Water and Environment Centre

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Water uses

Water use in agriculture

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Table of Contents

List of figures

List of tables

List of Boxes

List of Photos

Acronyms

CWR	: Crop Water requirement
ET	: Evapotranspiration
ETo	: Reference Evapotrapiration
FAO	: Food and Agriculture Organisation
FMIS	: Farmer Managed Irrigation System
ICID	: International Commision for Irrigation and Drainage
ICOLD	: International Commission of Large Dams
IFAD	: International Fund for Agriculture Development
IMF	: International Monetary Fund
IMT	: Irrigation Managemet Transfers
IWRM	: Integrated Water Resource Management
ISF	: Irrigation Service Fee
LA	: Latin America
RAM	: Readily Available Moisture
SSIS	: Small Scale Irrigation System
TAM	: Total Available Moisture
USDA	: United States Department of Agriculture
WHO	: World Health Organisation
WUA	: Water Users Association
WWF	: World Water Forum

1 Water, agriculture and society

1.1 Water: a global issue

Water is an essential part of human life. It is vital to human metabolism as well having a major influence on our health. It is vital for plant growth and survival of animals. It is also a source of other societal needs, especially transport and power, and is essential for many industrial activities. Finally, water bodies provide us with recreation and relaxation. In many societies water bodies like rivers and lakes have spiritual significance, and may be treated as religious entities.

Water is so essential in societal needs that we often look at the different sectors of water use. Looking at the changing needs of different water sectors is an essential part of both regional planning and water planning. The sectors of water use identified in economic planning are:

- agriculture
- public health (water supply and sanitation, or domestic use)
- industrial use
- ecosystems (river, delta, wetlands)
- hydro-electric power
- transport (navigation)
- recreation

"A key characteristic of the world's freshwater resources is their uneven distribution in time and space. Until recently, water resource management focused almost exclusively on redistributing water to when and where people want it for their use. This is a supply-side (engineering) approach. However, there are many signs that water is running out - or at least getting a lot less plentiful in more places as populations and per capita water use grow - and damaging ecosystems from which it is withdrawn. So, we need to look at what water is used for and to manage these competing claims in an integrated framework." (Cosgrove and Rijsberman 2000:6)

Table 1.1: Global Water Use in the 20th Century

Use (in km^3)	**1900**	**1950**	**1995**
Agriculture			
Withdrawal	500	1,100	2,500
Consumption	300	700	1,750
Industry			
Withdrawal	40	200	750
Consumption	5	20	80
Domestic use			
Withdrawal	20	90	350
Consumption	5	15	50
Reservoirs (evaporation)	0	10	200
Totals			

Withdrawal	600	1,400	3,800
Consumption	300	750	2,100

source: Cosgrove and Rijsberman 2000, table 2.1)

A household uses between 25 l/capita (rural India) and 250 l/capita (United Kingdom) per day. Crops use water according to their type (see Table 2.2) and industrial products according to their production process (see Table 2.3).

Table 1.2: Some rough indications of water requirements of crop

(cubic metres per hectare per year or cropping season)

Crop	Water requirement	
Sugar Cane	18,000	irrigated wet crops
Rice	15,000	
Lucerne	12,000	
Vegetables	12,000	
Wheat	9,000	irrigated dry crops
Cotton	9,000	

Table 1.3: Water requirements for industry

Product	Water requirement
1 tonne of steel	225,000 litres
1 loaf of bread	1700 litres
1 litre of beer	400 litres
1weekend newspaper	400 litres

During this course, you may hear a lot about efficiency. Mostly we talk about efficiency in a technical sense, in terms how close supply meets requirements. However, people now discuss 'allocative efficiency' - to look at the allocation of water to different uses (sectors) which yield different values to society. As water becomes scarcer, there is pressure to shift water into more valuable use - to raise allocative efficiency. How can this be done? Supposing you are a country like Jordan where water is scarce, but currently still used for 'low value' agriculture for reasons of national security and land occupation. You could chose to shift water into industry that will earn sufficient income for you to buy these crops and import them. However, you can think of this as 'imported water' or 'virtual water' supporting your economy.

The British professor Tony Allan introduced the concept of “Virtual Water” in a paper in 1997. “Virtual water” refers to the water needed to produce food products and imported into a country (in a virtual way) when the food products are imported. Thus, if Egypt imports 1 kg of wheat, they virtually import 1,000 litres of water (if 1 ha produces 9 tonnes and uses 9,000 m^3 of water). Main argument of Allan is that it is much more economically sound to import food than to invest in expensive irrigation systems in arid and semi-arid regions like the Middle East and North Africa as the wheat produced in the United States is grown with free-of-costs rainwater.

The self-sufficiency in fresh water of arid countries is closely related to food production and food import. As a human being only needs 1 cubic metre per year for drinking water, and about 50 to 100 cubic metres per year for other domestic uses, and an individual needs 1,000 cubic metres to raise food for one year If this last part is imported, even arid countries in the Middle East can be self-sufficient in freshwater. Thus, the international politics and economics concerning cereal trade are equally important to study when looking at water scarcity in the Middle East. Scientists looking only at the watershed as a closed hydrological system miss that point.

References and further reading

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1.2 World food requirements and the role of irrigation in food supply

The debate about agriculture and food production has orientated itself around two major debates: sustainable agriculture and food security. Adequate water supplies are essential to both, and indeed it is water that will be the key scarce resource in the next century.

Sustainable agriculture has been a topic of major concern over the last decade. We will use the following definition:

"Food production that can be continued indefinitely without destroying the natural bases which supports it"

This brings in concerns for adequate stocks and flows of food to meet basic needs, produced without negative impacts on the environment.

For food security, we also have to look at availability of resources to produce food and peoples access to these resources, and not only methods of production. In the past, the main concern was availability and access to land. More recently, three other concerns have arisen: biodiversity, soil fertility and water availability, and also how these interact. In this lecture, we will look at some of the problems of water availability. We also have to look at entitlements; how people produce goods and earn incomes to access and acquire food. We return to this issue of access and entitlements in a later lecture.

So, we need more food, but it also has to be at reasonable prices, and accessible to people. We also have to look for better nutrition, not just cereal supply.

Irrigated agriculture currently provides around 30% of all food crops, and over 45% of all grains. It supports over 55% of rice and wheat production: this is expected to increase to 65% by the year 2000. Irrigation will provide at least 66% and possibly 80% of incremental food needs required by 2025.

Very considerable attention is being given also to rain fed agriculture, to provide food, prevent migration and maintain the environment. However, irrigation is essential for future world foodstuffs.

Here are indicated the rates of increase in food production which are needed

- Agriculture as a whole: 2% per year
- Irrigated agriculture: 3% per year

The current irrigated area worldwide amounts 271 million hectares, of which more than 65% is in Asia.

Irrigation has already been introduced on most of the available land with possibilities for irrigation, although some new sites still exist. In addition, land will go out of production as cities expand. Thus, what strategies are we now looking at for production, and what are their future prospects? Better management and conservation of water will play a major role in future food security. There are different ways of looking at available water:

Green water: Rainwater utilised by vegetation or lost through evaporation (i.e. used in evapotranspiration). Some 25% of this is already used in agriculture. The remainder must supply other human uses, and other natural vegetation needs. Total yearly amount of green water is estimated at 60,000 km^3 of which 60% is used for rain fed food production.

Blue water: available in rivers, lakes, and aquifers, and requiring technology to access it and move it. Some of this is accessible i.e. quite easily accessed. Over 50% of this is now used. Some is hardly accessible (deep aquifers, river flows in floods), but people are already looking at it. A major concern is to see how 'blue water' already mobilised can be managed better. Total yearly amount of blue water is estimated at 40,000 km^3 of which 2,500 km^3 is withdrawn for irrigation (see Table 2.1). Groundwater is thought to play a major role in Blue water use for irrigation during the next decades (FAO 2003).

A strategy that has been used is the ***Green Revolution Package*** (1950's-1980's). This strategy to increase yields rested heavily on improvement of crop varieties, increased used of chemicals and expanding areas under irrigation. The components of this strategy are elaborated below. We cannot underestimate its importance despite some negative impacts. In Asia, it has given production growth rates of 3-4% a year during the 1970's and 1980's in many regions, above the rate of population increase. This has improved food supplies, almost eliminated famine and allowed export of food grains. However, its prospects as a single strategy for the future are limited.

The components of the Green Revolution strategy:

A. Varietal improvement.

Genetic manipulation has focused in hybrid maize, high-yielding rice and wheat, and in the 1960's gave a quantum leap in yields in many areas (40% with moderate fertiliser use).

Varietal improvement has targeted three key areas:

- larger edible fraction in plant biomass production,
- increased responsiveness to inputs,
- greater environmental tolerance, including things like pest resistance and photo-insensitivity.

Many of these have been mixed blessings e.g. people have other uses for plant residues besides food.

The 'quantum leaps' of the 1960's and 1970's have not been repeated. Estimates suggest that already 80% wheat and rice areas and 50% maize areas are using improved varieties. Considering prospects for the future it can be said that it is very uncertain that major new yield breakthroughs will occur. Emphasis is returning to farmers and their understanding of crops. Other areas of biotechnology/ecological agriculture are likely to become more irrelevant (see next section).

B. Agro-chemical use.

Very rapid increase in use of fertilisers, less in pesticides (average use in Asia still only 25% that of Japan). The major concern is that we are seeing diminishing returns from application of fertiliser as the soil becomes exhausted. Emphasis is returning to resource management at farm level.

C. Expansion of irrigated area.

Between 1960 and 1990, the area under irrigation grew from 100 million hectares to 170 million hectares. The biggest growth rate (2.5 million hectares per year) was in the decade 1970-1980. It is still growing, and will continue to grow for the next decades, but at a lower rate (1.5-0, 8 million hectares a year). There is less land available, but it is increasingly expensive and the best sites have already been developed.

At current trends, Asia will develop all its irrigable lands between 2015-2025. There is still a lot of theoretical potential in Africa. However, this faces many challenges, such as unreliable water supply, transport and marketing problems, and incidence of disease (e.g. tsetse fly in central Africa). So, irrigation expansion is not the only answer for the future.

The Green Revolution package has generated other concerns, apart from inadequacy for the future needs. It had many impacts on agrarian conditions, and fertilisers brought pollution problems. It is also very expensive in terms of energy use. Many fertilisers are derived from fossil fuels, and water for irrigation is often pumped from groundwater.

So, the work within elements of the Green Revolution strategy remains, but it is increasingly inadequate to meet future needs. So, what else is emerging?

The new strategy, which might be followed, is called *The Resource Management Revolution.* It consists of the following elements:

A. Targeting the yield gap.

This involves:

a) improving the performance of infrastructure and agricultural services, especially to improve efficiency.

b) improved resource management and environmental management, for example, managing our soils and water better so we have less waste and degradation, using less fertilisers and fossil sources of energy. Agriculture with low external inputs has received much attention.

c) emphasising other dimensions of biotechnology, notably biological engineering, greater attention to livestock, more research on agro-forestry species and new methods of cultivation (tillage*)*. Plant breeding remains the fifth important strand of biotechnology, and we can re-locate it here away from its link with agro-chemicals and land expansion. We know much can come from new areas of biological engineering, but it seems more benefits will come in temperate and humid areas, so it is still a challenge to find options for the semi-arid tropics. We also have to recognise public concerns over biological engineering.

d) using existing capacities of land and labour more effectively; we are returning to studies of land use and resource availability in a new way (more later!).

e) reducing production risks and empowering local management; for example negotiating more secure rights to land and water, promoting coping strategies and insurance mechanisms.

B. Promoting innovation instead of intensification.

Intensification of existing activities means getting more out of existing resources with existing technologies and institutions i.e. is production oriented.

Innovation in activities means changing the technologies and institutions to bring different benefits to different people i.e. it is benefit oriented. Innovation requires risk-taking.

Innovation can actually mean de-intensification. People do not always want further intensification, or that labour is not available. Sometimes the land itself cannot take it.

***C.* Promoting livelihood thinking and the new professionalism.**

This involves changes in behaviour towards better understanding of farmer's needs and knowledge, and not just changes in technology to be delivered to farmers.

***D.* Promoting the blue revolution for better water management and conservation.**

The key international document governing this discussion is the Dublin Statement of 1992. Its key principles are:

Box 1.1: The Dublin Statement

The Dublin Statement

Water management requires an integrated approach, linking social and economic development with protection of natural ecosystems.

Water development and management should be based on participatory approaches (This is sometimes re-written as management at the lowest possible level, although this is not the same thing!).

Recognition of women for their role in provision and management of water;

Water should be recognised as an economic good.

N.B. There is a fifth principle proposed in the water debate, but it remains controversial. This is: *"Government as promoter not provider."* It is not in the Dublin statement, but is said repeatedly alongside the above four.

The second World Water Forum, held in March 2000 in The Hague, took as its theme 'Towards Water Security', and worked to develop the Vision for water in the 21st century. The Forum looked particularly at Visions for 'Water for Food': Water for People: and water for Nature. Also all the regions presented their visions, and even some subject areas also developed a vision. There was much debate and also disagreement, which will carry through into the next Forum event. This forum set up:

Global water security targets:

- Comprehensive policies and strategies for IWRM in process of implementation in 75% of countries by 2005 and in all countries by 2015
- Proportion of people not having access to hygienic sanitation facilities reduced by half by 2015
- Proportion of people not having sustainable access to adequate quantities for affordable and safe water reduced by half by 2015
- Increased water productivity for food production from rainfed and irrigated farming by 30% by 2015
- Reduce the risk from floods for 50% of people living in the floodplains by 2015
- National standards to ensure the health of freshwater ecosystems, established in all countries by 2005, and programmes to improve the health of freshwater ecosystems implemented by 2015

1.3 How irrigation increases production options, and current intervention areas in irrigation

Irrigation is the supply of water for crop production. Conscious change in a situation is an intervention. Irrigation has been a significant area of public intervention to change production and livelihoods.

Irrigation can change several aspects of production - it can increase intensity of land use (more crops per year), it can increase yield and it allows different more valuable crops to be grown. The way irrigation is used depends a lot on the local climate and the availability of irrigation water.

In dry and seasonal climates, it allows several crops a year to be grown, as water is available:

In seasonal climates with a dry season, irrigation can allow early planting, so that crops can make maximum use of subsequent rain or warmer weather, and also sometimes early planting allows an early harvest before adverse weather (very wet, foggy, or cold) sets in. In climates with dry periods, it ensures water is available to overcome dry spells. In cold periods or cold nights, irrigation can be used as protection against frost damage

This means we have many areas where irrigation brings major increases in production against which quite high infrastructure costs can be offset. However, in other areas, irrigation may only be used part of the year. The cost of irrigation infrastructure depends on its complexity, materials and size - and it is often very expensive. Matching 'costs and benefits' - the costs of building systems with the income stream from irrigation - is an ongoing challenge in irrigation development.

In some areas, people invest all their work in irrigated crops. However, when holding sizes are small, families also take up other 'off-farm' employment, which may be in other people's fields or some distance away. In other areas, people may cultivate both rain fed and irrigation crops in different plots of land. It is sometimes quite hard to make realistic estimates of income and food supply. One problem facing many 'smallholder' irrigation schemes is that incomes remain very low - as prices are low and plots are small - although irrigation is still valued from the increased security it can bring.

New Irrigation systems are still being built - but at a much lower rate than 30 years ago. Much more intervention now takes place in rehabilitating or modernising existing irrigation infrastructure. The box below gives some of the technical objectives in current irrigation intervention- for which we must understand social context and not only the 'technical problem. These different problem contexts require you to understand much more about different ways of applying water and how different structures can control water - and how people are involved in both. However, today there is also a lot of work involved in reforming the organisations that manage irrigation, and modifying water laws. We return to this later in the chapter.

Irrigation systems not only support crop production: the water supply is also very important for domestic uses, for local agro-processing and for livestock breeding (often important in irrigation systems for providing traction as well as milk, meat and leather). Often reservoirs and streams supporting irrigation are used for fishing. There is now growing interest in 'multi-purpose use' of irrigation water, and how a water source may have many different livelihood dimensions linked with it.

1.4 Irrigation in Yemen

1.4.1 Yemen Background

1.4.1.1 Location

1.4.1.2 Climate

1.4.1.3 Soil

1.4.2 Agriculture

1.4.3 History of Irrigation in Yemen

1.4.4 Review of recently developed project

1.4.4.1 Tihama irrigation project

1.4.4.2 Wadi Zabid

1.4.4.3 Wadi Rima

1.4.4.4 Wadi Mawr

1.4.4.5 Marib Dam

2 Irrigation typologies

2.1 Introduction and definition

It is estimated that 15-20% of the worldwide total cultivated area is irrigated. This relatively small fraction of agriculture is however contributing as much as 35-40% of gross agricultural output. Irrigation is therefore considered a very important technique in assuring humankind's food supply.

Irrigation is defined as "artificially supplying and systematically dividing of water for agriculture and horticulture in order to obtain higher or qualitatively better production."

2.2 Classifications

2.2.1 Introduction

Irrigation systems show a large variety in size, method, infrastructure, objective, source, etc. Irrigation-jargon has come into existence to classify different irrigation systems. The classifications are not universal. Each country or region has its own classification, which is relevant for its irrigation systems.

With the help of the twelve characteristics (or parameters) of an irrigation system, described below, the main physical and operational aspects of an irrigation system can be defined. Upon describing one particular irrigation system one needs to specify for each of the thirteen indicators, which one applies to the concerned system. To get a complete picture of a system some more essential elements should be added, like: main crops, climate, river discharges, reservoir capacity, land tenure, history of irrigated agriculture and several other socio-economic characteristics of the irrigated agriculture.

2.2.2 Size

In classification according to size, mainly three classes are distinguished: large, medium and small scale. This terminology, however, is quite unclear, because what is medium sized in one region can be considered large-scale in another region (see Tables 4.1 and 4.2).

Table 2.1: Scale definitions in different countries
(in hectares)

Country/Region	Small	Medium	Large
India	< 2,000	2,000 - 10,000	> 10,000
Africa	< 50	50 - 500	> 500
Mexico	< 100	100 - 3,000	> 3,000

Table 2.2: Scale defiitions within Nepal
(in hectares)

Region	Small	Medium	Large
Hills	< 50	50 - 500	> 500
Plains	< 200	200 - 5,000	> 5,000

Quite often, the scale of the system is also used as an indication of the management type: small-scale is built and managed by the water users themselves and medium and large-scale systems are built, operated and maintained by State agencies. However, this need no be the case. In some countries small size irrigation systems are operated by State agencies and in other countries large size irrigation systems are completely operated and maintained by water users' associations (WUA). Hunt (1988) gives examples from different parts of the world to illustrate this: see Table 2.3.

Table 2.3: Size and type of organisation

Name of system	**Country**	**Size** (in hectares)	**Type of organisation**	
			Farmers	**Government**
San Juan	México	600	**X**	
Tayuban	Java	700		**X**
Zanjera Danum	Philippines	1,500	**X**	
Vicente Guerrero	Mexico	1,575	**X**	
12-Go	Japan	5,500	**X**	
Moncada	Spain	7,000	**X**	
Morelia #2	Mexico	8,000		**X**
New Cache La Poudre	USA	15,400	**X**	
Angat River	Philippines	26,900		**X**
Rio Mayo	Mexico	96,000		**X**
Fresno	USA	97,000	**X**	
Chia-nan	Taiwan	150,000	**X**	
Hindiyah Barrage	Iraq	209,000		**X**
King's River	USA	458,000	**X**	
Gezira Scheme	Sudan	730,000		**X**

(adapted from Hunt 1988:346)

Size is often used to give an indication of the complexity of the system: if you have a bigger system you will have a more complex network of irrigation canals and distribution of the water within this network will become more difficult. However, in this respect the field size should be taken into account. If the fields are relatively big (like in the USA) the number of farms to be served in a certain area is less, and this reduces the complexity of the distribution. In some areas with highly fragmented land holdings (like in Asia) even a small system might have many users and therewith a complex distribution network and a complex irrigation organisation. Therefore, if scale refers to the complexity of the water distribution, a better indication of the scale of a system is the number of users, and not the total command area.

References and further reading

Hunt, R.C., 1988, "Size and the structure of authority in canal irrigation systems", in: *Journal of Anthropological Research*, Vol. 44, Nr. 4, pp. 335-355.

2.2.3 Irrigation application method

The irrigation method refers to the way the irrigation water is applied to the crop. Main factors influencing the use of a certain method are costs (availability) of labour, cost (availability) of water, the crop and the topography of the plot.

Surface irrigation:

- River flood (recessed floods and spate irrigation)
- Wild flooding

- Basin
- Border
- Furrow

Sprinkler

- Overhead sprinkler (fixed or moveable)
- Mini-sprinkler
- Side-roll system (linear-move)
- Centre-pivot

Micro irrigation (or "trickle"):

- Drip
- Micro sprinkler (spray irrigation)
- Subsurface irrigation (underground drip lines)

Subsurface irrigation (groundwater recharge or controlled drainage)

River flood

Rivers come out of their beds in the rainy season. On the floodplains crops can be grown after the flood has recessed. These are often rivers with no or low discharge during the greater part of the year. This is the case in arid regions like Jemen, parts of Tunisia and Eritrea. Flooding can be favoured by building temporary or permanent obstacles in the riverbed. This is called *spate irrigation*. In North Africa it is called *épandage des crues*.

