselecting one or a few irrigation methods which could be established without serious restricting factors. In addition to this, priority has to be given to the particular aims to be achieved and which will vary from case to case, e.g. water saving, utilizing a labour intensive system or low initial investment. Also, the technical and economic feasibilities of improving existing irrigation methods, and of ascertaining the compatibility of new methods with a partially retained existing system, should be measured against the cost/benefit of innovation (see Chapter 4.2).

If these requirements can be obtained by one or a few of the preselected irrigation methods, as step four, the selection of the irrigation method most economic, cultivation specific and generally appropriate to local conditions, can be done. In the event that through none of the preselected irrigation methods can any required priority be achieved, then compromises must be reached by selecting those irrigation methods which are relatively most appropriate to the local conditions, i.e. where the lowest and least critical restraint points can be observed. Here, too, the examination of the possibilities of altering critical or restrictive local conditions has to be seriously considered.

The fifth step after having selected an irrigation system which seems to be the most appropriate to the local conditions consists of planning the irrigation specific agrotechnology as well as carrying out marketing research for the purpose of assuring returns on the required inputs, i.e. investment. In particular, there must be reasonable proof of whether high initial investments compared with low running expenses will be more favourable or vice versa.

Since each irrigation method requires specific agrotechnologic operations for crop production, the necessary cultivation techniques e.g. in soil preparation, crop planting and harvesting etc., will differ. Therefore, the introduction of new irrigation methods requires not only investment in the irrigation sector alone, but also in the choice of new cultivation operations, firstly in terms of follow-up investments on machinery, particularly for the purpose of specific soil preparation and cultivation work. Especially with drip irrigation, in comparison to surface and sprinkler irrigation, the precise droplet water distribution in high irrigation frequencies requires a strict control of irrigation and often also of the cultivation techniques (Ref. Chapter 4.3). To avoid overwatering or water stress, the irrigation water has to be directed to the plants by technical devices, which are automatically controlled by the soil moisture respondens, e.g. by the use of tensiometers or porous resistance blocks. These technical devices will normally support and assure the effective use of drip irrigation systems.

Further significant opportunities of varying cultivation techniques by watering with drip irrigation arise in the cultivation of crops which otherwise are normally ridge planted, such as tomato, paprika and melons. Under drip irrigation they can be grown on flat tilled surfaces, mostly in double rows as indicated on Figure 4.11, thus representing a considerable saving in land preparation and associated labour demand. In orchards, drip irrigation layout can be made to conform with other cultivation or tree spacing; even the cultivation work in crust breaking and weed control is minimized.

In this thesis we have had to confine attention to the relationship between conditions and requirements in term which relates almost entirely to the internal characteristics of irrigation systems. In this Chapter we have identified the criteria by which we can asses the appropriateness to local conditions of different irrigation methods, almost entirely in terms of 'on farm' conditions.

However, particularly in evaluating the drip irrigation method, attention has had to be drawn to the wider implications of the identified requirements for successful and optimal use of drip irrigation. In particular, certain points need to be emphasised. First as a sophisticated engineering system it requires skilled operation and good technical backup services. Secondly, as a sophisticated agricultural system it requires relatively skilled farmers able to appreciate the delicate environmental and biological responses involved. Thirdly, since drip irrigation requires high capital investment for installation, if returns are to be adequate then production may have to be concentrated in high-value products. This in turn has implications for marketing and processing - both in off - farm technology and in organisation. Question of location etc. also clearly become relevant to what must be intensive commercial farming.

Figure 4.13 : Summarized overview about the different steps for the selection of irrigation methods as being appropriated to local conditions.