One can also make use of rivers with a proper discharge the whole year around, and that gives flooding in the rainy season. In this way floating rice is cultivated in parts of Bangladesh, Thailand and Malaysia. Rice has already started growing before the floods and during the flood, rice grows along with the rising water levels' sometimes until 2 meters high. For this cultivation practice, use is being made of special rice-varieties, which have the disadvantage of giving rather low yields. This type of agriculture is called *flood rice agriculture*.

Another kind of agriculture system takes place on the floodplains after recession of floods. Sowing of the crop is done just after the flood has left. Crops grow on the water that has come into the soil during the floods. This type of agriculture is *called flood recession agriculture*. A well-known place where this is practiced is along the Senegal River in the northern part of Senegal.

Wild flooding

Wild flooding is a method of application water to a field from a canal. It means the flow from the canal is just released into the field without much further control of the water. The field will generally have a gentle slope and the water will just more or less spread across the field by flowing. In many cases the farmer will have made some furrows or borders in her or his field to divert the water. However in general wild flooding is practiced in case the farmer is not interested in an even spreading of the water, but is rather interested in saving labour. It must be clear that this method will result in low application uniformity and efficiency.

Basin irrigation

In basin irrigation fields are provided with small benches (bunds). Water is let into horizontal basins (level basin irrigation) during a short time, after which it infiltrates. The infiltration rate is an important parameter in this type of irrigation because most crops cannot survive when there is a layer of water on the field for some hours.

In rice-cultivation, which is most often practiced by basin irrigation, water can flow continuously into the basin, because rice grows best with a water-layer on the field. Basin irrigation is the oldest and most practiced form of irrigation.

Most soils are fit for basin irrigation. Strongly permeable soils however ask for small dimensions in order to obtain uniform infiltration. In sloping areas this method is costly because of the necessity of land levelling to create horizontal fields. Small basins are problematic in mechanised agriculture.

Border

Border irrigation consists of a long and small strip (border) of land, between 3 and 30 meter in width, having a bench on both sides. The border has a uniform slope. Water is let in at the upper reach, and flows down along the slope. During this water infiltrates, just like the case in basin irrigation, this method is less suitable for crops that cannot stand inundation for a long time.

Border irrigation definitely needs a uniform slope in the direction of the flow. Perpendicular to the direction of the flow the border should be absolutely horizontal. The length of the strip is determined by the infiltration rate of the soil (this will be further explained in Part B of this course). These requirements can only be fulfilled in mechanised agriculture (land levelling with help of laser, etc.). Border irrigation is therefore almost only practised in the USA.

Furrow

In this method the crop is growing on specially made ridges, and furrows between these ridges are supplied with water. In this way crops that cannot stand inundation can be grown. Furrow irrigation knows four basic appearances: as level furrows, as graded furrows, as contour furrows, and as zigzag furrows. Water supply to the furrows comes from the irrigation canal at the head-end of the furrow. Siphons can be used to apply water to the furrow at the exactly designed flow rate.

Row crops are especially suited for this irrigation method, just like crops that are damaged by inundation. Examples of these crops are maize, potato, cotton and vegetables. Another advantage of furrows is that there is no crusting, like for example in the case with sprinklers. Disadvantages of furrows are the labour, which is required to make ridges and furrows, and the salinization of the ridges, which might occur under certain conditions.

Level furrows can be found in "modern" and "traditional" agriculture. In the Perimètre Irriguée Villageois (PIV) along the Senegal-river, basins are used in the hot season to grow rice, and level furrows with ridges are created to make the irrigated cultivation of maize possible.

Graded furrows need a precise tuning of length of the furrows to infiltration rate, slope and discharge It therefore also required mechanised agriculture as is widely spread in the USA.

Zigzag furrows are used to reduce the slope of the furrow and lengthen the time of infiltration. They can be found on the steep slopes of the Andes.

Surge flow is now a new method mainly applied in the USA. In surge flow the flow to each furrow is intermitted. By not applying the whole volume in a continuous flow the infiltration time becomes larger. Some current scientific research in furrow irrigation focuses on surge flow. Surge irrigation is the intermittent application of water in furrows. A butterfly valve with a computer controller is used to direct the flow to either side of the valve. By alternating flow on each side, an intermittent wetting and soaking cycle is created in the furrow. This wetting and soaking action settles soil particles in the bottom of the furrow and may reduce the intake rate of the soil. If the intake rate is reduced, water will advance down the furrow faster. Faster advance can result in a more uniform application, reducing the amount of water needed to effectively irrigate the field.

Sprinkler

In sprinkling water is supplied under pressure through pipes and distributed over the land by sprinklers under a pressure of 2 to 5 bars[1]. There are permanent installations (e.g. in orchards and vineyards), semi-permanent and portable installations. These systems do not need levelling of the land. Operation is fairly simple, but maintenance requires specialists. The purchase is expensive, and the materials often have to be imported. Some installations move through the fields pulled by cables or a tractor (center-pivot and linear moving side-roll systems). This however, does need landlevelling.

Sprinkling gives the opportunity to:

Photo 2.1: Different size of Sprinklers

- Irrigation of slopes
- irrigation of highly permeable soils
- frost-protection
- automation
- application of fertiliser, etc.
- Potentially efficient use of water (not necessarily!)

Disadvantages are:

- high costs of purchase and maintenance
- wind-sensitivity
- slaking of soils, because of drops hitting the soil (especially if they fall from a high crop)
- Overhead sprinkling has the disadvantage that a relative high percentage of the water first hits the leaves and might cause damage there, due to sunburn and fungi diseases. In addition, sprinkler irrigation may cause higher evaporation losses. Mini sprinklers have been invented to sprinkler below the crop canopy.

Drip or trickle irrigation

In drip irrigation water is conveyed through pipelines and supplied to the plant by tubes. To do this, the tubes have at regular distances emitters with an opening of about 1 mm^2. These holes cannot be smaller; otherwise, they would be clocked too quickly. Still these holes give

[1] 1 bar = 10 meters of water = 1 atm. = 10^5 Pa = 100 kPa

much too high discharge for a permanent outflow. Therefore, instead of using a normal hole, special emitters or drippers have been developed. In these emitters, the discharge is reduced by means of zigzag grooves or tubes to a discharge of about 2 to 8 litres per hour. Still these discharges are too high to work continuously, so the dripping should be applied only a limited number of hours per day. Drip irrigation is commonly applied when water is scarce, labour expensive and/or investments will be paid back by higher yields.

Advantages of the system are:

- lower evaporation
- low losses due to conveyance and possibly low application losses
- simple to automate and to combine with application of fertilizer, etc.
- it requires little labour input (but checking of the functioning of all emitters takes a lot of labour!)
- pressures needed are low (1 bar), so energy costs are low.

Disadvantages are:

- systems are sensitive to blocking
- high costs for installing and maintenance
- salinisation (less leaching)

Micro sprinkler (spray irrigation) and subsurface irrigation (underground drip lines) are just two examples of the enormous variety the drip-enterprises are offering on the market. Check internet for hundreds of types of emitters, etc.

Subsurface irrigation

During dry periods, water can be supplied by increasing the water level in the drainage-system. The drainage system may consist of ditches, tubes or a combination of these. Water reaches the root zone by capillary rise. This method is not very effective and knows very high losses. However, it can contribute to overcoming dry periods. In the lower parts of the Netherlands, water levels are for this reason dammed up during dry periods.

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2.2.4 The source: surface or groundwater or conjunctive

If surface water comes from a river, different methods can be used to extract the water and put it into a canal:

- Just a simple canal starting at the bank of the river without any damming of the river to up-head the water.

- By means of a water-intake structure: this means a weir across the river to head-up the water and upstream of the weir a "head work" which can be used to regulate the flow into the canal. The weir can be temporal (has to be rebuild after heavy rainfall, like in spate irrigation) or permanent.

- By means of a dam in the river that creates a storage reservoir from which the canal can take water.

- By means of a pump from the river.

Groundwater can be extracted in several ways

- Natural spring (in that case groundwater actually becomes surface water).

- Artesian wells. Water that comes to surface under pressure.

- Qanat system (or horizontal well): this is an ancient technique in which a horizontal mine is excavated (often under a riverbed). Ancient qanat (or falaj) systems can be found in China, India, Pakistan, North Africa, Spain, Mexico and Peru.

- Open wells. Water can be taken out by buckets, Persian wheels or pumps.

- Tube wells. These are bored or sprouted wells, with a diameter of just some decimetres. A pump (at the bottom of the tube if the well is deeper than 4 meters) brings the water to the surface. Shallow tube wells take water from the directly accessible groundwater layer (water table) and deep tube wells take water mostly from confined aquifers.

In many irrigation systems both surface and groundwater is used for irrigation, this is called "conjunctive use." The canal system then feeds (by leakage) the groundwater, which is used as a source of irrigation. Especially in schemes in northern India conjunctive irrigation gains popularity. The surface canal water does not reach the tail end. The tail-enders supplement the surface water by pumping from shallow tube wells, the groundwater is replenished by the leaking canals in the head-end.

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2.2.5 Perennial or seasonal irrigation

Water sources might enable irrigation the whole year round (perennial) or just a part of the year (seasonal). This depends on discharge-characteristics of the source, and on the possibility of storage. If there are for example reservoirs, water sources that would otherwise not provide water the whole year round, can now give sufficient water for continuous irrigated agriculture. In this way irrigated agriculture can also be practised during the dry season, which leads to more yields per year.

In some climate conditions irrigation is only required during one season of the year. In the other season the rainfall might be sufficient or the temperatures might be too low for crop growth. If irrigation is needed depends also on the crop.

2.2.6 Gravity or lift irrigation

The elevation of the field in relation to the elevation of the source and the fall needed to convey water horizontally from source to field, determine if water can transported by gravity alone, or if additional lifting devices are needed.

In non-gravity systems often water is pumped out of the river or reservoir into the canal-system, in which it is transported by gravity to the fields. Sometimes the canals are situated below the field level (e.g. in Egypt). This implies that at field-level farmers need a pump or another lifting device in order to get water on the fields. This gives an incentive for the farmers to irrigate efficiently if they have to pay the pumping costs per used unit of electricity of fuel. In general, pumping of water has to be reduced to a minimum to reduce operation costs.

Irrigation in the higher parts of the Netherlands is comparable to that. Water in the ditches (the main function of the ditches is drainage) is pumped up and used in sprinklers.

2.2.7 Complete or supplementary irrigation

When artificial water supply supplements rainfall (sometimes dew is also important) and the available soil moisture, it is called supplementary irrigation. The irrigation growing season coincides with the rain fed growing season. Irrigation increases production and gives more certainty in getting a yield. In this case, the rain fed farming system remains intact or crop-diversification is realised by introducing crops that require more water.

In case of complete irrigation the whole crop water requirements are fulfilled by irrigation. This often means that agriculture will take place in the dry season (or in very arid area where water can be taken from an aquifer or rivers flowing from a humid area). If the rainfall pattern in the rainy season is rather irregular, this rainfall is not taken into account when determining the irrigation requirements. Irrigation in this case also supplies the whole crop water requirements.

2.2.8 Supply-based or demand-based

In a supply-based irrigation system it is centrally determined what would be the discharge in the main canal and how this flow is divided over the secondary and tertiary blocks. The farmer receives a centrally determined amount of water. This amount might be based on calculations of the crop water requirement by a central irrigation agency based on the crops the farmers are supposed to grow. The volume of water a farmer receives might also be determined by a water right. In many small-scale irrigation systems built and managed by farmers themselves the investments a farmer (and his/her family) makes in the building of the system is related to the amount of water the farmer will receive. This principle is called "hydraulic property" creation (see Coward 1986).

In on-demand systems the farmer decides when she or he takes water and at what discharge. It is more or less comparable to most domestic water supply systems: you open the tap and you can regulate the flow and duration of the outflow. On-demand puts high demands no the system: conveyance-capacity must be guaranteed. Storage of water needs to be situated near the users. The water delivery to the farmers is measured to be able to let the farmers pay the volume of water they have used.

In many systems the farmers are given the freedom to choose the timing and duration of their water turn, but they have to request this some days in advance from the irrigation agency. This is called an "on-request" system. In most systems the flow delivered at farm level (called "main d'eau") is fixed, for example 20 or 40 l/s. The total volume of water, which one farmer can request in a complete irrigation season is in most cases restricted. The volumetric quota is mostly a maximum amount of water per hectare, sometimes differentiated per crop.

2.2.9 Upstream or downstream control

Water flow in the main and secondary canals has to be controlled in a way the water can be delivered to the tertiary blocks as scheduled. Basically two modes of physical control are possible: upstream or downstream control. In the upstream control mode the amount of water flowing into a certain canal is determined by the control structure in the head (so upstream) of the canal. In the downstream control mode, the water flow in a canal is determined by the control structures, which take water from the canal. A domestic water supply network is downstream control. You, as a water user at home, determine with the tap in your kitchen or bathroom how much and when you take water. The network just responds to your action by supplying you the water you want. This is downstream control. Downstream control is the physical mode of control that fits well with the "on-demand" water allocation described above.

Photo 2.2: AMIL gate to regulate water in upstream control mode (Portugal)

Most irrigation systems in the world are upstream controlled. Thus, the farmers cannot take any amount of water at will by turning on the tap; they have to wait until the irrigation agency delivers water to their plot. Upstream control puts the control over the water with the irrigation agency. This is the physical control principle that fits best with "supply-oriented" or "on-request" allocation described above.

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2.2.10 Continuous or rotational flow

In continuous supply a canal or a farmers' plot receives water 24 hours per day, 7 days in the week with a low discharge. In rotation the flow to a canal or plot is scheduled for only a limited time of the week and the flow will return there with a certain frequency.

In most irrigation systems, the flow in the main and secondary canals is continuous. The discharge is adapted to the schedule, but is not intermitted. Inside the tertiary block the flow is rotated among the farmers' plots. Only in paddy cultivation, one often sees continuous flow at field level: the "sawa" system.

Worldwide there have been established many different ways to rotate water among the farmers in the tertiary block. By changing the frequency and duration (but keeping the "main d'eau" or water flow at field level constant) of the water turns to the plots the water supply can be adapted to the crop water requirements

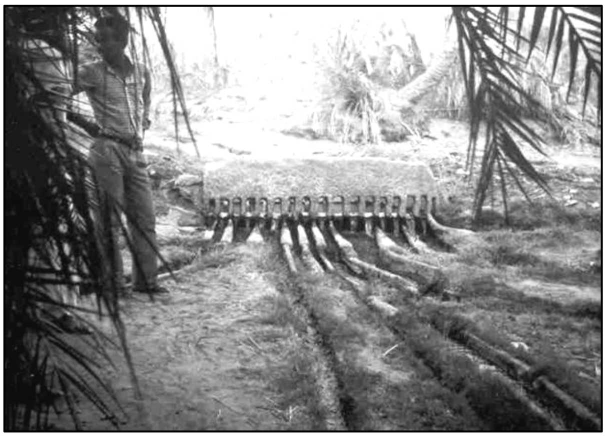

Photo 2.3: Proportional division structure

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2.2.11 Farmer or state operated

Last ten years the issue of management of irrigation systems by the water users themselves has become one of the top items discussed in the world of irrigation management. In most countries one can find small irrigation schemes that have been built, maintained and operated by groups of farmers. Those systems are called Farmer Managed Irrigation Systems (FMIS). Besides those "traditional" or "indigenous" systems the governments have built (with help of foreign financing) new large-scale irrigation systems. These new systems were (and are) operated, maintained and heavily subsidised by the government.

What started to become clear some twenty years ago is that the FMIS were functioning much better than the new-built large-scale government systems. As water users are organised better and are paying for the investment of the construction and the operation and maintenance of their system they take good care of the infrastructure of their system and use the water they receive efficiently. In State operated systems the users do not feel responsible for the infrastructure and just expect the government agency to deliver water to them and repair the system. As they pay nothing or little for the water they use they waste the water. Governmental agencies are often hierarchical organisations in which decisions about water distribution are made at central level. In that case there are opportunities for bona fide and unreliable employees who can make corrections respectively manipulations to the system for own purposes (corruption). This is a very general black and white picture, but in many case studies around the world this general picture was more or less confirmed.

After the discovery of the good functioning FMIS and the negative evaluation of many new-built government-run irrigation systems two things happened to boost the so-called "Irrigation Management Transfer" (IMT) movement. First the neo-liberal policies of International Monetary Fund (IMF) and the World Bank pushed the principles of the Structural Adjustment Programmes in many low-income countries. This implied reducing of the government spending especially on the bureaucracies like the big irrigation agencies. Second the failure of the top down model of agricultural planning practiced in many new-built large-scale irrigation projects put the governments to realise that a farmer needs flexibility in farm management to be able to cope with the divers conditions of climate and market to sustain a livelihood. The call for more participation in the decision taking in the organisation of the water management articulated well with the neo-liberal policies of breaking down the government involvement. Results of the IMT process can be seen in countries like the Philippines and Mexico where subsidies for irrigation have been cut and large systems have been transferred to Water Users' Associations (WUA’s).

Now in many large-scale irrigation systems there is a "combined" management: in the tertiary and maybe secondary level there are WUA who manage the system. The main system is still controlled by the government.

Roughly speaking one can say that most large-scale irrigation systems in Asia and Africa are (still?) government managed, at least at the main and secondary levels. Only in USA, Europe and Latin America (in LA 56% is privately run) larger areas of irrigated land can be found managed completely by WUA or private companies. However, in official government statistics the small scale FMIS are often overlooked. In Tunisia sixty percent of the irrigated area is government run. The forty percent privately owned and managed systems are mostly small systems using shallow groundwater.

2.2.12 Productive and protective irrigation

The distinction between productive and protective irrigation is mainly made in India. In colonial India many systems have been designed to give only water for protection of the crop (and livelihoods) and not provide sufficient water for optimal crop production. In protective irrigation the water is spread on an as big as possible area so that the maximum amount of families can profit from it. Result is that in a dry year the yields will not be very high (deficit irrigation), but at least many families can save their crop and will have at least something to eat. Per unit of water this gives more production increase than if the same unit of water is used in productive irrigation.

In productive irrigation the water scheduling is fit as good as possible to the crop water requirements. The productivity per unit of land is maximised (maximum crop production per hectare), but the productivity per volume of water used is less optimal.

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2.2.13 Volumetric payment or area-based fees

Last ten years the issue of payment of the water fee per volume of water used has received increased attention. Main idea is that it induces water saving if a farmer has to pay for the volume of water she or he uses. In an on-demand and an on-request system, irrigation water delivery can be charged by volume. Volumetric charging can be based on payment per volume allocated or per volume actually received at field level. An example of charging per volume allocated is the other case under study: Chancay-Lambayeque. An example of charging per actually received volume at field level is described by Van Bentum (1995): the Campo de Cartagena system in Spain.

There is a long tradition of debate on the desirability and feasibility of volumetric charging corresponding to consumption at field level, especially in gravity open canal systems (e.g. Erry 1936, Repetto 1986, Small and Carruthers 1991, Guillet 2000, Lee 1997, Grimble 1997). Main advantage claimed is the reduction of volume used by the user, and therewith reduction of wastage and thus increased efficiency. In Peru another goal of volumetric charging seems to be important: it proves to be an effective way to increase “Irrigation Service Fee” (ISF) recovery. It is an ‘administrative point of control’: before each turn the water user has to pay for the volume to be received. As the WUA does not get subsidy of operation of the system the fee recovery is very important.

Main problem put forward is the need and difficulty to measure and register water consumption at field level in open canals in a system with many smallholders. If not the volume received but the volume assigned is billed the problem arises that the delivery should be very close to the allocation otherwise the users will protest.

3 Irrigated agriculture: problems and risks

3.1 Introduction

From chapter 2 it has become clear that irrigation worldwide generates an enormous increase of the productivity of land and contributes to an important part of world food production. These arguments were (and still are) used to defend the construction of many large dams and implementation of many large-scale irrigation systems by development banks, national governments and donor agencies.

However, since the 1970s it has become clear that large-scale irrigation system development can also have enormous negative impacts on local livelihoods and nature. Following are eight problems or risks faced by large-scale irrigation systems.

3.2 Problems of irrigation developments

3.2.1 Financing operation and maintenance

Designing and building a large-scale irrigation system proved to be a difficult and costly operation. However, maintaining it proved to be an even greater financial burden. In Low Income Countries often the construction of large-scale systems is financed by loans or grants from High Income Countries. The operation and maintenance, however, are supposed to be financed by the national government itself. This proved to be a heavy financial burden for many countries. Often a problem is "solved" in a particular way. The system is allowed to deteriorate for several years. Then, a foreign grant or loan is taken to rehabilitate the system.

Often the maintenance costs were not important design-criteria during the design of canals and structures. Thus sedimentation of the canals and reservoirs and maintenance needed for the division structures is often more costly than strictly necessary. For example a lined canal constructed with prefab-concrete slabs on pillars, like you will find many in Tunisia, is quick to install but needs more regular upkeep than lined canals dug into the earth.

Besides the financial aspect, the organization of maintenance neither is an easy task. Only recently articles and books have been published about "asset management" in irrigation systems. In asset management, each component of the irrigation system - but also the machinery and tools used to operate and maintain the system - is registered, monitored and evaluated. Each structure, machine and tool has an economic lifespan and should be rehabilitated, replaced or renewed after this lifespan, Sometimes earlier when the structure or machine is damaged. If all components are monitored at a regular bases and a database is kept with all the information, decisions can be taken easily on maintenance and replacement of all structures and machines in an irrigation system. Very few systems work with this type of asset management. (see Malano and Van Hofwegen 1999)

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Malano, H.M. and P.J.M. van Hofwegen, 1999, *Management of Irrigation and Drainage Systems, A Service Approach*, IHE Monograph 3, A.A.Balkema, Rotterdam.

3.2.2 Health risks

(Much of this paragraph is, with kind permission, copied from PhD thesis of E. Boelee 2000. Otherwise not for citation).

Higher and more diverse food production in irrigated agriculture brings health benefits to farmer families in the newly irrigated areas. People may gain access to more varied and higher quality nutrition through increased income from cash crops. The construction or rehabilitation of irrigation schemes has other positive impacts on the human environment through increased employment possibilities, which would raise income and subsequently increase access to health services and education. The irrigation system may also influence the wider physical environment in a positive way and thus increase human wellbeing. E.g. seepage from earthen irrigation canals improves the quality of ground water. In South Asia, hand pumps are installed along the canals to extract this sweet water for drinking.

Diseases may also be reduced with the development of water resources. Water-washed diseases like louse-borne infections and infectious eye and skin diseases may be reduced dramatically. The higher availability of water, regardless of quality, enhances personal hygiene practices (Cairncross & Feachem 1993). This effect is especially widespread in arid and semi-arid regions, where irrigation systems may be the main source of water for all purposes. In dry regions other vector-borne diseases may also be diminished, such as African trypanosomiasis or sleeping sickness (Hunter et al 1993). Tsetse flies prefer high air saturation deficits and are probably chased away from the relative humidity of irrigated fields (Takken 1989).

Negative impacts of irrigation development on health often consist of vector-borne diseases (e.g. Oomen et al 1988/1990, Bolton 1992, Hunter et al 1993, Steele et al 1997). The exact cause of increase in disease often remains indistinct, even in the case of epidemics. Sometimes this un-clarity has led to cases where irrigation has been mentioned as the cause of an outbreak of water-related diseases without thorough proof. Often health hazards are not caused by the irrigation system as such, but resulting from accompanying phenomena such as (seasonal) migration (Birley 1995). Generally a whole complex of factors associated with water resources development changes the human and biological environment and triggers other causes. Even when outbreaks of water-related diseases conclusively follow from irrigation development, the importance of this impact is extremely difficult to determine. After all, the human environment interacts with the irrigation system in more than one way and human health may profit more from increased food availability than it would suffer from diseases. However, these impacts may reach different groups of people. Farmers who own land may benefit directly from increased yields while landless labourers only suffer from the water related diseases without improving their health in any other way. Positive health impacts do not cancel out the negative ones if they affect different groups of people to various degrees.

Changes in the water availability through irrigation may alter the cropping pattern. The replacement of subsistence crops by cash crops could lead to malnutrition through micronutrient deficiencies (Birley 1995). On the other hand, increased income from cash crops may increase access to food, education and health care.

A classification of transmission mechanisms is important as these are related to the appropriate environmental strategies for disease control (abstracted from: Cairncross and Feachem, 1993). Four routes are distinguished (see also Table 3.1).

A. Water-borne route

Truly water-borne transmission occurs when the pathogen is in the water that is drunk by a person or animal, which may then become infected (cholera, typhoid, infectious hepatitis, diarrhoeas, and dysenteries). The term ‘water-borne disease’ is also often, abusively, used instead of the term ‘water-related disease’. Transmission of such diseases is not strictly through water, but could take place through all other ‘faecal-oral’ routes as well (e.g. contaminated food).

B. Water-washed route

Caused by insufficient personal hygiene, often induced by low availability of water. Depends on quantity of water available, rather than on quality (diarrhoeal diseases, skin and eye infections).

C. Water-based route

A water-based disease is one whose pathogen spends a part of its life cycle in a water snail or other aquatic animal. All these diseases are due to infection by parasitic worms (helminths) which depend on aquatic intermediate hosts to complete their life cycles (schistosomiasis; Guinea worm).

D. Insect vector route

Diseases spread by insects, which either breed in water or bite near water (Malaria, yellow fever, dengue, river blindness).

Table 3.1: Four types of water related transmission route flor infections and the preventive strategies appropriate for each

Transmission Route	Preventive strategies
Water-borne	Improve quality of drinking water
	Prevent casual use of unprotected sources
Water-washed (or Water-scarce)	Increase water quantity used
	Improve accessibility and reliability of domestic water supply
Water-based	Reduce need for contact with infected water 1)
	Control snail populations 1)
	Reduce contamination of surface waters 2)
Water-related insect vector	Improve surface water management
	Destroy breeding sites of insects
	Reduce need to visit breeding sites
	Use mosquito netting

1) Applies to schistosomiasis only.
2) The preventive strategies appropriate to the water-based worms depend on the precise life-cycle of each and this is the only general prescription that can be given

(Source: Cairncross and Feachem, 1993)

The prevalence rate of a disease is the ratio between the number of cases and the number of people exposed tot the disease.

The incidence rate of a disease is the ratio of the number of newly diagnosed cases of a disease during a defined period divided by the population in question.

The construction of an irrigation scheme interacts with the biological environment and may create habitats for vectors and intermediate hosts of diseases. Simultaneously interaction with the human environment with these habitats exposes people to the disease agents. The association between irrigation and vector-borne diseases is probably as old as irrigation itself and has been systematically reported since the second half of the nineteenth century. Water related diseases, of which malaria and schistosomiasis are the most widespread, each have their own specific transmission cycle and relate differently to water and the irrigation environment.

Breeding sites for malaria mosquitoes, *Anopheles* species, are found in clear surface water, well available in irrigation schemes and an increase in vectors almost invariably leads to an increase in malaria. Wet rice fields are notorious for providing almost ideal breeding sites and rice field breeding *Anopheles* account for a great deal of the malaria transmission in rice-growing areas of the world (Gratz 1988).

Box 3.1: Expansion of irrigated area leading to malaria epidemics

In the mid 19th century the building of irrigation canals in India was followed by large malaria outbreaks (Bradley 1995). More recent studies in India show malaria rates that are 6-9 times higher (depending on the season) in villages along irrigation canals than in villages 40 km away (Hunter et al 1993). In the Indus River Basin Irrigation Development Project in Pakistan 25 large and medium sized dams were constructed for irrigation, causing a sharp rise in malaria infections. The 38000 ha Helmand River Irrigation Project in Afghanistan led to a similar increase in malaria (Diamant 1980).

Box 3.2: Disease outbreaks after vector population increase

In Burkina Faso a rice irrigation scheme was started in the Tiao river valley in 1955 that very quickly became an intense area of onchocerciasis (river blindness), transmitted by small black flies. Virtually the whole population was affected and 50% of people over 40 were blind by 1962 (Hunter et al 1993). In France and former Czechoslovakia the expansion of rice growing has resulted in an increase in various viral infections through the increase of vector mosquito populations (Mather & Trinh Ton That 1984).

In Cameroon a rice project brought almost 20 000 hectares under irrigation. Prevalence of schistosomiasis rose from 15 to 40% in schoolchildren. In Madagascar, schistosomiasis prevalence at schools within the irrigation scheme was 69%, while outside the scheme it was 7%. In Mali schistosomiasis is 5 times more common near irrigated rice fields of the Office du Niger than in traditional villages, while the rate of severe infection is 7 times higher (Hunter et al 1993). In the Caribbean Islands schistosomiasis has spread as well with water resources development. In Puerto Rico the shift from coffee production to sugar cane, supported by the development of irrigation systems, resulted in the spread of schistosomiasis in the 1930s (Oomen et al 1988).

The recommendations in the literature for measures that can be incorporated into the design of new irrigation systems can hardly be tested in practice, as extension of the area under irrigation is only possible in a few regions of the world. For the few cases where health aspects are taken into consideration in the design of new irrigation schemes, the exact location of the system and the siting of villages is an important factor. The distance between irrigation infrastructure and habitation may determine how often and how intensely the population is exposed to vectors or infested water. For several mosquito species, the flight range is known and when houses are located at a larger distance from the breeding sites, people will be less exposed to possibly infective bites. However, the benefits of having a canal nearby the house may be numerous too. During construction, when all the equipment is in the field, last minute adjustments to the design can be made and additional provisions like bridges and fences can be included in the works.

Box 3.3: Environmental control in colonial Indonesia

In Indonesia the so-called "hygienic exploitation" was developed at the beginning of this century by civil engineers together with medical specialists and entomologists. The efforts were directed mainly against malaria. First the local vector was identified and then the habitat of this Anopheles species was dealt with, the so-called species sanitation. All kinds of measures were experimented with in order to diminish vector populations in canals, ponds and rice fields. In a lot of cases vector density and malaria incidence decreased significantly. A good example is the management of marine fishponds that could sustain large populations of vector mosquitoes. A water management regime, the so-called hygienic exploitation, involved frequent drying of the ponds and thus reduced floating alga that provide shelter to larvae against fish. It led to strong reductions in malaria prevalence (Takken et al 1990).

The diverse character of multiple use of irrigation water and the lack of quantitative data, make it very difficult to estimate its overall effect on human health. The assessment of exact health impacts of drinking water supply projects is already hampered by methodological problems (Blum & Feachem 1983, Hoddinott 1996). Studying the effects of the use of irrigation water for domestic purposes is even more difficult, because this type of water use has hardly been studied at all in the context of irrigation ecology. Generally speaking, it seems that for the whole of multipurpose uses, there may be more health benefits than health hazards. However, to encourage the use of water for health improving activities, certain conditions should be met:

- Adequate provisions for safe drinking water, laundry, bathing, sanitation, solid waste disposal,
- Good roads along the canals,
- Continuous water flows in canals or intermittent flow with short rotation cycles,
- Flexible water distribution,
- Special water rights for other activities than irrigation,
- Upstream pollution control (with special attention to drainage, pesticides, and human activities in canals).

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3.2.3 Tail-end problem

The “tail-end problem” refers to the effect that relatively less water is delivered to the users located at the end of the irrigation canals compared to the users situated at the head-end of the watercourses. Three effects may cause the tail-end problem. First the seepage from the distribution canals. Especially in un-lined canals in light soils the seepage losses can be high. However, also in lined canals that are not maintained well the losses by leaking can be considerable. Second is the effect of water stealing by water users located along the canal. Water stealing by upstream water users is a problem in most large-scale irrigation systems with open canals. Third is the effect of the combination of undershot offtakes and overflow structures in the ongoing canal. The hydraulic behaviour of such a combination of flow division structures causes the effect that the upstream offtakes will take a relative constant out flow with fluctuations of the water flow in the feeder canal. This means that shortages in the main canal system will automatically be felt more in the tail-end of the system. This configuration of flow division structures is often found in irrigation schemes.

In some special cases the tail-end problem does not refer to relative shortages of water in the tail-end area, but refers to problems of too much water in the tail-end areas. This occurs for example in irrigation systems in Indonesia during the monsoon period. The abundance of water concentrates in the lower part of the system: the tail-end. There flooding of the land can cause problems.

In general, however, the tail-end problem refers to relative water scarcity in the downstream parts of the irrigation scheme. As described above the tail-end problem is related to technical problems (seepage, leaking and the type of offtake structures) and social problems: water stealing along the canals. Clearly the solutions for the tail-end problem include technical as well as social-organisational options. Against the seepage the canals can be lined with concrete. Against the leaking the maintenance should be improved. However, also social-organisational options can be thought of, like e.g. schedule extra water for the tail-end farmers to compensate for the losses. In addition, the financing of the lining and the organisation of the maintenance are in most cases more socio-technical matters than pure technical matters.

The solution for the hydraulic behaviour of the offtakes is change in division structures. Horst (1998) suggests the use of proportional overflow structures, because these structures distribute all fluctuations occurring in the main system proportional over all areas of the system. Thus it will not be only the tail-end suffering when there is less water than planned at the intake if the system. The proportional division structures, however, limit considerably the flexibility of the distribution of the water in the canal network.

Water stealing is a problem that can be combated with both technical and social measures. Technical measures are putting pad locks on the division gates, or converting the open canal system into a closed pipe system. The social control of water stealing is an important issue in the study of irrigation water management. The prevention of water theft by putting fines on water stealing proves to be very ineffective in most cases. It is virtually impossible to have police officers patrolling all canals day and night to fine offenders. Thus, the water users, among themselves should find means to control each other, monitor, and punish water stealing effectively. In this respect the social power relations between the water users in a tertiary block is important. If a big and powerful landowner is situated at the end of the tertiary canal, it was often found that no tail-end problem occurred. The head-end farmers did not dare to steal the water from the big landowner. In the case the landowner is situated in the head-end of the tertiary canal (which is often the case, and not coincidentally…) the tail-end problem was found to be very big. The big landowner can just take any water she or he wants and only the “leftovers” are for the small landowners in the tail end (see e.g. Mollinga 1998 on India).

Ostrom and Gardner (1993) found that the tail-end problem was related to the amount of labour required in the maintenance of the long feeder canals in small-scale Farmer Managed Irrigation Systems (FMIS) in Nepal. When relatively much labour was required (e.g. because the weir in the river was washed away frequently) the tail-end problem was less because the head-enders had to led through more water for the tail-ends in exchange for their labour. If the main and intake system of the scheme did not need much labour for maintenance (e.g. because a development organisation built a permanent weir in the river) the tail-end problem was relatively more severe: there was more difference between the water delivered to the tail-end area compared with the water delivered to the head-end area. This because the head-enders could take all the water they wanted because they did not need the co-operation of the tail-enders to get water.

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3.2.4 Social differentiation (including gender issues)

Introduction or (or change in) irrigated agriculture causes a number of fundamental changes in the livelihoods of farmers. In most cases, irrigation increases production, but also increases the labour requirements and the need for other inputs like fertilizer and pesticides. As patterns of production, labour and inputs use change this always has different percussions for different groups of people. Until the 1970s it was believed (in the international donor communities) that through the "trickle down" effect all rural people would benefit from increased production, also when at first instance only the more well-to-do farmers would be able to adopt and profit from the new (green revolution) technologies. In the '80s it became clear that this proposition could not be upheld. It was shown that poor people in many cases did not profit from the introduction of irrigation (or other new technologies) and that the income gap between the rich and poor became only bigger (see Shiva 1991, Harriss 1985). This is called "social differentiation". In some cases the poor people became even poorer due to the introduction of irrigation.

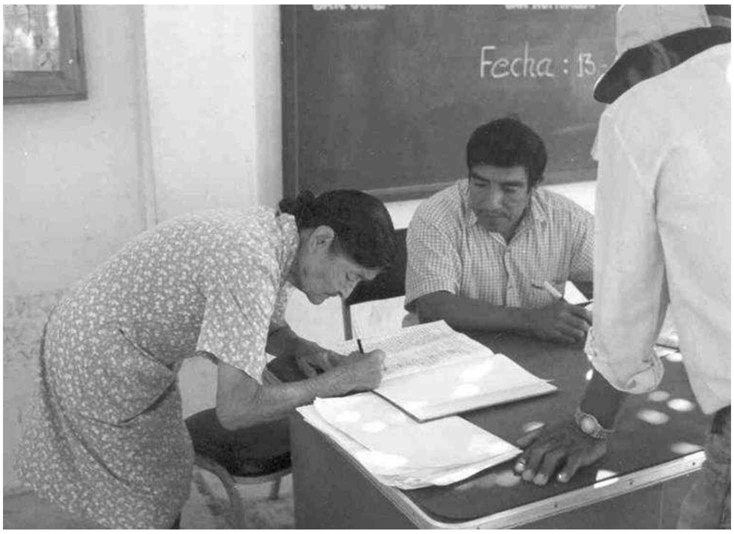

Photo 3.1: Female water user signing at a meeting of WUA

In many cases these "poor people" were the women. The men were automatically taken as the head of the household who should participate directly in the project. The assumption was "Farm households have a single production unit headed by individual males who command the resources of individual household members." However, this is often not according to the reality: there might be more than one production unit, and the head of the household does not necessarily command the resources of other members. Women might have their own productive subsystems in which they can have considerable autonomy with regard to labour allocation and income utilisation.

Box 3.4: Irrigation and Gender in Gambia and Sri Lanka cases

The Jahaly Pacharr project became operational in 1984. It was a special project, financed by IFAD, because it aimed at building a large-scale irrigation system (1,500 ha) for rice production with special attention for the role of women. Idea was to allocate rice plots to women. Women traditional grow rice in the swamp and tidal areas in Gambia. There exist three types of land. One is the land of the women: *kamanyango* (individual land right), the other is the land of the man (also *kamanyango*) and the last is the land of the household: *maruo*. The women work on their plot and also on the household plot, however, they have only the control over the produce of their own plot. The production of the household plot is controlled by the men. The men work mainly on their own plot. Under special conditions the women work a limited time on the men's plot. In earlier rice irrigation systems the goal of producing a marketable surplus of rice was not met because the plots were allocated to men but they did not have the labour to double-crop them.

Some years after the project started it seemed to have failed. The men have managed to get the control over the plots. Rice became a commercial crop, therefore, the men became interested in the traditional "women's crop." What went wrong? The project did not define the new irrigation plots for women as *kamanyango* land for women. Now, the men could get the majority of the plots as their individual *kamanyango* land in the initial stage of the land allocation. In the latter stage, 65% of the land did go to women, but not as their *kamanyango* land, but as a household plot: *maruo*. Thus, the women had no access to the produce (nor the benefit of the selling of the surplus), but did have to provide labour on this household plot. Thus, securing the double-crop (project aim), but women did the labour but did not get the rewards. In some parts the new irrigation schemes were built on the place where previously the women had their tidal rice plots.

The Mahaweli Scheme in Sri Lanka provides and other example. Kumar (1987:249) writes: "The consequence is that there is a large majority of subsistence farmers, as we have seen, earning approximately Rs. 300 to Rs. 400 a month, while a few rich farmers, with capital largely gained from compensation from land lost through reservoirs, as well as those situated at the head of channels, are able to make a profit by obtaining high yields from paddy cultivation. (…) Those who are rich within the scheme earn over Rs. 5000 per month would be traders, mill owners and middle-class people who have leased land from poor farmers who are unable to cultivate their allotment." Moreover, here again "The most negative effect of the scheme is the deprivation of land rights for women, which has made them economically dependent and without access to loans or credit." (ibid.:250

Source: (Carney 1988 and Kumar 1987:249)

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3.2.5 Salinity and sodicity

Two basic processes can lead to salinization: deficit irrigation and lack of drainage. With each irrigation gift salts are brought into the soil. If these salts are not leached out the salts will accumulate and surpassing a certain limit will affect the crop growth. As irrigation water always contains a certain amount of salts it is always necessary to flush out these salts. In some regions the rains in the wet season will wash out the salts brought into the soil during the irrigation period. In other, more arid, areas the irrigation water itself will have to leach out the salts. In that case extra irrigation water has to be supplied above the crop water requirements. This extra water is called the leaching requirement.

Photo 3.2: Cracked soil with white surface because of salts in Cotton field

Just supplying more water is not sufficient. The leach water should also be able to leave the soil. Therefore, drainage is an indispensable part of irrigation. In many irrigation projects this part was forgotten. The result is an irrigation system with nice irrigation channels in which the soil each year becomes more saline. Eventually the soil surface turns white and the soil properties are affected irreversible. In most cases, this salinization effect can be reversed by constructing drains and intensive leaching of the soil.

It is estimated that worldwide about 50 million hectares, or 20% of the irrigated area, has suffered a build-up of salts in the soil. Salinity is especially concentrated in the arid zones. Here deficit irrigation (thus little leaching) causes a build up of salts. Examples are the North Coast of Peru, the Southern former USSR countries and Western USA. In for example vast regions in Pakistan and India salinity is related to water logging. In Tunisia salinity of the soil due to irrigation is a problem in different regions. In e.g. the oasis areas, the salinity seems to be caused by over irrigation causing water logging in the lower areas of the oasis.

Some chemical background (adapted from: Van Dam and Aslam 1997)

Salinity usually refers to the total dissolved concentration of major inorganic ions (i.e. Na, Ca, Mg, K, HCO_3, SO_4 and CL) in irrigation, drainage and groundwater. Individual concentrations of these cations and anions in a unit volume of water can be expressed on a chemical equivalent basis, (milli-equivalents per litre) meq/l, or on a mass basis, mg/l. Total salt concentration (i.e. salinity) is then expressed in terms of either the sum of the cations or anions, in meq/l, or the sum of cations plus anions, in mg/l. A practical index of salinity is electric conductivity EC, expressed in units of deci-Siemens per metre (dS/m). An approximate relation (because it also depends upon the specific ionic composition) between EC and total salt concentration is:

1 dS/m = 10 meq/l = 700 mg/l (Rhoades et al. 1992)

thus 1 gram NaCl per litre ≈ 1.4 dS/m

EC is sometimes also expressed in other units:

1 dS/m = 10^3 MilliS/cm (mS/cm) = 10^3 Millimhos/cm (mmhos/cm) = 10^6 Micromhos/cm (μmhos/cm)

Salinization denotes the gradual increase of inorganic ions in soils, which might be caused by the use of salty irrigation water, insufficient leaching of irrigated soils, and/or capillary rise from salty groundwater. Extraction of soil water by plant roots and/or evaporation of soil water at the soil surface will increase the salinity of the remaining soil water. In case of irrigation, the salinity concentrations, in general, increase with depth, while in case of fallow fields, or fields with shallow groundwater tables, the highest salinity concentrations will be found in the top soil.