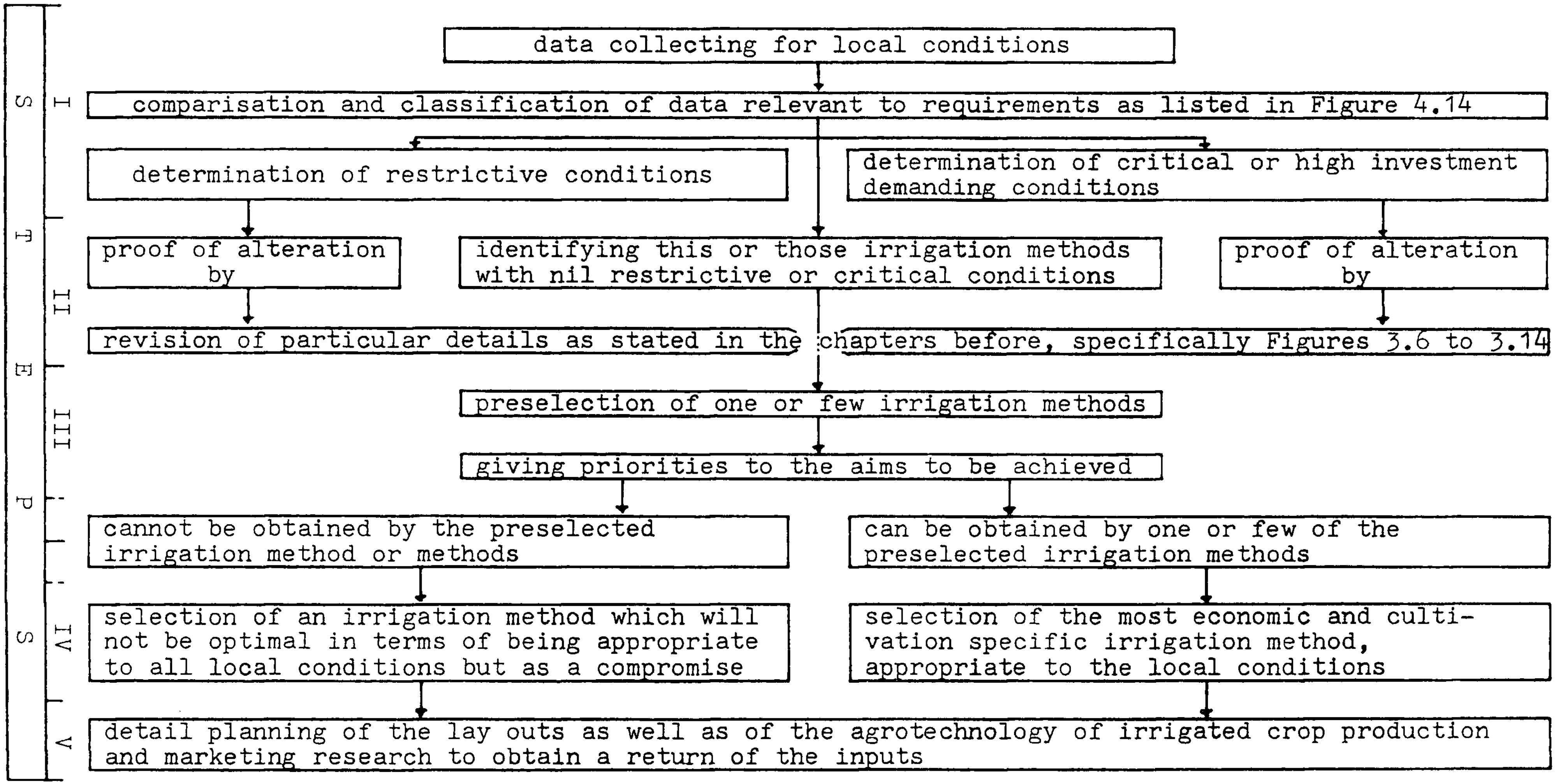


Figure 4.14 : Summarized but abstract overview about different conditions, affecting the construction, cost and serviceability of different irrigation methods (Ref.: Nomenclature)

c o n d i t i o n s		surface irrigation	sprinkler irrig.	drip irrig.
Climate	arid	+	+	+
	semi arid	+	+	+
	humid	+	+	+
Water quantity	limited	X	X	+
	moderate	(+)	(+)	+
	unlimited	+	+	+
Water salinity	low	+	+	+
	moderate	(+)	(+)	+
	high	X	X	(+)
Water impurity	low	-	-	+
	moderate	-	-	+
	high	-	-	Y
Topography - slope -	even	(+)	+	+
	slight	+	+	+
	moderate	+	+	+
	steep	Y	+	+
Soil	fine	+	(+)	+
	medium	+	+	+
	coarse	X	+	(+)
Drainage -permeability-	high	(+)	+	+
	moderate	+	+	+
	inhibited	(+)	(+)	(+)
Plant water demand	high	(+)	+	+
	moderate	+	+	+
	low	+	+	+
Energy for water distribut.	available	/	+	+
	limited	/	(+)	+
	restricted	/	X	(+)
Capital	available	+	+	+
	limited	+	(+)	(+)
	restricted	(+)	X	X
Management	trained	+	+	+
	moderate	+	+	(+)
	low level	(+)	X	X
Labour	available	+	+	+
	restricted	(+)	(+)	+
	trained	+	+	+
	moderate	+	+	(+)
	low level	(+)	(+)	X
Agro-technology	advanced	+	+	+
	moderate	+	(+)	(+)
	low level	(+)	(+)	X
Spare parts	available	/	+	+
	limited	/	(+)	(+)
	restricted	/	X	X