Concentration of the soil water solution may lead to precipitation of ions, while dilution, e.g. in case of rainfall or irrigation with water with low ion concentrations, may result in dissolution of ions from the solid phase. A dynamic equilibrium exists between the ion concentrations in the soil water and he precipitates. In case of calcite or lime, which is one of the first solids formed upon concentration of many irrigation waters, the chemical equilibrium reaction is described by:

$$CaCO_3 + CO_2(g) + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

The exchange phase is a transition zone between the predominantly negative charged clay minerals and organic matter and the soil water solution. The cations in the soil water are attracted or adsorbed to the clay minerals and organic matter, while the anions in the soil water are repulsed. The sum of the anions and cations in this exchange phase (meq/l) will be equal to the negative charge of the clay minerals and organic matter (meq/l), and is called the cation exchange capacity, CEC.

The thickness of the transition layer, which is also called diffuse double layer, depends on the valence of the cations and the ion concentration of the soil water solution. At larger valence (Ca^{2+} instead of Na^+) the thickness becomes smaller. Also larger ion concentrations in the soil water result in thinner diffuse double layers. The thickness of the diffuse double layer has important consequences for the stability of the soil aggregates.

Sodification refers to an increase of Na with respect to Ca and Mg in the soil water solution and thus in the exchange phase. This will increase the thickness of the diffuse double layer, especially when the ion concentrations in the soil water are relatively low. A larger diffuse double layer weakens the chemical bonds between the clay platelets and organic matter. Individual clay platelets or organic particles may release from aggregates or aggregates may break down into smaller aggregates. The density of the soil increases and permeability and tilth properties are negatively affected. Repulsed clay platelets or small aggregates can lodge in the pore network, which further decrease the permeability.

A commonly used measure for the sodification risk is the Sodium Adsorption Ratio, SAR $(mmol/l)^{1/2}$

$$SAR = \frac{[Na]}{[Ca + Mg]^{1/2}}$$

where total analytical concentrations are used (mmol/l), with no account of ion association.

Also, the Exchangeable Sodium Percentage ESP (%) can be used:

$$ESP = 100\frac{[NaX]}{CEC}$$

One of the causes of high SAR and ESP values in the soils is the small solubility product $(CA^{2+})(CO_3^{2-})$, which for irrigation water upon concentration in the root zone may lead to precipitation of $CaCO_3$. If the concentration of Ca in the soil water is less than the concentration of CO_3, Ca will decrease rapidly. The amount of Ca^{2+} with respect to CO_3^{2-} is conveniently expressed in the Residual Sodium Carbonates RSC (eq/l):

$$RSC = CO_3^{2-} + HCO_3^{-} - Ca^{2+} - Mg^{2+}$$

The RSC indicates, in the end, when irrigation water gets concentrated due to water extraction by roots and evaporation, whether Ca^{2+} or Na^{+} becomes the dominant ion in the soil water solution and exchange phase. The positive RSC, the larger the risk for sodification of the soil.

The soil water ion concentration in irrigated top soils will closely reflect the ion composition of the irrigation water. Therefore, the ion concentrations in the irrigation water are an important criterion for the sodification hazard of the soil. To judge the suitability of irrigation water, the criteria mentioned in Table 3.2 can be used.

Table 3.2: Irrigation water quality criteria

	Usable	Marginal	Hazardous
EC_w (dS/m)	0 - 1.5	1.5 -2.7	> 2.7
RSC (meq/l)	0 -2.5	2.5 -5.0	> 5.0
SAR $(mmol/l)^{1/2}$	0 -10	10 –18	> 18

see also Table 3.4

Table 6.3 lists the criteria for evaluation of the salinity and sodicity of soil water extracts. EC_e is the Electric Conductivity of the soil water extract. To measure the EC of the soil water this extract is always diluted with fresh water with about a factor 2. This means that if the measured EC_e is 2 dS/m, the actual salinity of the soil water, as it sits in the soil, is about 4 dS/m.

Table 3.3: Soil quality criteria

	$EC_e < 4$ dS/m	$EC_e > 4$ dS/m
ESP < 15 %	non-saline, non-sodic	Saline
ESP > 15 %	sodic (pH > 8.5)	saline-sodic

derived from USDA (1954)

Table 6.4 lists the tolerance of different types of crops to the EC of the irrigation water. In fact, it would be better to judge the tolerance to the salinity of the soil water extract, which not only depends on the irrigation water applied but also on leaching by irrigation and rainwater.

Table 3.4: Salt tolerance of crops
(in dS/m of irrigation water).

Vegetable crops	**Fruit crops**	**Field crops**	**Forage crops**
Beets 2.7 Broccoli	Olive 1.8 Fig	Barley 5.3 Cotton	Ryegrass 3.7 Lucerne
1.9 Tomato 1.7	1.8 Grapefruit 1.2	5.1 Sugarbeet 4.7	1.3 Clovers
Cucumber 1.7 Spinach	Orange 1.1 Lemon	Wheat 4.0 Soybean	1.0
1.3 Watermelon 1.3	1.1 Walnut 1.1	3.3 Sorghum 3.3	
Cabbage 1.2 Potato	Peach 1.1 Apricot	Peanut 2.1 Rice	
1.1 Sweet corn	1.1 Grape 1.0	2.0 Corn 1.1	
1.1 Pepper 1.0	Almond 1.0 Plum	Sugarcane 1.1 Flax	
Lettuce 0.9 Onion	1.0 Avocado 0.7	1.1 Cowpea	
0.8 Carrot 0.7	Strawberry 0.7	0.9	
Beans 0.7			

(source: Awas 1984 cited in Southorn 1997, Table 1.2)

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3.2.6 Water logging

Water logging means the saturation of soil with water. It usually is caused by the raising of the groundwater table. Irrigation can cause water logging when more water is applies then the crops can uptake and the percolated water is not drained from the soil. Water logging of the root zone gives damage to crops. One exception is rice, rice benefits from a saturated soil. The roots of other crops need oxygen in the soil. The effect of the water logging on the yield depends on the time the root zone is water logged, the crop-stage and the type of crop. Some crops are very sensitive to water logging and will already be affected if an irrigation gift saturates the root zone for some hours. Farmers are mostly aware of this and they will give only shallow water gifts to those crops. A farmer in Peru explained this in a paradoxical phrase: “the crops dry out if you give them too much water.”

Water logging has another effect. If percolated water is not drained away salt concentration, in the groundwater and topsoil, will increase. In the dry or non-irrigated period saline groundwater might raise to the surface of the soil by capillary rise; and at the surface, the salts will accumulate as the water evaporates. It then is a matter of time before salinity becomes a problem to the crop. In many areas (e.g. in Pakistan) salinity is caused by water logging.

Solution to the problem of water logging can be two fold. First of all drainage systems should be installed to drain away the (saline) groundwater. In some places they pump up the ground water to use it (again) to irrigate. Skimming wells in Pakistan intercept the shallow groundwater that infiltrates from the irrigated fields before it reaches the deeper groundwater lawyers that are too saline to be used for irrigation. Second measure can be to reduce the irrigation gifts as to reduce the percolation, and therewith the groundwater recharges. However, in most cases this second measure will not be sufficient and has to be taken together with installation of a drainage system.

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3.2.7 Groundwater depletion

"Perhaps the biggest revolution in water resource management has been the small, cheap diesel or electric pump that gives farmers the means to invest in self-managed groundwater irrigation. In irrigated areas of Pakistan private investment in groundwater development through tube wells (360,000 in 1993 alone) has been an engine of growth. In India almost half of all irrigated areas depend fully or partly on groundwater. In China more than 2 million pumps irrigate some 9 million hectares (Postel 1999). In the United States one of the world's largest groundwater aquifers, the Ogallala, has been developed through privately financed wells feeding sprinkler systems. While groundwater irrigation has contributed substantially to world's food production and provided farmers with a dependable source of water, it has also led to massive overuse and falling groundwater tables. A lack of regulation of this common resource, combined with subsidised diesel fuel or electricity for the pumps, gives farmers an incentive to use groundwater as if there were no tomorrow." (Cosgrove and Rijsberman 2000:8)

Besides the examples mentioned above other countries with intensive irrigation for commercial food production that now suffer from severe groundwater depletion are Mexico, Spain and Morocco. In some areas the massive extraction of groundwater leads to a fall of the groundwater table of several metres per year. If the water drawn is from a confined aquifer that is not fed by rainfall we speak of groundwater mining. In some places in the United States and other counties like Libya, Yemen and Mexico the "ancient" water is mined in alarming speed. As these aquifers are not renewed the rapid use of these aquifers will soon lead to big problems.

In Tunisia over extraction of groundwater and ancient groundwater mining is also a problem. Government installed deep tube wells (500 m) in the 1960s that now lead to severe draw down of the water stored in deep aquifers in Sidi Bouzid. In the same region, privately owned shallow wells (with diesel pumps) cause a problem of the overexploitation of the shallow groundwater.

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3.2.8 Big dams and other ecological damage to river ecology and negative effects on livelihoods

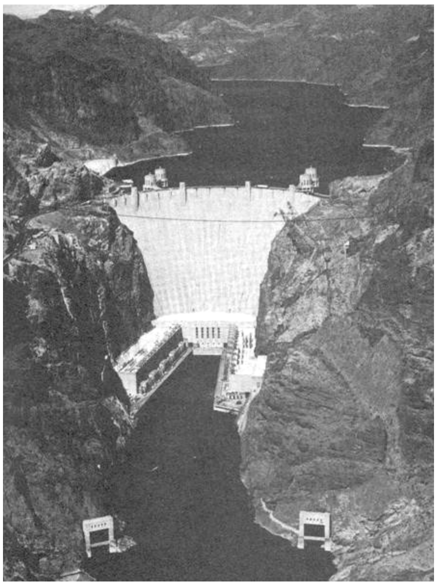


Photo 3.3: Hoover dam, USA

In the last two decades large dams have attracted more and more critique. Before that, projects of building reservoirs for irrigation and power generation were associated with development and "taming nature". More specific, dams are regarded as providers of electric power, water and food, tamers of floods, greeners of deserts, and guarantors of national Independence. Electric power generation is the most important goal of the many big dams, but providing irrigation water for dry periods is a good second. Many dams are multi-purpose: they generate electricity, store water for irrigation and consumptive use, and they tam floods at the same time.

The Hoover dam in the Colorado River in the USA built in 1935 was the first major dam built (Photo 6.3). Since then many more have followed: see Table 6.2. Another famous one is the Aswan High Dam in the Nile completed in 1970. The International Commission of Large Dams (ICOLD) estimates that there are now 40,000 large dams, while in 1950 there were only 5,000.

Recently plans for big dam construction have come into the media because of the public protests against the projects. Two famous examples are the Narmada Sagar and Sardar Sarovar dams replacing 620,000 people and the Three Gorges Dam in China replacing 1.3 million people.

Table 3.5: Countries with the most large dams

Country	Number of major dams* (1994 data)	Number of large dams** (1986 data)
China	10	18,820
USA	50	5,459
CIS (former USSR)	34	±3,000
Japan	19	2,228
India	7	1,137

Spain	4	737
South Korea	-	690
Canada	26	608
Great Britain	-	535
Brazil	19	516
Mexico	5	503
France	5	468
South Africa	-	452
Italy	9	440
Australia	-	409

*Major dams: either one or more of the following criteria: higher than 150 metres, having a volume of at least 15 million cubic metres; reservoir storage capacity of at least 25 cubic kilometres; or generation of at least one gigawatt.
**Large dam is dam higher than 15 metres, or between 10 and 15 metres high and wider than 500 metres and capacity of over 1 million cubic metres; maximum flood discharge at least 2,000 cubic metres per second, 'special difficult foundation problems'; or 'unusual design'.

source: McCully 1996:Table 1.1

List of mayor points of critique on large dams:

- Forced resettlement of people who live on the place of the reservoir-to-be without proper compensation
- Damage to riverine ecosystem
- Damage to nature on flooded river banks, also valuable agricultural land can often be found on the fertile river banks that get flooded
- High building costs
- Flooding of cultural heritage
- Risk of breaking of a dam
- Short life-time of the reservoir due to silting up
- Profits go only to the dam-construction-companies, electricity-companies and the large land owners
- Control over water centralised in one authority

The Colorado River in the Western USA does not reach the ocean anymore. All its water is used for irrigation and other purposes on the way. Another example of excessive water extraction is the River Nile. Its normal discharge is almost completely used (and re-used) for irrigation and other applications, leaving only a small volume at the outflow. This reduction in outflow has major influences on the ecology of the estuary of the river, for example through earlier sedimentation of suspended material and through a changed salt-content. The reduction of flow also increases proportionally the concentration of chemicals in the water, which forms an additional harm to this ecology.

Box 3.5: Dam in the Senegal River

The Senegal River Valley is a typical example of an original wetland where ecology and agricultural production (food crops, cash crops and livestock) were in equilibrium.
In the upper-valley rainfed agriculture was the predominant form of agricultural production, the middle-valley was characterized by the importance of floodwater-farming. Yearly inundations from the highwater from the

river Senegal and its contributories were the source of water and nutrients for a traditional form of agriculture. Intrusion of salt water from the Ocean during the season of low water discharge of the river created a delta-area with fluctuating and brackish water, forming an important bird sanctuary in the region. Because of the presence of salt and brackish water (and soils) the delta area of the river was not suitable for crop production. Here one would find extensive herding only.

Decrease of rainfall in the region and consequently absence of flooding were the reason for subsequent crop failures. This Sahel-drought in the sixties and seventies forced farmers and government to find other ways and means to produce the required food for survival. Trough a number of externaly financed projects small scale irrigation-schemes were constructed that pumped the required water from the river. At that stage these constructions did not interfere with the ecological environment, as the irrigation schemes were constructed outside the floodplains.

Meanwhile, however, the involved governments (Senegal, Mauretania and Mali) decided to construct 2 dams in the river, the Manantali dam in the upstream part, in Mali, to serve to store water, another dam in the delta, about 35 km from the outflow, to stop the intrusion of salt water into the delta. The two dams would create sufficient storage of sweet water and allow the delta to be cultivated.

Mainly economic and political arguments have been used to allow for these investments and constructions. But in practise, the dams do major environmental damage to the region in question. The water infrastructures have caused an explosion of Schistosomiasis, a water related disease that was hardly known in the region before. Moreover, the changed water flows and

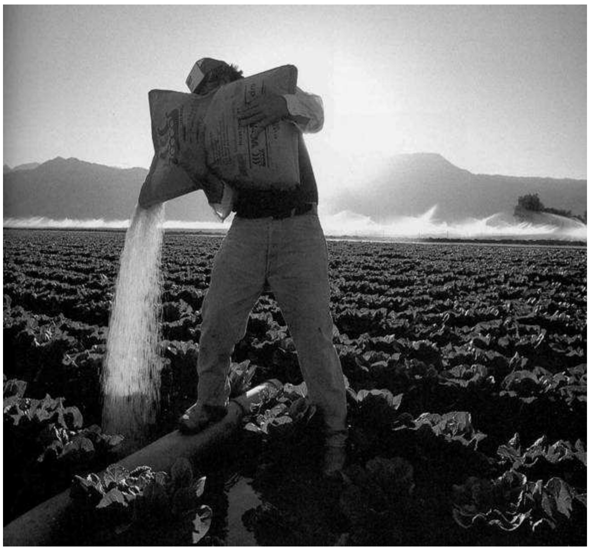


Photo 3.4: Farmer pouring nitrogen fertilizer in a furrow that is being irrigated

Other dangers of irrigated farming are related to the intensification of the production system, which more often than not involves an increase in the use of agro-chemicals, such as chemical fertilisers, herbicides, fungicides and pesticides. A very first risk concerns a possibly injudicious use of these inputs, which may form a direct health risk to the people. Chemicals may also come in the drainage water of the system, which, in its turn, could contribute to the water source of a different water application.

Newly established (large) irrigation schemes generally cause a major change in the ecological environment. This could also have negative influences on the health situation where such new environment allows the built-up or easier spreading of water related diseases (see above)

McCully (1996) offers several alternatives to big dams: First small dams higher up in the catchment: this causes less damage and gives more democratic control. In Tunisia however the construction of many small dams in the upper catchment of the Medjerda causes problems to fill the big reservoir Sidi Salem in dry years. Second: increase water use efficiency, so no new dams need to be built. This applies to irrigation as well as drinking water systems. Third, use water harvesting techniques to increase yields in rain fed agriculture. Fourth, recharge groundwater and use groundwater at a rate it can be replenished. Fifth, use the natural floods of rivers.

References and further reading

Dhawan, B.D.(ed.), 1990, *Big Dams: claims, counter claims*, Commonwealth Publishers, New Delhi

McCully, P. 1996, *Silenced Rivers, The Ecology and Politics of Large Dams*, Zed Books, London.

Singh, S, 1997, *Tamming the waters: political economy of large dams in India*, Oxford University Press, New Delhi.

International Rivers Network (www.irn.org)

4 CLIMATE

4.1 Introduction

The management of water for irrigation requires accurate estimates of crop water use and available water supply from rainfall. If plants are well watered and all other conditions are favorable, the amount of water lost by the crop surface is greatly determined by the physical atmospheric environment and most particularly by radiation and air temperature which provide the required energy to vaporise the water. The transport of water vapour from the evaporating surface into the lower atmosphere depends on wind speed and air humidity.

Several procedures have been developed to estimate crop water use in relation to radiation, temperature, humidity and wind speed. The crop water use may also be derived from the amount of water which evaporates from a storage tank. The accuracy of these estimates depends largely on the accuracy of the measurements of the variables involved.

In this section the definition, units and measurement of the key physical parameters in irrigation planning and management i.e. temperature, humidity, wind speed, solar radiation, precipitation and evaporation are discussed.

Further reading and reference:

FAO Irrigation and Drainage Paper Nr.27 "Agrometeorological field stations" and *WMO publication Nr.134 "Guide to Agricultural Meteorological Practices."*

4.2 Weather stations

Most meteorological data relevant to irrigation planning and management are collected at meteorological stations. However, there are differences in weather stations depending on the purpose for which they were established. There are aeronautic (or general use), hydrometeorological and agrometeorological stations. Aeronautic stations are normally sited at airports, and collect data relevant to use in aviation. Hydrometeorological stations are sited in hydrologic water-sheds and near dams. They collect mainly precipitation data for use in hydrological analyses. Agrometeorological stations are sited in cropped areas where instruments are exposed to atmospheric conditions very much the same as the surrounding crops.

In addition to the three types of weather stations mentioned above, there are stations sited at schools for teaching purposes, and at locations such as farms and large agricultural projects (kept by individuals). One of the functions of a National Meteorological Service is to guide the establishment of all stations in the country, regularly collect data for the keeping and processing at a central location, and publishing them in meteorological bulletins for use by interested parties.

Of the various types of stations, agrometeorological stations are most relevant to irrigation planning and management because ideally they are representative for the environmental conditions of the area concerned. Data from other stations may be used in the absence of agrometeorological stations in the area concerned. However, this requires careful consideration of the data. For example, temperatures measured at airports represent in general urban conditions with higher temperatures than those found in rural agricultural areas.

4.3 Temperature

Agrometeorology is concerned with the temperature of the air at the level of the crop canopy. For purposes of irrigation planning and management daily minimum and maximum temperatures are most relevant. From these the daily mean temperature is calculated as:

$$T_{mean} = \frac{T_{\min} + T_{\max}}{2}$$

Heat energy is used in the process of evapotranspiration for the conversion of liquid water into water vapour. The higher the air temperature, the more energy will be available for evapotranspiration.

4.3.1 Definition and units

For the determination of temperature different scale systems have been developed and are in use. At meteorological stations, the temperature is given in either degrees Celsius (°C) or degrees Fahrenheit (°F). Conversion from one unit into the other is given by (Annex 1) :

$$(°F - 32)\frac{5}{9} = (°C)$$

In some calculations, the temperature scale of Kelvin (K) is used : 0°C = 273.15 K.

4.3.2 Temperature measurement

Temperature is measured with thermometers. They are based on the principle, which the physical characteristics of certain substances change as the temperature changes. When substances are heated they expand, and when cooled they contract. By heating or cooling solids change in length and liquids change in volume. Some substances, especially metals, also change their electrical characteristics, such as electrical resistance. The behaviors of these physical and electrical characteristics are used to construct thermometers.

Thermometers, used for the measurement of ambient air temperature, should not be exposed directly to the air but be placed in shelters, which prevent direct heating of the thermometers by the sun.

Thermometers can be classified into three groups depending on the characteristic used as a measure of the temperature. They are : liquid-in-glass, mechanical (thermographs) and electrical thermometers.

Liquid-in-glass thermometers

These are based on the principle, that the expansion rates due to temperature changes of the body (normally glass) and that of the liquid contained in the body are different. The liquids commonly used are mercury (for temperatures above -38.8 ^{o}C) and ethyl alcohol (for temperatures below -38.8 ^{o}C).

Thermographs

Thermographs are commonly based on the differential expansion of two different metals (bimetallic) laterally joined and formed into a bar or a helix. One end of the bar or helix is fixed, and the curvature is a function of temperature. The free, moving end, has a pen attached, which traces a fine line on a chart fixed to a rotating drum, thereby providing a continuous recording device (**Photo 4.1**).

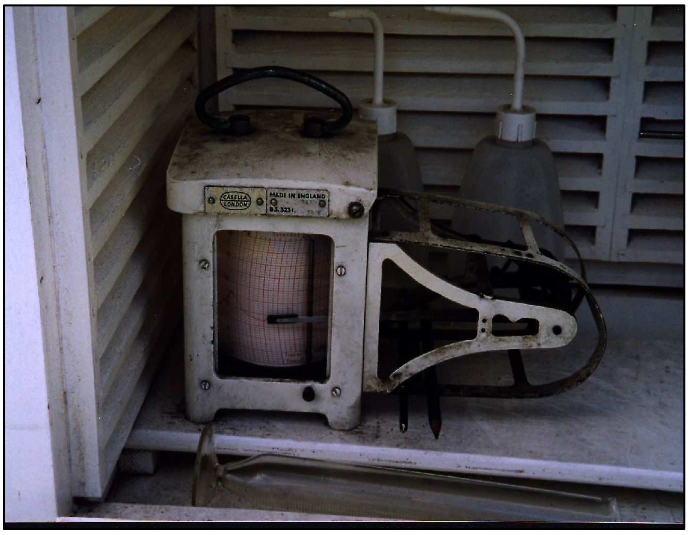


Photo 4.1: A bimetallic thermograph

Electrical thermometers

Electrical thermometers have an advantage over liquid-in-glass thermometers in that they can be integrated in modern digital electronic data acquisition, recording, retrieval and transmitting systems. The most common of such sensors are resistance elements and thermocouples.

4.4 Humidity

Humidity generally refers to an expression of the moisture content of the air. Air contains molecules of various gaseous constituents in addition to other foreign particles. When water evaporates from soil or plant surfaces gaseous water (vapour) is formed and mixes with air.

Under given atmospheric conditions a fixed volume of air has the capacity to absorb only a certain quantity of water vapour. When this capacity is reached the air is said to be saturated. A moist surface or well watered crop in contact with saturated air cannot evapotranspire more water into the air. Any measure of atmospheric humidity therefore gives an indication of the evaporative demand (or: potential) of the air.

4.4.1 Definitions and units

Of the various ways of expressing the moisture content of the air, the most common are:

Saturation vapour pressure (e_a)

The saturation vapour pressure is the vapour pressure of the saturated air. It is the maximum possible for the given temperature. The saturation vapour pressure increases with temperature (**Figure 4.1**).

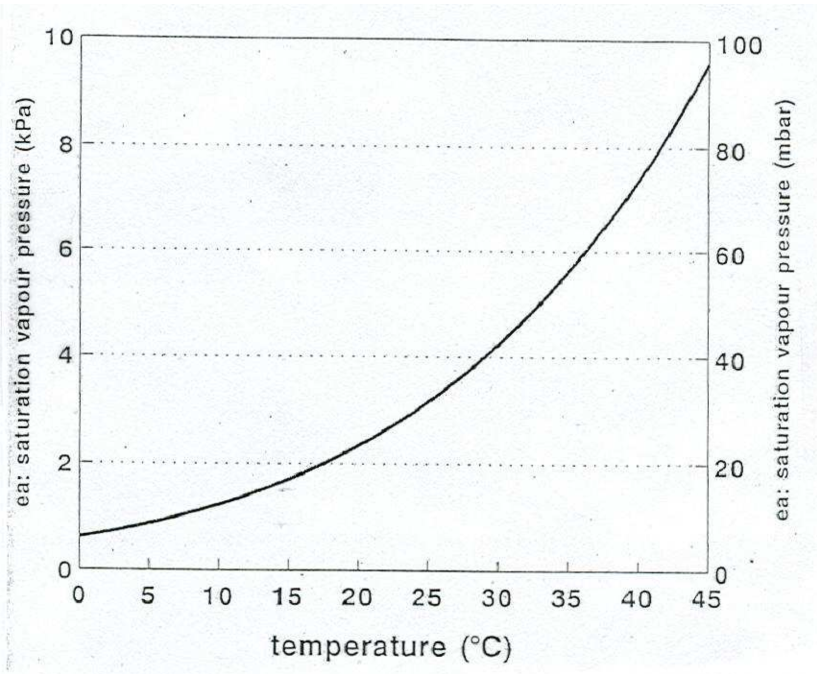


Figure 4.1: Saturation vapour pressure s a function of temperature

Actual vapour pressure (e_d)

The actual vapour pressure is the pressure exerted by water vapour actually contained in the air. Units : [mbar] or [kPa]

Vapour pressure or saturation deficit (e_a-e_d)

The vapour pressure deficit is the difference between saturation and actual vapour pressure i.e. a measure of the actual evaporative capacity of the air. Units : [mbar] or [kPa]

Dewpoint temperature (T_{dew})

The dewpoint temperature is the temperature at which the air would become saturated if it were progressively cooled. Units : [^oC] or [K]

Relative humidity (RH)

The relative humidity is the ratio of the actual amount of water vapour in the air and the amount of water vapour which the air would hold when saturated at the same temperature or RH = 100 e_d/e_a %. It is the ratio between the amount of water the air actually holds and the amount it could hold at the same temperature. The fraction is commonly multiplied by 100 giving the relative humidity (RH) as a percentage. Relative humidity is frequently used in common day language, with 90 - 100% representing a humid atmosphere and values below 50% indicating a dry and arid environment. As the temperature changes during the day, RH also changes substantially (**Figure 4.2**). Besides RH, the air temperature must be given before any humidity condition is fully defined. For this reason vapour pressure is a more acceptable meteorological unit.

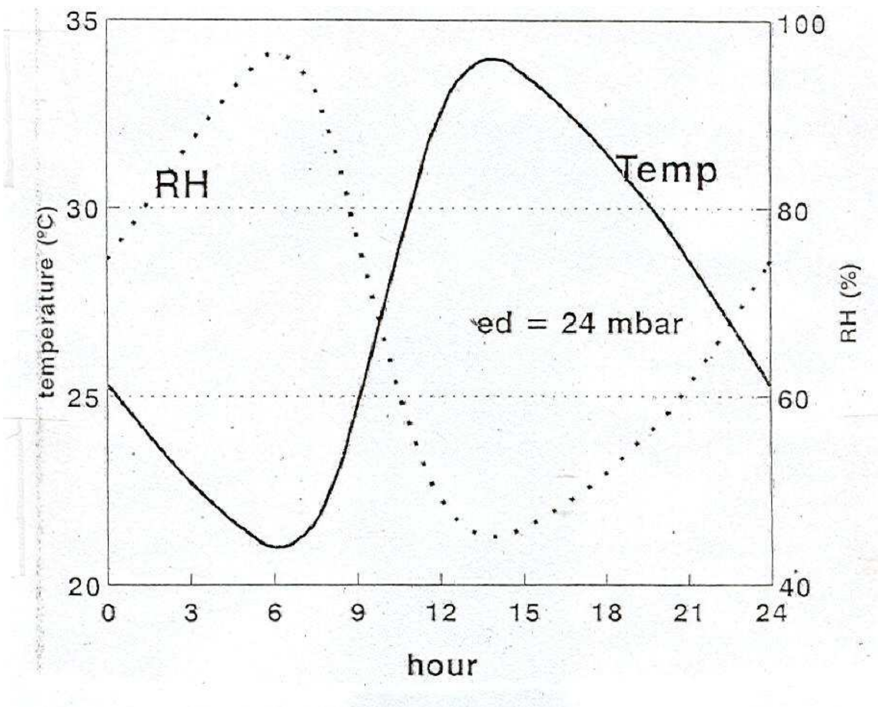


Figure 4.2: RElative humidity shown as a function of air temperature throughout the day for a given constant ed value of 24 mbar

4.4.2 Measurement of atmospheric humidity

It is difficult to measure e_d directly. Therefore, most field instruments are designed to measure either RH or T_{dew}. RH is measured either directly (eg. with hair hygrometers) or indirectly from psychrometer readings, which measure wet and dry bulb temperatures. The indirect method is the more accurate and most commonly used.

Psychrometers

The most common humidity measuring device is the psychrometer using the familiar dry and wet bulb thermometers (**Photo 4.2**).

The bulb of the wet bulb thermometer is covered with a muslin wick constantly moistened from a water reservoir. There are ventilated and non-ventilated types. Evaporation of water from the wick around the wet bulb will both increase the vapour pressure and reduce the temperature of the air stream by extracting from it the latent heat required for evaporation. After a while, a steady lower temperature is reached which is defined as the wet bulb temperature. The temperature decrease is a function of the speed of air passing by the bulb. In non-ventilated psychrometers the air speed is not constant, varying with the wind speed outside the shelter. Conditions around the bulb are, therefore not constant. This can cause errors in measurement. In ventilated psychrometers an electric fan is used to maintain a constant air speed around the bulb, and so eliminate this source of error.

Differences between ventilated and non-ventilated psychrometers need to be taken care off when converting the temperature readings to vapour pressures.

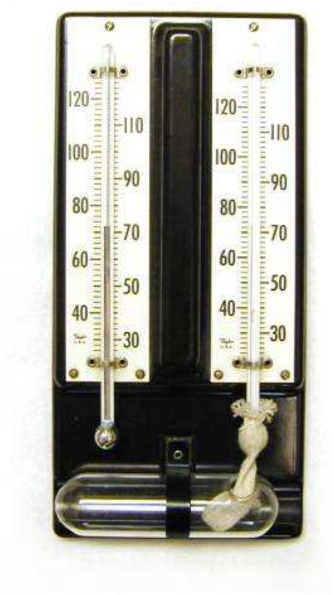


Photo 4.2: Dry and wet bulb thermometer

The classical psychrometers are not ventilated and kept in louvered wooden screens of weather stations. Both the dry and wet bulb thermometers should be read simultaneously, as far as possible.

Hair hygrographs

Hair hygrographs are based on the hygroscopic nature of the human hair. The hair changes its dimensions (length) in response to changes in the humidity of the surrounding air. The hygrograph is designed such that changes in the length of the hair are monitored and calibrated to indicate changes in air humidity. Use of this device is satisfactory in environments where extreme temperatures and very low humidities do not occur.

4.4.3 Determination of vapour pressure

a - Saturation vapour pressure: $e_a = f(T)$

As mentioned before, it is not possible to measure vapour pressure directly. However, saturation vapour pressure (e_a) is related to air temperature and thus can be calculated once the air temperature is known. This relationship is expressed by the equation:

$$e_a = 0.6108\, e^{\left(\frac{17.27\,T}{T+237.3}\right)}$$

where

e_a = saturation vapour pressure [kPa]

T = air temperature [^oC]

Values of saturation vapour pressure as a function of air temperature are given in **Figure 3.2**

b - Actual vapour pressure: e_d = f(wet bulb depression)

The actual vapour pressure (e_d) can be determined from the so called wet bulb depression i.e. from the difference between the dry and wet bulb temperatures as this difference is related to the water vapour content of the air and the nature of ventilation of the psychrometer. This relationship is expressed by the following equation:

$$e_d = e_{a,Twet} - \gamma_{asp}\,(T_{dry} - T_{wet})\,P_{atm}$$

where

e_d = actual vapour pressure [mbar] or [kPa]
γ_{asp} = 0.00066 for Assman aspiration at 5 m/sec
= 0.0008 for natural ventilation at 1 m/sec
= 0.0012 for indoor ventilation at 0 m/sec
T_{dry} = dry bulb temperature [^oC]

T_{wet} = wet bulb temperature [°C]
P_{atm} = atmospheric pressure [mbar] or [kPa]
$e_{a,Twet}$ = saturation vapour pressure at wet bulb temperature [mbar] or [kPa]

The atmospheric pressure (P_{atm}) in kPa can be calculated from the altitude z of the station with the following equation:

$$P_{atm} = 101.3 \left(\frac{293 - 0.0065\, z}{293} \right)^{5.256}$$

where
z = altitude (elevation) of station above sea level [m]
(For $P_{atm,sealevel}$ = 101.3 kPa and $T_{average,sealevel}$ = 20 °C = 293 K).

An example of the use of psychrometer readings is presented in **Table 4.1**

Table 4.1: Determination of actual vapour pressure and relative humidity from psychrometer readings

Air temperature : 28 °C Elevation of station above sealevel : 10 m Readings from Assman type psychrometer : - dry bulb temperature : 28°C - wet bulb temperature : 21°C
$e_{a,Twet} = 0.6108\, e^{(\frac{17.27 \times 21}{21 + 237.3})}$ 6 = 2.49 kPa (T = 21°C, Table 1, Annex 2) $P_{atm} = 101.3 (\frac{293 - 0.0065 \times 10}{293})^{5.256}$ 7 = 101.18 kPa (Table 2, Annex 2) e_d = 2.49 - 0.00066 (28 - 21) 101.18 = 2.02 kPa $e_a = 0.6108\, e^{(\frac{17.27 \times 28}{28 + 237.3})}$ 8 = 3.78 kPa (T = 28°C, Table 1, Annex 2) RH = 100 (2.02/3.78) = 53 %
Actual vapour pressure = 2.02 kPa = 20.2 hPa = 20.2 mbar Relative humidity = 53 %

c - Actual vapour pressure: e_d = f(relative humidity)

The actual vapour pressure can also be calculated from the relative humidity (RH), measured with hygrometers, using the equation:

$$e_{d,Tmin} = e_{a,Tmin} \frac{RH_{\max}}{100} \qquad e_{d,Tmax} = e_{a,Tmax} \frac{RH_{\min}}{100}$$

Care should be taken, that RH and temperature values should be recorded at the same time. Furthermore the use of mean values of averaged wet and dry bulb temperatures and average RH values should be avoided.

Note that relative humidity will be minimum for maximum temperature and vice versa (**Figure 3.3**).

d - Actual vapour pressure: e_d = f(dewpoint temperature)

Finally, if humidity data are lacking, an estimate of vapour pressure can be made (in humid climates) by assuming the minimum temperature (T_{min}) to be equal to the dewpoint temperature (T_{dew}). Thus:

$$e_d = e_{a,Tdew}$$

4.5 Wind

Wind blowing across the land transports water vapour away from a cropped or evaporating surface. This maintains the gradient of water vapour between the surface and the air and therewith the evapotranspiration.

4.5.1 Definition and units

Wind is a two dimensional vector quantity expressed by its speed and its direction. In this sense it is termed as wind velocity. Wind speed is expressed as the average velocity in m/s or as the total wind run in km/day.

Wind direction is given in degrees, and refers to the direction from which the wind is blowing. For the computation of evapotranspiration of water from the soil and from the plant surface wind speed is the relevant variable. As such wind direction will not be discussed here.

4.5.2 Measurement of wind speed

Wind speed is measured with anemometers, which are of the cup or of the propeller type. They consist of a rotor and a signal generator. The cup or propeller rotor is turned by the force of the wind passing by it. The angular velocity produced is normally proportional to the wind speed. The rotor drives a signal generator of which exist several types: alternating or direct current generators, magnetic pulse generators and turncounting dials. The signal from the current and pulse generators is normally sent to a read-out or to a data processor. **Figure 4.3** shows an anemometer with a counter readout.

Photo 4.3: Cup counter anemometer

Air velocity can also be measured by a digital thermo-anemometer. The air velocity is calculated by determining the electrical energy required to sustain a thermistor at a constant temperature.

Surface friction tends to slow down wind passing over it. In other words, wind speed is slowest at the surface, and increases with height until a constant, main stream, value is reached at a certain height above the surface.

For this reason anemometers are placed at a chosen standard height in an open field location. The standard height in meteorology is 10 m. Anemometers are located in the field at a point at least 10 times the height of the nearest obstruction.

In agrometeorology the standard height is usually 2 m. If wind speed is measured at a height other than 2 m, then the observed values are converted to 2 m height wind speed, using the following relation:

$$U_2 = \frac{4.868}{\ln(67.75\,z - 5.42)} U_z$$

where
z= height (m) of wind speed measurement above local ground level

The corresponding multipliers or correction factors are given in **Figure 4.4**

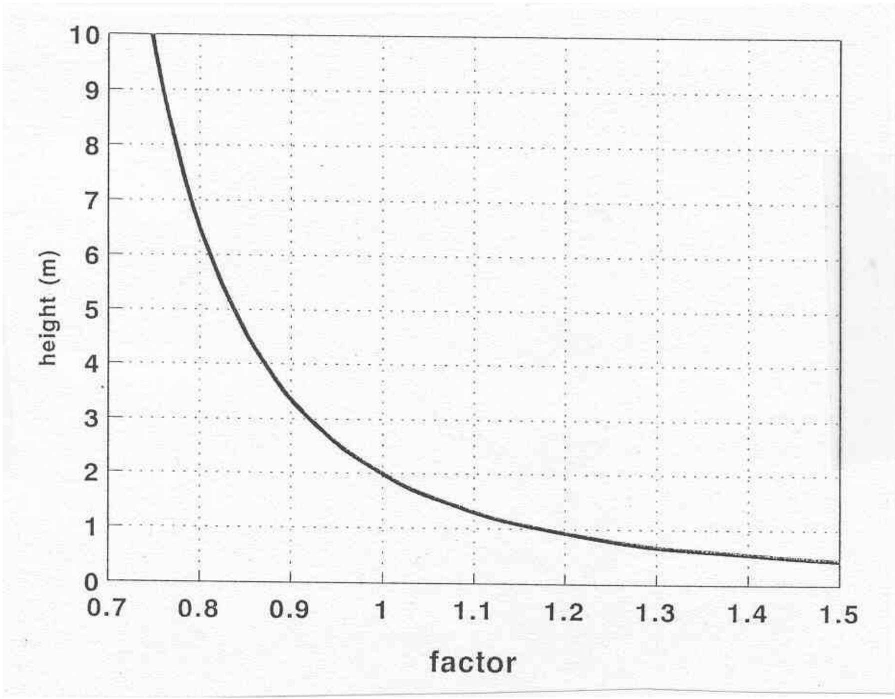


Figure 4.3: Factor to convert wind speed (Uz) measured at given height above ground level to wind speed (U2) at standard height

Since wind speed at a given location often varies with time, it is necessary to express it as an average over a given time interval. With turn-counter register anemometers the reading at the beginning and end of the averaging time are recorded. The total wind run is found by subtracting the initial reading from the final reading. Average wind speed over the measuring period is then computed in the unit required.

4.6 Solar radiation

Radiation from the sun is the most important energy source for the earth-atmosphere system. Plants capture solar energy and use it in the production of primary substances from which plant dry matter and yield are formed. Solar energy is also used in plant canopies to evaporate and transpire water. The phase change of water from liquid to vapour requires input of energy. The rate at which energy is supplied for converting water to vapour determines directly the evapotranspiration rate.

4.6.1 Definitions

a- Extra-terrestrial radiation (R_a)

Solar radiation is electromagnetic radiation emitted by the sun. The quantity reaching the top of the earth's atmosphere is called extra-terrestrial radiation (R_a). Almost all of this radiation is shortwave radiation. R_a is different for different latitudes and various throughout the year (**Figure 4.5**).

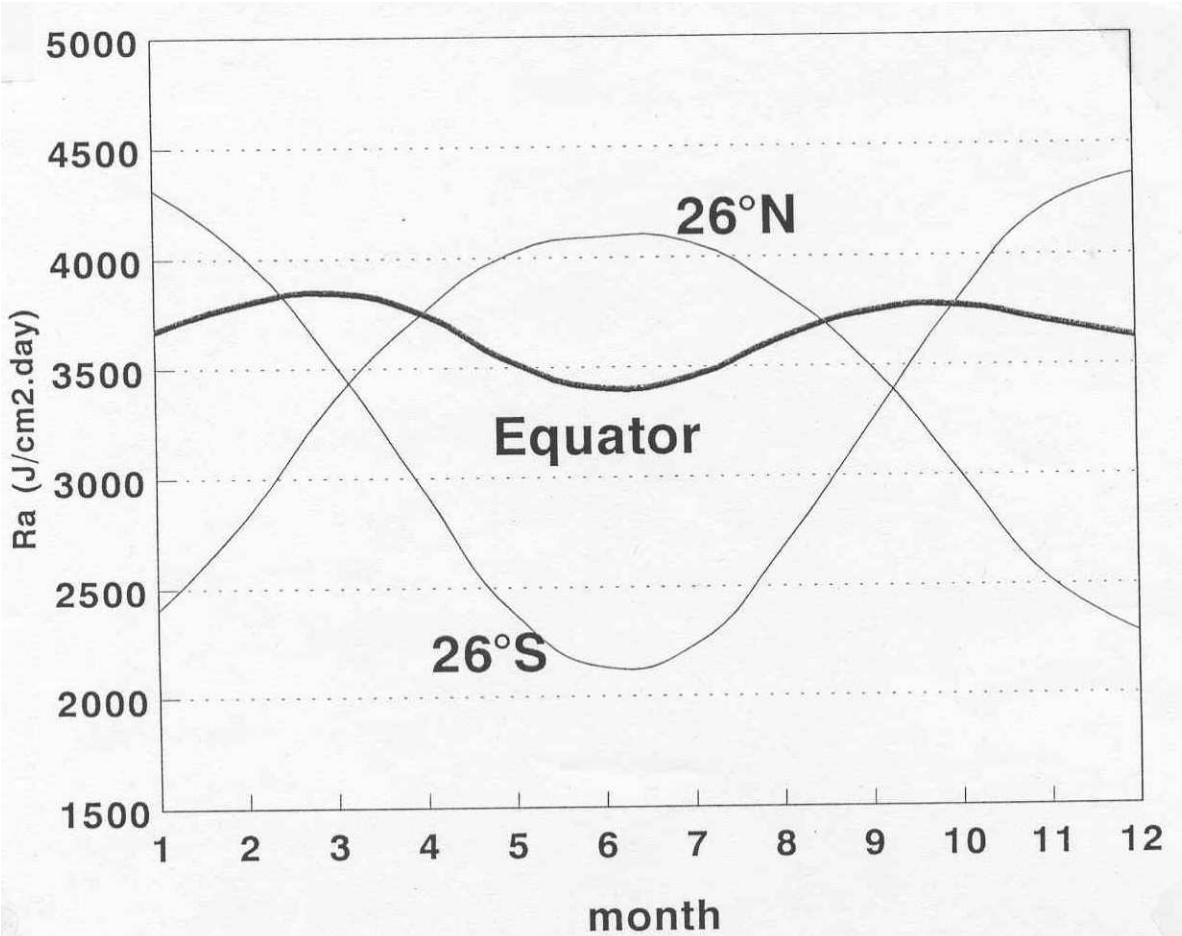


Figure 4.4: VAriation throughout the year of the setra-terrestrial radiation (Ra) at the equator, 26 North and 26 South

b - Solar radiation (R_s)

At its passage through the atmosphere (**Figure 4.6**) some of the radiation is either absorbed, scattered or reflected by atmospheric gasses, clouds and aerosols. The fraction reaching the soil surface is the solar radiation (R_s). At a bright day R_s is about 75 % of R_a, on a clouded day it might be as small as 25 % of R_a.