- = no influence
/ = not required
+ = required

(+) = critical condition
Y = high demand of investment
X = restrictive condition

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CHAPTER FIVE

CONCLUSION

In this thesis the advantages and disadvantages of surface, sprinkler and drip irrigation in terms of their main characteristics and requirements have been described. Drip irrigation has been compared with other irrigation methods by the use of theoretical data as well as through practical case study examples. As a result of this, we have shown that the successful operation of any irrigation method depends on its specific appropriateness to local conditions. An attempt was then made to develop a check system which allows us to evaluate whether drip irrigation or other irrigation methods would be more appropriate to various local conditions. This was adapted as an objective, because drip irrigation represents a relatively new irrigation method for which codes of practice based on practical experiences are not as well established as for the traditional irrigation methods such as surface and sprinkler irrigation.

We can summarise the 'on-farm' situation as follows. First, drip irrigation in almost all cases is a recommendable technology for watering row crops such as vegetables in greenhouses or under open air conditions, as well as orchards and shrubberries. Secondly, in particular where there is a shortage of irrigation water, or irrigation water contains a high salt content, in conditions of difficult topographies, heavy soils with low infiltration rates or where there is an extreme tendency to the formation of soil crust, in all these cases drip irrigation can be recommended as being the primus inter pares of the irrigation methods. Lastly, labour shortage on one hand as well as, on the other, the desire to cultivate intensive and high valued crops, both favour the use of drip irrigation.

Generally, drip irrigation might be seen as a technology which provides high water use efficiencies of up to 90%, associated with nearly absolute control over the placement and amount of water applied; these features perhaps make it the obvious choice for arid and semi-arid regions.

The agrotechnological consequences of the application of drip irrigation are not so severely restricting that they represent in themselves in many cases serious inhabitions of the use of this method. For example, the intensive utilization of limited water resources had been realized by drip irrigation and the method favoured equally suitable in regions as different as Israel and many parts of the U.S.A.. Theoretically this could have provided the basis for the choice of this method of irrigation in other countries with serious problems of water shortage as in Egypt or sub-humid India and Pakistan. Here, we have to recognise other factors which militate against the use of highly sophisticated irrigation techniques, for example inappropriate

- macro and micro-economic situations such as inadequate transport networks, low purchasing power of large sections of the population. Further, in many such countries we find a low level of education and technical training of the farmers. These factors are relevant also to most of inter-tropical Africa.

In most of the less developed countries, the general policy for reclaiming new irrigated areas as well as the improvement of already cultivated regions, is based on extension on areas covered by surface flooding irrigation. This in many cases is also well regarded as being relatively labour-intensive as well as within the capacity of broad number of farmers. Nevertheless, we also find isolated installations of drip and sprinkler irrigation, mostly managed by trained local or foreign management in such regions. During personal stay in Northern Senegal in 1978 it was observed that The State Sugar Company had taken the decision to change the furrow irrigation system to drip irrigation for a few thousand ha of sugarcane using plastic pipes extruded by the estate company. In this case, the lower direct demand for labour required by drip irrigation produced unfavourable side effect on employment. However, such effects, assuming a dynamic general development movement, could be negated if the general level of farm mechanisation rises with a consequential rise in demand for 'off-farm' labour. For example, the extension of the irrigated area with the subsequent increase in range of farm products, etc, can create new working places in the processing industries for agricultural products as well as in the manufactures and repair services. These examples are used only to illustrate the more general contextual social and economic systems within which to appropriate any particular irrigation technology have to be measured. However, all things being equal, we can assent that the technology of drip irrigation cannot be successfully introduced into a poorly or non-mechanised farm structure or into poorly commercialised societies, but it can be easily embeded at a broad level into mechanised farming structures and sophisticated societies.

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