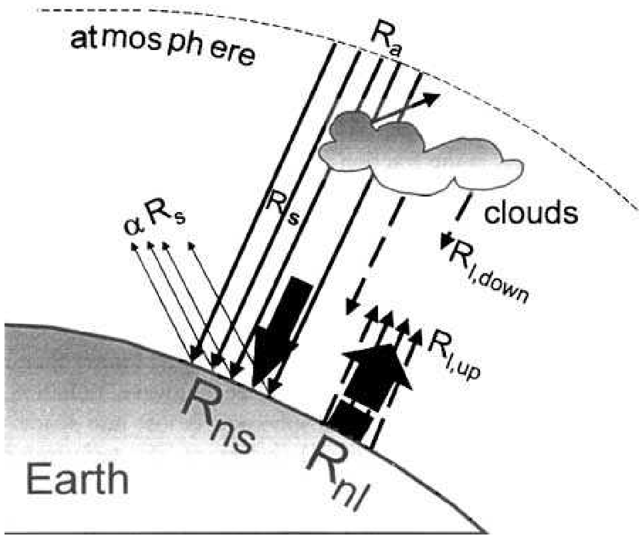


Figure 4.5: Variation components of radiation

c - Net shortwave (solar) radiation (R_{ns})

Of the solar radiation (R_s), reaching the surface, a fraction (α) is reflected back directly by the soil and the plant cover and only the net shortwave radiation (R_{ns}) is of use for the plants, or $R_{ns} = (1- \alpha) R_s$. The fraction reflected by the surface is known at its albedo and its value is different for different surfaces. Most green vegetation cover has a value of $\alpha \approx 0.25$. Water has a value of $\alpha = 0.08$

d - Global (or total) radiation

The shortwave radiation absorbed by clouds will increase the temperature of the clouds and thus increases the longwave radiation emitted by the clouds. Total radiation is the sum of the radiation received on a horizontal surface i.e. the net shortwave and the incoming longwave radiation.

e - Net longwave radiation (R_{nl})

The global radiation absorbed by the earth is converted to heat energy. By several processes including emission of longwave radiation, the earth loses this energy. The difference between outgoing and incoming longwave radiation is called net longwave radiation (R_{nl}). Since the outgoing longwave is (normally) greater than the incoming, R_{nl} represents an energy loss.

f - Net radiation (R_n)

Net radiation (R_n) is the balance between the energy absorbed and emitted by the earth surface. Or the difference between the net shortwave and the net longwave radiation :

$R_n = R_{ns} - R_{nl}$

4.6.2 Units

Radiation is measured in energy (calorie, joule) received over an area (m^2, cm^2) per unit of time (sec, day). It is usually expressed in $cal/cm^2.day$, $J/cm^2.day$ or $MJ/m^2.day$

Energy is required to evaporate water. The energy required, called the latent heat of vaporization, is a function of temperature. For practical purposes, its value can be taken as 2450 J/g. Thus, the solar energy may be expressed in equivalent evaporation in mm, using a conversion factor of 2450 J/cm^3 (assuming the density of water is 1 g/cm^3). Hence, an evaporation of 1 mm/day corresponds with an energy equivalent of 245 $J/cm^2.day$, 2.45 $MJ/m^2.day$ or 58.6 $cal/cm^2.day$.

4.6.3 Measurement of global shortwave radiation

Global shortwave radiation is direct and diffused radiation received on a horizontal surface. It is either measured directly with pyranometers or indirectly from measurements of sunshine or from cloudiness observations.

a - Direct methods of measuring solar radiation

Solar radiation is measured with pyranometers (radiometers or solarimeters). They usually consist of an absorption surface and a sensor which converts the solar energy absorbed into an electric current which is measured and recorded. Pyranometers are usually calibrated by comparison with standard pyranometers (i.e. pyranometers of known calibration).

The instrument should be installed free from any obstruction above the plane of the pyranometer at all times of the year. There should also be no objects nearby that can reflect sunlight or emit artificial light onto the sensor.

b - Indirect measurements of solar radiation

Where pyranometers are not available solar radiation is usually estimated from measured duration of bright sunshine hours, or cloud observations, and known extraterrestrial radiation and day length, according to the following relationship:

$$R_s = \left(a_s + \frac{n}{N} b_s \right) R_a$$

Where:
R_s = incoming solar radiation [mm/day] or [$MJ/m^2.day$ or $J/cm^2.day$]
R_a = extra terrestrial radiation [mm/day] or [$MJ/m^2.day$ or $J/cm^2.day$]
n = actual bright sunshine hours (Campbell Stokes)
N = maximum possible sunshine hours for the latitude
n/N = cloudiness fraction
a_s = fraction of extraterrestrial radiation (R_a) on overcast days
a_s ≈ 0.25 for the average climate.
a_s+b_s = fraction of radiation on clear days ≈ 0.75
b_s ≈ 0.50 for the average climate.

Values of a_s and b_s may have to be determined locally, from measured radiation and sunshine records. For a number of regions local values have been determined experimentally. For average conditions values for a_s = 0.25 and b_s = 0.50 are recommended for use.

Table 4.2: Determination of solar radiation from measured duration of bright sunshine

actual bright sunshine hours : 8 hours Latitude 28°S, November
R_a (November, 28°S) = 17.2 mm/day (Table 3, Annex 2) = 4,214 J/cm^2.day = 42.1 MJ/m^2.day = 1008 cal/cm^2.day N (November, 28°S) = 13.5 hours (Table 5, Annex 2) R_s = (0.25 + 0.50 8/13.5) R_a = 0.546 R_a
Solar radiation (R_s) = 2,302 J2/cm^2.day = 23.0 MJ/m^2.day = 551 cal/cm^2.day = 9.4 mm/day

The Campbell Stokes sunshine recorder is the instrument commonly used to measure sunshine hours. It records periods of bright sunshine by using a glass globe to concentrate solar radiation onto a paper card strip on which the solar heat burns a trace. As the sun moves across the sky the burn spot moves, resulting in a line trace, the length of which can be measured in hours (**Photo 4.4**).

Strict guidelines have to be followed in ordering, installing and day-to-day changing of the cards and converting the solar trace on the cards to hours of bright sunshine. Each instrument comes with detailed instructions.

Photo 4.4: The Campbell Stroke Sunshine recorder

Further reading and reference

FAO Irrigation and Drainage Paper Nr.27 or *WMO Publication Nr.134.*

4.7 Precipitation

Precipitation is the most important source of water to the soil, and so to crops. In the tropics precipitation is mainly in the form of liquid rainfall. The annual total and distribution of rainfall is the basis for the classification of climates from humid to arid. Rainfall effectively stored in the soil is used for the evapotranspiration of crops. Any shortage of rainfall will result in stress and reduced crop production. Rainfall deficit determines, therefore, *where* and *when* irrigation is needed.

4.7.1 Definition and units

Precipitation occurs when water vapour condenses in the air and falls as liquid or solid to the surface. It is expressed in mm. A rainfall of 25 mm means that if all the rain, that falls on a unit area of say, 1 m^2, were to stand on the surface without run-off, evaporation or infiltration into the soil profile, it will be 25 mm deep representing a volume of 25 liters for a surface of 1 m^2. Gauges in British Commonwealth countries are traditionally calibrated in inches, and many historical data may be in inches (1 inch = 25.4 mm).

Rainfall data are usually summarized in weekly, 10-day, monthly and annual totals. The appropriate totalling interval to choose should depend on the intended use of the data.

4.7.2 Measuring precipitation

Precipitation is measured with gauges. A typical gauge consists of a cylinder with an open top and vertical sides. The top opening is of a known area, and it is through the opening that precipitation is captured. The captured precipitation is led through a passage below the cylinder to either a collection container or a monitoring device (see **Figure 4.6**). The location of a gauge should be an open level ground. Tall objects and obstructions can modify the wind pattern around the gauge resulting in abnormal distribution of precipitation in the vicinity of the gauge.

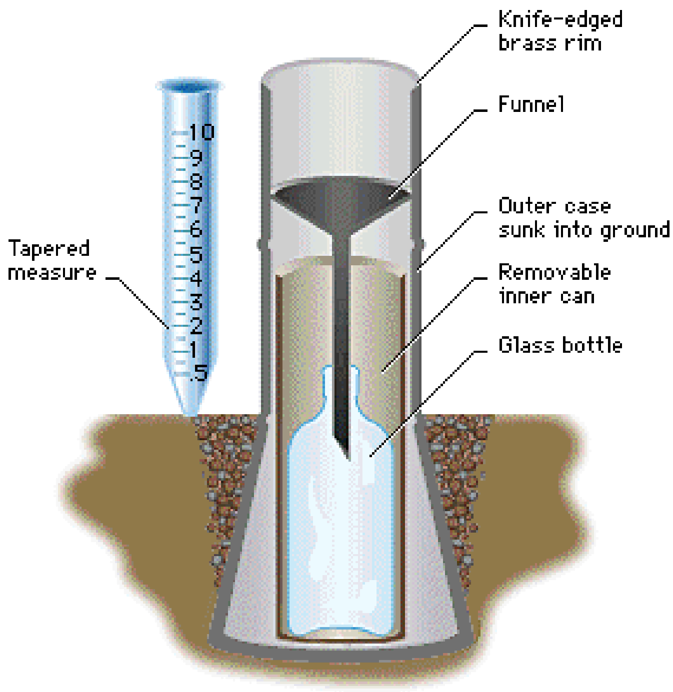


Figure 4.6: Non-recording rainfall gauge and measuring cylinder

4.8 Evaporation

Evaporation is the process by which water in the soil, lakes, rivers and oceans is returned to the atmosphere as water vapour.

Evaporation can be directly measured with the help of certain devices (evaporimeters). The potential evapotranspiration can be estimated from the amount of water lost through evaporation (Chapter 4).

4.8.1 Definition and units

Evaporation occurs when liquid water changes to vapour and the vapour is removed from the evaporating surface. The process thus involves a phase change and vapour transport.

The phase change requires energy to supply the latent heat of vaporization of water (≈ 2.45 MJ/kg or 2450 J/g). In crop canopies most of this energy normally comes from solar radiation. The transport process involves the movement of the evaporated water from the surface into the lower atmosphere. The process depends on prevailing wind speed, roughness of the surface and the vapour pressure difference between the surface and the lower atmosphere.

Evaporation is expressed in the mass (or volume) of water evaporated per unit surface area per unit time. This is then expressed in depth equivalent of water, usually in mm/day.

4.8.2 Measuring evaporation

Actual evaporation from natural water, soil and crop surfaces is difficult to measure. This is because it is difficult to simulate a natural surface of a large enough extent and to control and measure the evaporation from such surfaces. Therefore, evaporation from artificial surfaces is empirically correlated to actual evaporation from natural surfaces. The most widely used evaporation measuring devices are atmometers and evaporation pans and tanks.

a - Atmometers

Atmometers measure evaporation from a wetted porous surface. The porous surface is either of ceramic or filter paper. The evaporation surface is exposed to the atmosphere to allow free evaporation. Water is supplied constantly from a reservoir as it evaporates. A common atmometer is the Piche evaporimeter (**Photo 4.5**)

Photo 4.5: Piche Atmometer

Although atmometers are simple to construct and maintain, it is difficult to relate evaporation measured with them to evaporation from natural surfaces. Different empirical relationships exist for different atmometers and even for the same atmometer under different exposures and climate. Generally atmometer data are used in water resources management only when no other data are available.

b - Evaporation pans and tanks

Evaporation pans and tanks are widely used evaporation measuring devices. Evaporation is determined by measuring the change in level of water surface. Tanks and pans are either buried below ground level, with the water level at about ground surface, or placed above the ground. (See **Figure 4.9 and Photo 4.6**)

Above ground exposure (Class A pan) has the advantage of being inexpensive, easy to install and maintain. Problems resulting from splash of water and dirt from external sources are less than for sunken pans. Leaks are also easily detected and repaired. A disadvantage is that the tank sides can intercept radiation energy causing increases in the rate of evaporation. This is not the case with sunken tanks.

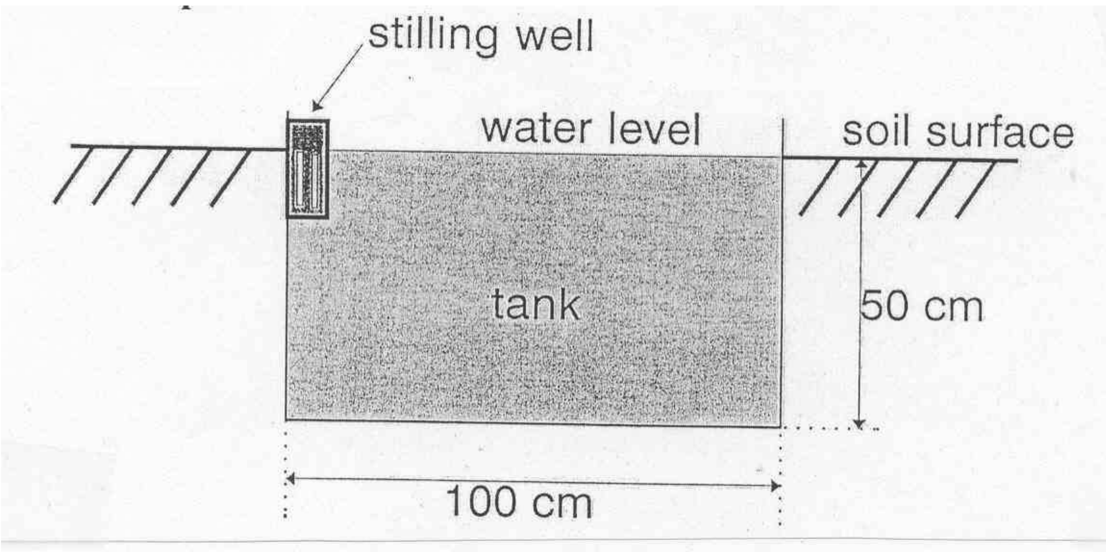


Figure 4.7: Colorado Sunken pan

Photo 4.6: Class A Pan

There are several types of pans and tanks. Since type of pan and local environment have a pronounced effect on readings obtained, it is most essential, when reporting pan data, that a clear description of type of pan, conditions of the pan and pan siting and environment should also be reported.

Unless a specific type of pan is used in the country, it is recommended that for areas where no evaporation measurement programme exists the Class A evaporation pan should be installed. The Class A pan is used more frequently than any other. The pan is 25.4 cm deep with a diameter of 120.7 cm. It is raised 5 cm above the ground with wooden supports constructed to allow free air circulation below the tank. The water level is monitored with a hook gauge or a fixed-point gauge placed in a stilling well within the tank. The stilling well reduces rippling effects when measurement is being made.

The pan should always be filled to 5 cm below the rim, the water level should not be allowed to drop to more than 7.5 cm below the rim. This is important since due to a difference in air turbulence above the pan, readings may differ by up to 15 percent when the water level in the pan falls 10 cm below this accepted standard.

Screens over the pan are not a standard requirement and should preferably not be used. Screens may, however, be needed in places where birds or animals drinking from the pan are a problem. In such cases the screen should be made of fine wire and some comparative observations between screened and unscreened pans should be made to evaluate the effect of the screen on evaporation.

Fairly accurate relationships between evaporation measured with the class A pan and crop canopy evaporation have been developed.

4.9 Climatic Databases

Meteorological data are reported and compiled in various forms, including climatic databases. CLIMWAT is a climatic database containing data from a total of 3,262 meteorological stations from 144 countries. The original database has been compiled by the Agrometeorological Group of the FAO Research and Technology Development Division and has been converted into a format suitable for use by the computer program CROPWAT.

The climatological data included are maximum and minimum temperature, mean daily relative humidity, sunshine hours, wind speed, precipitation and calculated values for reference evapotranspiration and effective rainfall.

For the use of this database in combination with the CROPWAT program see *the FAO Irrigation and Drainage paper 49, CLIMWAT for CROPWAT.*

Quite often meteorological observations within the area of an existing scheme or potential project are not available. Data from stations outside the area have then to be used. In this case it is important that the outside locations are representative of that area. If not adjustments have to be made.

Extensive areas of uniform topography with no lakes, rivers or oceans nearby generally have uniform meteorological conditions. However if topography and surface conditions change over short distances meteorological conditions also vary accordingly. The following aspects are generally valid:

- Temperature changes with altitude,
- Humidity changes with distance from large water surfaces or extensive irrigated areas,
- Wind speed differs between valleys and highlands. They are also affected by tall obstacles such as windbreaks,
- Sunshine (solar radiation) is affected by cloudiness and topography.

4.10 Weather variability

Meteorological conditions vary in time and space. At the location where a weather station is sited the air temperature, humidity, wind and solar radiation will vary from hour to hour and day to day. For practical applications these variations are averaged out over time intervals, the length of which depend on intended application.

Meteorological data are analyzed in various statistical ways to achieve various objectives. The overall objective in agriculture is to relate biological, soil and crop observations to the atmospheric environment. Major statistical methods of data analyses are:

- Frequency distribution
- The mean
- Distribution of sequences of consecutive occurrences
- Correlation methods
- Simple and multiple regressions
- Extreme value distributions
- Climatic periodicities.

Further reading

WMO Publication Nr. 134 "Agricultural Meteorological Practices".

Below we will deal with the most important concepts and methods of data analysis.

4.10.1 Periodic means

The statistical method most relevant to irrigation planning and management is the computation of average or mean values. Meteorological data can be processed into short-term or long-term totals or means. In climatology long-term means are used to compare climatic regions. In irrigation planning and management short-term: 7-day, 10-day means and monthly means are preferred, and are used to determine mean rates of crop water use. In fact, for real time irrigation scheduling mean daily data are used. Means refer to average conditions over time or space, and are computed as the arithmetic mean given as:

$$\overline{X} = \frac{\sum x_i}{n}$$

where

$\overline{X}$ = the mean
x_i = individual observations (i = 1 .. n) over a certain time or area.
n = number of observations

4.10.2 Standard deviation

In statistical work the most widely used measure of the amount of variation among a set of individual observations x_i is the standard deviation, s. The formula defining s is :

$$s = \sqrt{\left[\frac{\sum(x_i - \overline{X})^2}{(n-1)}\right]}$$

where

$\overline{X}$ = the mean
x_i = individual observations (i = 1 .. n)
n = number of observations

4.10.3 Coefficient of variation

A measure often used in describing the amount of variation in a set of individual observations is the coefficient of variation, CV :

$$CV = \frac{s}{\overline{X}}(100)$$

where

$\overline{X}$ = the mean
s = the standard deviation

The coefficient of variation is dimensionless. The coefficient expresses the standard deviation as a fraction or sometimes as a percentage of the mean. In temperate climates for example, the standard deviation of annual rainfall is about 10 to 20 % of the mean, while in more arid climates, the coefficient of variation will be much larger, even sometimes as large as 100 % or more.

Table 4.3 and **Figure 4.11** illustrate this negative correlation between the coefficient of variation and the mean annual rainfall amount. It was derived from an analysis of annual rainfall data from localities with mean annual rainfalls of less than 600 mm and embraces the semi-arid to arid belt located in the Near East and Northern Africa.

Table 4.3: Determination of mean, standard deviation and coefficient or variation of meterological data

Annual rainfall (mm) of Dagana (16°31' N, 15°30' W), Matam (15°38' N, 13°15' W) and Bakel (14°54' N, 12°28' W) in the semi-arid belt of West Africa (Senegal).

Year	Dagana	Matam	Bakel
1969	374.3	522.5	574.2
1970	174.7	277.5	456.3
1971	314.9	431.0	534.6
1972	78.5	171.5	375.7
1973	222.2	219.5	409.5
1974	205.8	327.5	681.5
1975	263.9	406.5	666.8
1976	269.1	303.5	316.9
1977	153.2	194.0	383.0
1978	324.3	246.3	523.8
1979	245.8	247.6	393.2
1980	217.9	208.5	363.8
1981	259.7	370.8	528.8
1982	151.8	274.9	591.0
1983	43.5	303.4	449.5
1984	61.0	191.0	250.6
1985	202.7	346.0	528.0
1986	138.3	338.9	462.5
1987	155.9	459.1	428.8
1988	252.8	420.1	650.0
1989	219.5	356.5	458.8
1990	176.9	350.2	374.5
Mean	204.9	316.7	472.8
Standard Deviation	83.7	94.6	114.6
Coefficient of variation	41 %	30 %	24 %

Note the negative correlation between the coefficient of variation and the mean annual rainfall. Compare the results with **Figure 4.11**

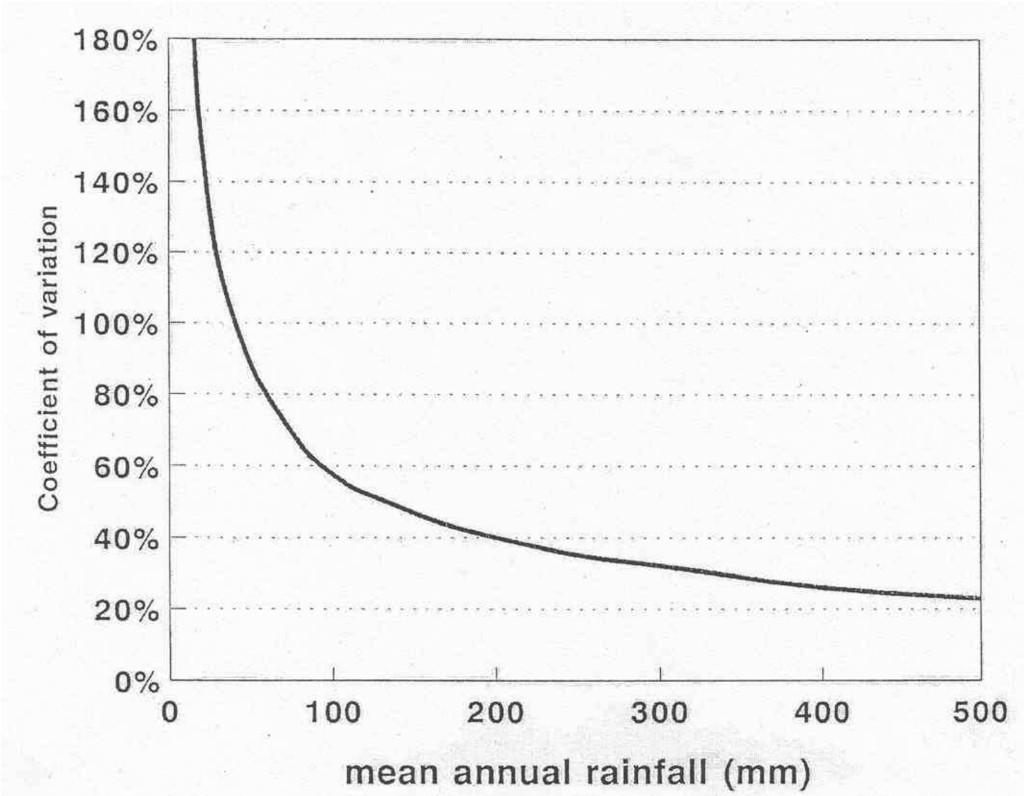


Figure 4.8: Coefficient of variation of annual rainfall shown as a function of the mean annual amount

5 EVAPOTRANSPIRATION

5.1 Introduction

The reference evapotranspiration (ET_o) is the rate of water used by a standard crop of grass growing under optimal conditions. It gives a measure of the effect of climatic conditions on crop water use. However the crop of interest will differ from the standard grass, so that the crop water use (ET_{crop}) will be different from that for grass under the same climatic conditions. In addition evapotranspiration of the crop changes over the growing season. Experimentally determined ratios of ET_{crop}/ET_o, called crop coefficient (k_c) are used to relate ET_{crop} and ET_o.

5.2 DEFINITIONS

a. Evaporation (E)

Evaporation is the loss of water by vaporization and the vapour removal from surfaces as soil surface, lakes, rivers, wet vegetation (following rain, overhead irrigation, dew). The vapour transfer is controlled by:

- climatic factors determining the level of evaporation,
- the ability (for soils) of the soil to conduct moisture to the surface.

b. Transpiration (T)

Transpiration is evaporation from a plant surface. It is the loss of water from plant tissues, predominantly through stomata (and a small percentage through the cuticula). It is water that has passed through the plant, entering at the root hair. Only a very small proportion of the water absorbed is consumed in the plant's metabolic activity. The transpiration is controlled by:

- climatic factors determining the level of transpiration,
- the vegetation (type, plant development, environment),
- the soil moisture condition.

c. Evapotranspiration (ET)

Evapotranspiration is the sum of water loss from the soil surfaces through evaporation (E) and water lost through plants by transpiration (T). Evapotranspiration (ET) forms the total amount of water lost by the crop canopy to the atmosphere. Evaporation from the soil surface is included because it is, in most cases, an unavoidable loss of water from the root zone, which has to be replaced by either rainfall or irrigation. The evapotranspiration is controlled by :

- climatic factors determining the level of evapotranspiration,
- the vegetation (type, plant development, environment),

- the soil moisture condition.

The proportion of E and T depends on the amount of bare soil surface in the canopy. At sowing 100% of ET comes from evaporation (E), while at full crop cover more than 90% of ET comes from transpiration (T).

d. Reference evapotranspiration (ET_o)

The effect of climate on crop evapotranspiration is estimated by the evapotranspiration of a reference crop under standard or reference conditions. As such the plant characteristics affecting the transpiration have no longer to be considered. It is assumed as well that the reference crop is well watered. Hence the soil moisture conditions are optimal and only climatic factors will determine the level of evapotranspiration. This evapotranspiration is called "reference crop evapotranspiration". ET_o is traditionally defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". This definition was later, for use with the FAO Penman-Monteith calculation method for ETo (see section 4.3.2 and *FAO Irrigation and Drainage paper 56*), refined to 'the evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistence of 70 s m^{-1} and an albedo of 0.23' (see **Figure 5.1**).

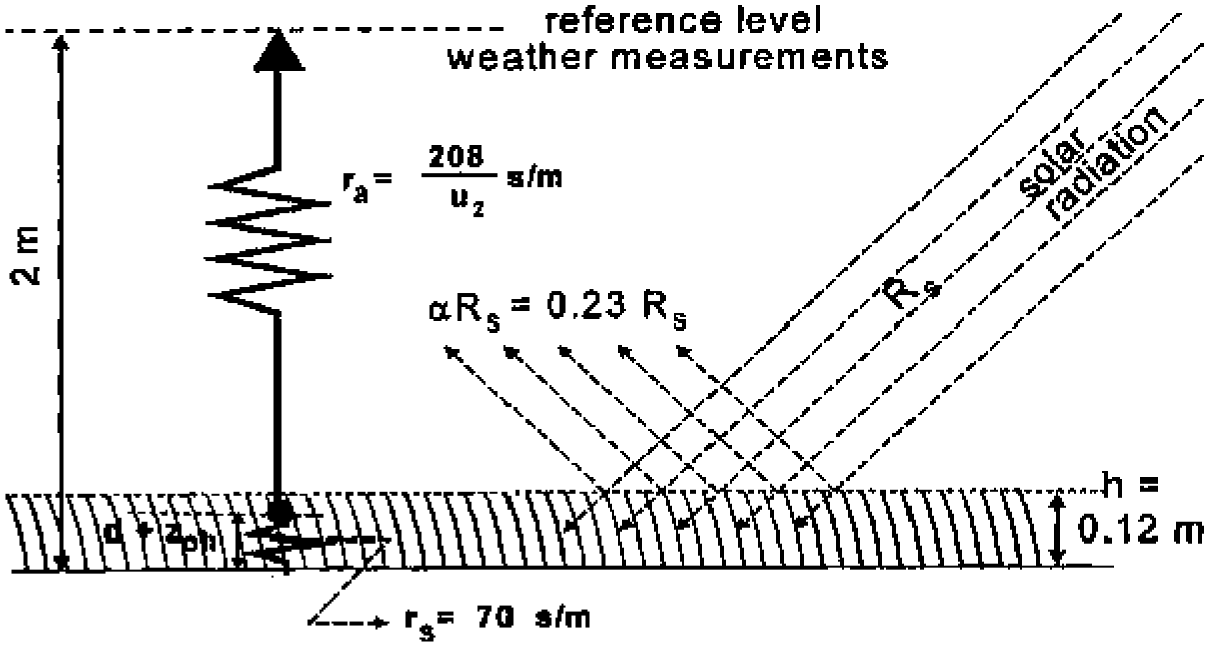


Figure 5.1: Characteristics of the hypothetical reference crop

Notes:
Rs: surface resistance describes the resistance of vapour flow through stomata, total leaf area and soil surface
Ra: aerodynamic resistance describes the resistance from the vegetation upwards and involves friction from air flowing over vegetative surfaces. For details, see FAO Irrigation and drainage paper 56.

The mean level of the reference evapotranspiration for different agro-climatic regions is given in **Table 5.1**.

Table 5.1: Reference evaporation ETo for different agro-climatic regions

	Mean daily temperature (°C)		
	< 10 —— cool	20 —— moderate	> 30 warm
Regions	ET_o (mm/day)		
TROPICS			
Latitude 0 - 20°			
Humid	3 – 4	4 – 5	5 – 6
sub-humid	3 – 5	5 – 6	7 – 8
semi-arid	4 – 5	6 – 7	8 – 9
arid	4 – 5	7 – 8	9 – 10
SUBTROPICS			
Lat. 20 – 40°			
Summer rainfall			
Humid	3 – 4	4 – 5	5 – 6
sub-humid	3 – 5	5 – 6	6 – 7
semi-arid	4 – 5	6 – 7	7 – 8
arid	4 – 5	7 – 8	10 – 11
Winter rainfall			
(sub)humid	2 – 3	4 – 5	5 – 6
semi-arid	3 – 4	5 – 6	7 – 8
arid	3 – 4	6 – 7	10 – 11
TEMPERATE			
Lat. 40 – 60°			
(sub)humid	2 – 3	3 – 4	5 – 7
(semi)-arid	3 – 4	5 – 6	8 – 9

e. Crop evapotranspiration (ET_{crop})

The effect of crop characteristics on crop water requirements is given by the crop coefficient which presents the relationship between the reference (ET_o) and potential or maximum (ET_{crop} or ET_m) evapotranspiration of the crop (**Figure 5.2**).

$$ET_{crop} = k_c \, ET_o$$

Values of k_c vary with the crop and its stage of growth. When defining potential crop evapotranspiration (also called crop water requirements) it is assumed that the crop is disease free and that the crop is growing in large fields under conditions of optimum availability of water, and optimum agronomic management". From this definition the factors determining the level of potential evapotranspiration are :

- climatic factors determining the level of evapotranspiration (ET_o),
- crop characteristics (e.g crop height, roughness, albedo etc.) affecting the transpiration (k_c).

f. Actual evapotranspiration (ET_{act})

When the soil moisture conditions are not optimal the crop is under stress and the actual evapotranspiration (ET_{act}) will be smaller than the potential (ET_{crop}). The actual crop evapotranspiration is the evapotranspiration of a given crop occurring under the moisture conditions existing at that moment.

g. Units

The evapotranspiration is normally expressed in mm/day or mm/month or mm/growing period (often called the consumptive use).

Figure 5.2: Factors in determininination of ETo and ETcrop

5.3 DETERMINATION OF EVAPOTRANSPIRATION

Evapotranspiration is not easy to measure. Methods based on the soil water balance are required to determine evapotranspiration. Lysimeters are special devices in which the different components of the water balance can be measured.

5.3.1 Soil water balance

The principle of the water balance is the equation: *inflow – outflow = change in water storage* for a certain space (e.g. rootzone) over a certain time period (see Figure 4.2). The evapotranspiration can be calculated by determining the other components of the water balance.

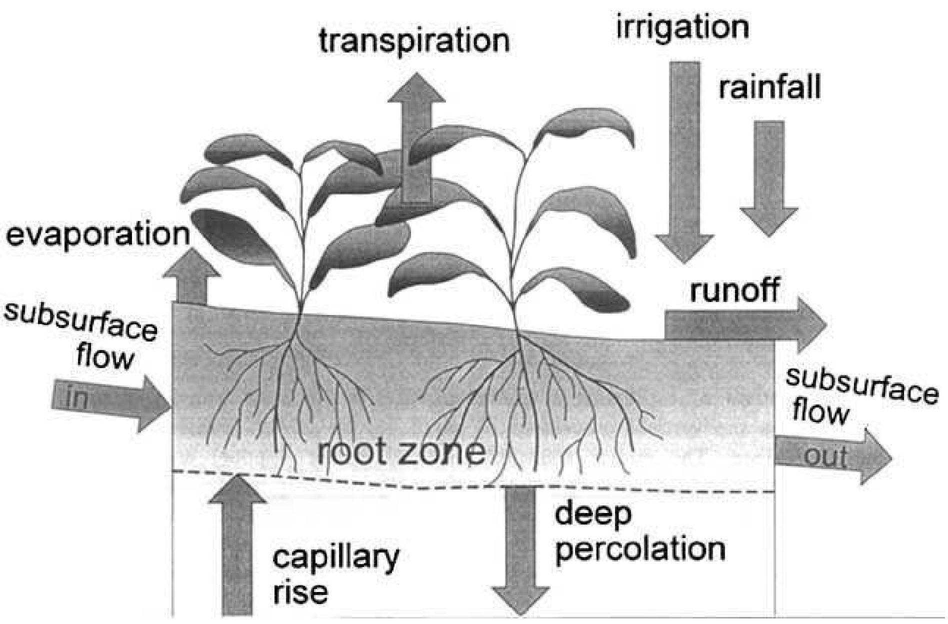


Figure 5.3: Soil Water Balance

INFLOW:	**OUTFLOW**:
Precipitation	Evapotranspiration
Irrigation	
Surface Inflow	*Surface Outflow* *(Run-Off)*
Subsurface Lateral Inflow	Subsurface Lateral Outflow
Groundwater Inflow	Deep Percolation
(Capillary Rise)	*(Drainage)*

Δ S = Change in Storage = D_{rz} (θ_f - θ_i)

Where:

Dr = depth of rootzone

θf = (final) moisture content end of period

θi = (initial) moisture content beginning of period

It depends on each particular situation which components are relevant. In many situations , except under conditions with large slopes, subsurface flows (SSLI and SSLO) are minor and can be ignored. Other fluxes such as deep percolation and capillary rise from a water table are difficult to assess and short time periods cannot be considered. The soil water balance method can usually only give ET estimates over long time periods of the order of week-long or 10-day periods.

5.3.2 Lysimeters

A lysimeter is a special device in which the different components of the water balance can be measured. Lysimetry, in its simplest form, involves the volumetric measurement of all incoming and outgoing water of a container which encloses an isolated soil mass with a bare or vegetated surface. This permits to calculate evapotranspiration (see **Figure 5.4**). The lysimeter surroundings should be covered by the same crop over an area big enough for advection effects on the lysimeter to be negligible.

Though use of a lysimeter gives a direct measurement of ET, it is only for specific research purposes that such devices are used as their operation and maintenance requires special care and their costs and labour requirements preclude their use as routine field instruments. For more information, see *FAO Irrigation and drainage paper 39, Lysimeters*.

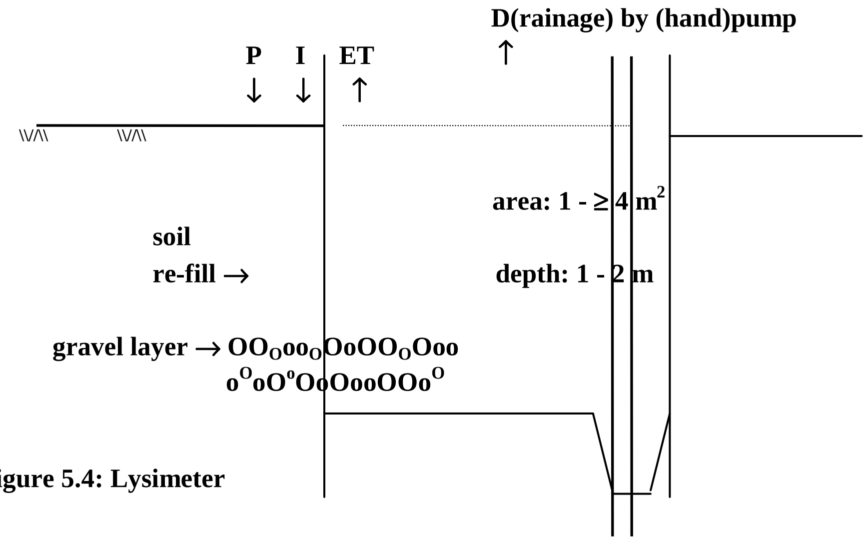


Figure 5.4: Lysimeter

Water Balance Lysimeter:

$$P + I = ET + D \; (\pm \Delta S)$$

$$\Delta S = 0 \;\text{ when }\; \theta_{final} = \theta_{initial} = \theta_{field\ capacity}$$

(Note: the soil is at field capacity after drainage of excess water)

5.4 DETERMINATION OF REFERENCE CROP EVAPOTRANSPIRATION (ET_o)

Reference crop evapotranspiration can be determined directly with lysimeters or indirectly through calculation from meteorological data or measurement from evaporation pans.

5.4.1 Pan evaporation

Pan evaporation data can be used to estimate ET_o as it is a measure of the integrated effects of radiation, wind, temperature and humidity on evaporation from a specific open water surface. The pan responds in a similar fashion to the evaporative capacity of the air as a crop, although several factors may produce significant differences in water losses. These physical differences between pan and grass make adjustments necessary. The main differences are:

- The albedo or reflectivity of water in the pan is 5-8%, whereas for grass it is 20-25%.
- Pans can store heat which can be used to evaporate water even at night, whereas crops transpire only during day time.
- There are differences in microclimate (wind turbulence, humidity and temperature) around the pan compared to a crop.
- Some heat can be transferred from the environment to the pan, especially in sunken pans. This can enhance evaporation.
- Local advection of heat depending on the siting of the pan can affect the evaporation.

Therefore an adjustment factor is necessary to relate ET_o to pan evaporation. The relation is expressed as:

$$ET_o = k_{pan} \; E_{pan}$$

Where:

E_{pan} = mean daily pan evaporation for the period [mm/day]

k_{pan} = pan coefficient

5.4.2 Calculation methods using meteorological data

Meteorological data are widely used in calculating crop water requirements. Many formulae are developed and tested from purely empirical ones based on only one variable to sofisticated ones based on the analysis of physical processes. In this section some of these calculation methods will be dealt with.

a. Penman-Monteith equation

Recent studies have shown the very convincing performance of the method based on the so-called Penman-Monteith approach.

The Penman-Monteith equation is based on a direct integration of crop resistance, albedo and air resistance factors and as such results directly in the determination of the crop evapotranspiration (ET_{crop}) so that use of the crop coefficients (k_c) no longer applies.

As there is still a considerable lack of consolidated information on crop resistances it has been proposed for the time being to use the Penman-Monteith method for an imaginative crop with fixed parameters and resistance coefficients. This reference crop closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water. Thus the Penman-Monteith method calculates the evapotranspiration of the standard reference crop (ET_o). In this way the crop coefficients as listed by FAO for the modified Penman method (in *FAO Irrigation and Drainage paper 24, Crop water requirements*) also apply to the Penman-Monteith method.

General equation: Penman-Monteith

$$\mathbf{ET_0 = c\,[\,\underbrace{W\,R_n}_{\text{radiation term}} \quad + \quad \underbrace{(1 - W)\,f\,(U)\,(e_a - e_d)}_{\text{aerodynamic term}}\,]}$$

c	=	adjustment factor	f (U, RH, R_s)
W	=	weighing factor	f (T, altitude)
f (U)	=	wind related function	
(e_a - e_d)	=	difference actual vapour pressure and saturated vapour pressure	

From this original equation, on basis of the characteristics of the hypothetical reference crop the **FAO Penman-Monteith method** to estimate ETo can be derived:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34 u_2)}$$

where

ETo	=	reference evapotranspiration [$mm.day^{-1}$]
Rn	=	net radiation at the crop surface [$MJ.m^{-2}.day^{-1}$]
G	=	soil heat flux density [MJ. m-2day-1]
T	=	mean daily air temperature at 2 m height [^oC]
u_2	=	wind speed at 2 m height [ms^{-1}]
e_s	=	saturation vapour pressure [kPa]
e_a	=	actual vapour pressure [kPa]
$e_s - e_a$	=	saturation vapour pressure deficit [kPa]
Δ	=	slope vapour pressure curve kPa. $^oC^{-1}$]
γ	=	psychrometric constant [kPa. $^oC^{-1}$]

Further reading and reference :

FAO irrigation and drainage paper 56, Crop evapotranspiration, Guidelines for computing crop water requirements.

The computer program CROPWAT calculates the ETo with the Penman-Monteith method using the following input variables:

- Location (Altitude, Latitude)
- *Temperature*
- *(Relative) Humidity*
- *Radiation*
- *Wind Speed*

b. Radiation methods

$$\mathbf{ET_0 = C\ W\ R_s}$$

Where:

C	=	adjustment factor (general level of RH and day-time wind)
W	=	weighing factor (temperature, altitude)
R_s	=	incoming short wave radiation [mm/day]

Formerly, in The Netherlands the formula of Makkink: $ET_0 = 0.65\ W\ R_s$ was much used to calculate ETo during the period April- September

c. Empirical methods

Many locations have only air temperature. Simplified or empirical temperature-based methods are needed to estimate ET_o for these regions. Examples are the formerly much used formulas of Blaney- Criddle, Hargreaves and Thornthwaite. The Hargreaves equation is based upon solar radiation and temperature data. However the solar radiation is estimated from the difference between the maximum and minimum temperature. Consequently this method can be used for areas where available climatic data cover air temperature data only. The method gives a better fit with measured ET_o data than the Blaney Criddle method which requires similar climatological data. The Hargreaves equation for ET_o (grass) is:

$$ET_0 = 0.0023\, R_a\, (T_{mean} + 17.8)\sqrt{(T_{\max} - T_{\min})}$$

Where:
R_a = extra terrestrial radiation [equivalent mm/day]
T_{mean} = mean air temperature [°C]
T_{max} = mean maximum air temperature [°C]
T_{min} = mean minimum air temperature [°C]

The coefficient 0.0023 was obtained at Davis (California) from calibration with lysimeter data. Since the method lack some of the major weather parameters which affect the value of ET_o, some calibration and/or evaluation is recommended for varying climatic and topographic conditions.

In **Table 5.2** reference evapotranspiration calculated by Penman-Monteith and by Hargreaves are compared.

Table 5.2: Determination of ETo in Jakarta

Station : Jakarta (Indonesia), 6°11'S, 106°50'E, 8m elevation Month : August Mean air temperatures : 32.2°C (T_{max}), 21.1°C (T_{min}) Mean actual vapour pressure (e_d) : 27.2 mbar (2.72 kPa) Mean wind speed at 2 meter (U_2) : 0.8 m/sec Ratio of actual to maximum sunshine hours (n/N) : 79 %
Calculated : T_{mean} = (32.2 + 21.1)/2 = 26.65 °C e_a = 3.42 kPa = 34.2 mbar (Table 1, Annex 2) RH = 100 (2.72)/(3.42) = 80 % R_a = 14.0 mm/day (Table 3, Annex 2)
Method : Hargreaves (Temperature method) ET_o = 0.0023 (14.0) (26.65 + 17.8) √(32.2 - 21.1) = 4.8 mm/day
Method : Penman-Monteith ET_o = 4.3 mm/day

5.4.3 Determination of ETo per decade

Mean daily ET_o values are computed from mean monthly climatic data. In some cases this mean daily ETo value will be also sufficiently accurate to calculate crop water requirements in periods shorter than a month. But in other cases, for instance when irrigation water has to be delivered in short intervals and precise quantities (involving specific irrigation methods) and/or irrigation water is scarce and/or valuable crops are cultivated, the calculation of crop water requirements need refinement and consequently shorter periods are required. To convert monthly data to 10-days or decade values a graphical interpolation procedure, illustrated in **Figure 5.7**, can be followed.

Figure 5.5: Graphical dtermination of decade ETo values from monthly estimates

5.5 CROP EVAPOTRANSPIRATION (ET_{crop})

5.5.1 ET_o - ET_{crop} Relationship

ET_o is the rate of water use by a standard crop of grass growing under optimal conditions. It gives a measure of the effect of climatic conditions on crop water use. However, the crop of interest will differ from the standard grass in many aspects, so that the crop evapotranspiration (ET_{crop}) will be different from that for grass (ET_o) under the same climatic conditions. These differences include:

- Differences in leaf anatomy (such as waxy leaves and leaf hairs). Crops with these features exhibit lower ET_{crop}.

- Differences in transpiration pattern. Some crops, such as pineapple close their stomates during the day and transpire at night. In the absence of radiation ET_{crop} is lower at night.

- Differences in crop architecture, such as crop height and surface roughness. Tall crops, such as maize, are rougher, creating more turbulence in the air passing over them. Hence, they transpire more than the short grass canopy.

- Differences in albedo (reflectivity) caused by differences in pigmentation and ground cover.

Due to these differences, under full cover and optimal soil water conditions, some crops such as cotton and maize have $ET_{crop} > ET_o$; while others, such as citrus and pineapple have $ET_{crop} < ET_o$. **Figure 5.8** gives a schematic comparison between ET_{crop} and ET_o for various crops.

Figure 5.6: Ration ETcrop / ETo

Differences in the crop canopy and aerodynamic resistance relative to the reference crop are accounted for within the crop coefficients (k_c). These are equal to the experimentally determined ratios of ET_{crop}/ET_o. :

$$ET_{crop} = k_c \ ET_o$$

Note, that k_c values used, only relate to disease-free crops, growing in large fields under optimal soil water and fertility conditions and with full production potential under the given environment.

In addition evapotranspiration of the crop changes over the growing season (**Figure 5.9**). It increases from sowing to full cover as the crop increases its leaf area and the roots develop to tap water from a larger volume of soil. It then decreases from maturity to harvest as the leaves die off. Hence, for a given crop, k_c is not constant throughout its growth period. On average the value of k_c at any time depends on the crop growth stage. The rate of change of k_c within a growth stage depends on the length of the stage. Other factors, such as the frequency of rain or irrigation also affect k_c.

The day-to-day changes of k_c values for a crop are normally represented by a k_c curve, which begins from sowing and continues till harvest. It is usually determined experimentally, using lysimeters to measure ET_{crop} and ET_o. A typical k_c curve is given in **Figure 5.9**

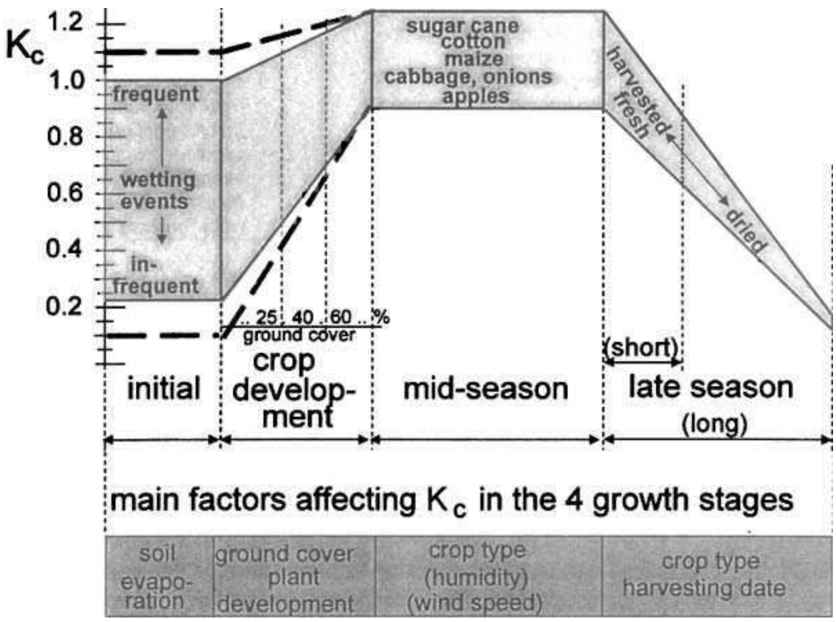


Figure 5.7: Example of variation of Kc over growing season

5.5.2 Cropping calendar

The **cropping pattern** is the sequence in which crops in a given area are grown. If in a certain area two crops of rice and one crop of vegetables are grown, then the cropping pattern is rice - rice - vegetables.

The **crop calendar** provides information on the sequence of the crops grown and on the timing of their cultivation, i.e. (trans)planting/sowing dates and harvest dates. In **Table 5.3**, a cropping calendar is given as an example. The information is graphically presented in **Figure 5.11**

Table 5.3: Crop Calendar

Crop	Area (%)	Planting		Harvest		Duration (days)
		from	to	from	To	
Rice (rainfed)	50	20 Jan	10 Feb	10 May	30 May	110
Rice (irrigated)	100	20 May	20 June	25 Sept	25 Oct	130
Vegetables	50	10 Oct	30 Oct	10 Jan	30 Jan	90

Figure 5.8: Cropping Calendar

The **cropping intensity** for a specific area is the number of crops planted on a defined area over a period of one year. The cropping intensity is expressed as a number or as a percentage (1.25 or 125%). For a certain area three rice crops grown within one year results in a cropping intensity of 3 or 300%. The same cropping intensity would be obtained for the cropping pattern of rice - rice - vegetables, since the definition mentions the number of crops. The kind of crops is not relevant.

In the example of **Figure 5.11**, four distinct areas can be distinguished, each with its own cropping intensity. On one quarter of the total area, only irrigated rice is cultivated. After the harvest of the rice crop, the land is fallow for the rest of the year. This part of the area has a cropping intensity of 1 or 100 %. On another quarter, two rice crops are grown within one year (cropping intensity of 2 or 200%). The cropping intensity of a third quarter is 300 % : rice - rice - vegetables. On the last quarter, rice and vegetables are cultivated (cropping intensity of 200 %). The overall cropping intensity of the total area is hence :

$$100\% \frac{25}{100} + 200\% \frac{25}{200} + 300\% \frac{25}{200} + 200\% \frac{25}{100} = 200\%$$

5.5.3 Crop stages and crop development

For all annual field crops the growing period can be divided into the following stages:

- The initial stage: From germination through establishment. Slow increase in vegetative cover. Much soil exposed with crop cover below 10%.
- The crop development stage: From the end of the initial stage to full ground cover. Rapid increase in vegetative cover until full cover is attained.
- The mid-season stage: From full cover to the start of maturity when leaves start to yellow and fall. Almost constant full ground cover.

- The <u>late season stage:</u> From the start of maturity to the harvest. Leaf yellowing and in some cases rapid defoliation. Old leaves transpire less.

The length of the total crop season and the duration of the growth stages should be determined from local information since they are site specific, depend on the sowing/planting date and can change depending on the planted variety. The planting date will determine the temperature regime for the rest of the growth period. This affects the rate of development of the crop and so the rate at which a growth stage progresses.

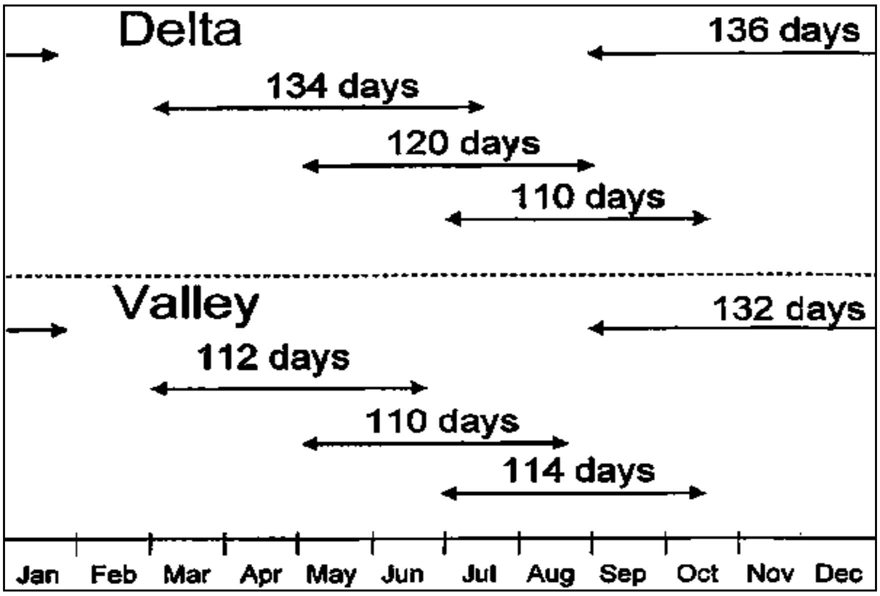


Figure 5.10: Length of crop season in function of sowing date for a rice variety (Jaya) at different sites in North of Senegal

5.5.4 Crop coefficients

a. Single season annual crops

Most field crops belong to this group. Their growing season can be divided into 4 stages: initial, crop development, mid-season and late season. The procedure, leading to the formation of individual crop k_c curve is as follows:

- Determine the average planting date from local information
- Determine the average duration of the 4 growth stages either from local information
- Determine the k_c value for the initial stage. At the initial stage k_c is low because of low transpiration. As ET_{crop} is the sum of evaporation from the soil and transpiration from the plant, k_c will depend on the length of time when the soil is wet and on the degree of wetness. E_{soil} is high in wet soil and decreases as the soil dries. The effect is important during the initial stage. Rain or irrigation (total amount and interval) determine to a certain extent the average levels of k_c. The k_c value of the initial stage

can be derived from **Table 5.3**. Values of the initial k_c for different crops which take the required irrigation interval into account are given in **Table 5.4**.

Table 5.4: Kc for initial crop development stage

Interval between irrigations or significant rain	2 days	4 days	7 days	10 days
k_c	0.9	0.65	0.5	0.3

- Select the k_c values for mid-season and at harvest (end of late season stage) from **Table 5.4**. A minor correction of the presented values might be needed in function of general climatic conditions, especially wind and humidity. It is recommended to increase the values with 5 % for dry and windy conditions, and to decrease the values with 5 % for cool and wet seasons.

- Develop a k_c curve. The procedure is presented in schematic form in **Table 5.5**. The resulting k_c curve for maize is given in **Figure 5.11**

Table 5.5: Example of the development of Kc curve for some crops

Crop	Maize	Cotton	Cabbage	Tomato
Initial stage				
Irrigation frequency	Long	Long	Frequent	Very frequent
Climate at sowing/planting	Warm	Hot	Warm	Cool
Length of growing season				
Initial stage	20	30	20	30
Development stage	35	50	30	40
Mid season	40	55	20	40
Late season	30	45	10	25
Crop Factor				
Initial stage	0.35	0.30	0.60	0.70
Development stage	-	-	-	-
Mid season	1.15	1.20	1.05	1.20
Late season	-	-	-	-
Harvest	0.60	0.65	0.90	0.65

The k_c curve for maize is shown in **Figure 5.17**

Table 5.6: Crop Coefficients

	Initial	mid-season	at harvest
1. Small vegetables	**0.70**	**0.95**	**0.75**
- Onions		0.95	0.75

- Carrots		1.00	0.75
- Lettuce		1.05	0.90
- Celery		1.05	0.95
- Spinach		0.95	0.90
- Radish		1.00	0.75
- Strawberry			
- Cabbage		1.00	0.85
2. Vegetables (Beets)	**0.50**	**1.05**	**0.90**
- Sugar beet		1.10	0.95
- Turnip		1.05	0.90
- Parsnip		1.00	0.90
- Beetroot		1.00	0.90
3. Vegetables (Leguminosae)	**0.45**	**1.00**	**0.50**
- Beans (green)	0.50	0.95	0.85
- Beans (pulses)	0.30	1.10	0.30
- Groundnut	0.40	1.00	0.55
- Peas	0.55	1.10	1.00
- Soya bean	0.40	1.05	0.45
- Broad beans	0.50	1.00	0.50
- Lentils	0.40	1.10	0.30
- Chicken peas			
4. Vegetables (Solananaceae)	**0.60**	**1.05**	**0.75**
- Tomatoes	0.70	1.10	0.60
- Potatoes	0.50	1.10	0.70
- Sweet peppers	0.70	1.00	0.85
- Eggplants	0.70	1.00	0.85
- Chilies			
5. Vegetables (Cucurbiaceae)	**0.50**	**0.95**	**0.70**
- Cucumbers	0.60	0.90	0.80
- Squash	0.60	0.90	0.70
- Melon	0.50	1.00	0.80
- Water melon	0.35	0.95	0.70
- Pumpkin	0.50		
6. Vegetables (Divers)			
- Artichokes	0.50	0.95	0.90
- Asparagus	0.60	1.10	0.70
- Pineapple	0.30	0.90	0.70
- Tobacco	0.60	1.10	0.85
	Initial	**mid-season**	**at harvest**
7. Fiber crops	**0.30**	**1.10**	**0.50**
- Cotton	0.30	1.15	0.65
- Flax	0.30	1.05	0.25
- Sisal	0.30	0.70	0.70
8. Oil crops			
- Sunflower	0.35	1.10	0.40
- Safflower	0.35	1.10	0.25
9. Cereals	**0.35**	**1.10**	**0.30**
- Barley	0.35	1.10	0.25
- Oats	0.35	1.10	0.25
- Wheat	0.35	1.10	0.25
- Maize	0.40	1.15	0.50
- Sorghum	0.40	1.15	0.40
- Millet	0.35	1.10	0.40
	Low	**mean**	**High**

10. Pasture & Fodder crops	**0.50**	**1.00**	**1.10**
- Pasture	0.50	1.00	1.10
- Alfalfa	0.40	1.10	1.20
- Clover	0.55	1.05	1.15
- Sudan grass	0.60	1.05	1.20

	Initial	mid-season	at harvest
11. Sugar cane	**0.50**	**1.15**	**0.65**

	range
12. Grapes & Berries	
- Grapes	0.50 - 0.80
- Coffee	0.90
- Tea	1.00
- Cacao	0.90 - 1.10

	range
13. Fruit trees	
- Dates	0.80 - 1.00
- Olives	0.40 - 0.70
- Citrus	0.65 - 0.90
- Deciduous fruit	0.50 - 0.85
- Palm trees	0.90
- Avocado	0.90
- Bananas	0.60 - 1.15

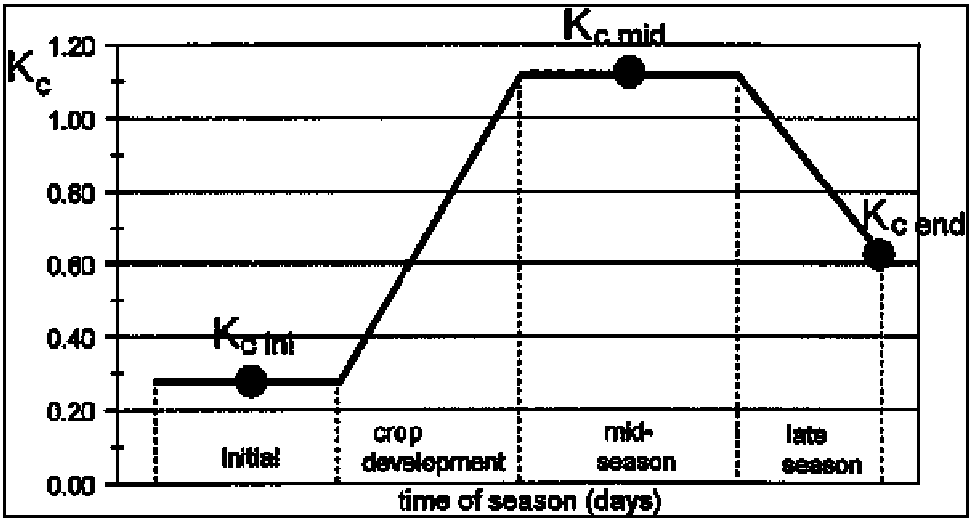


Figure 5.11: Example of crop coefficient curve

b. Rice

k_c values throughout the growth period of rice, whether wetland rice (paddy) or upland rice, do not differ much because surface conditions are always saturated. Differences are only due to humidity and wind conditions. Suggested values are given in **Table 5.7**.

Table 5.7: Suggested Kc values for rice

	1st & 2nd month	Mid Season	Last 4 Weeks

Wet season (RHmin > 70 %)			
- Light to mod. Wind	1.10	1.05	0.95
- Strong wind	1.15	1.10	1.00
Dry season (RHmin < 70 %)			
- Light to mod. Wind	1.10	1.2-1.25	0.95-1.00
- Strong wind	1.15	1.3-1.35	1.00-1.05

Further reading and reference:

FAO Irrigation and Drainage Paper Nr. 24. Special cases and examples are also given in *FAO Irrigation and Drainage Paper Nr. 46 (CROPWAT manual).*

5.5.5 Calculation of ETcrop

Crop evapotranspiration (ET_{crop}) is computed from ET_o and k_c by the equation :

$$ET_{crop} = k_c \; ET_o$$

A summary of the steps required to calculate ET_{crop} (for an example, see **Table 5.8**) are:

- Calculate ET_o over the growing period.
- Plot a curve of the monthly ET_o values
  Eventual refinement: interpolate 10-day estimates
- Construct a k_c curve for the crop
  Eventual refinemernt: interpolate 10-day k_c values as explained for ET_o.
- Finally calculate ET_{crop} for each month as: $ET_{crop} = k_c \; ET_o$.
  Eventual refinement: ET_{crop} for each decade

Table 5.8: Example of the calculation of ETcrop

Maize – length of season : 125 days
Initial stage (20 days): 15 May - 5 June
Crop development (35 days): 6 June – 10 July
Mid season stage (40 days): 11 July - 20 August
Late season stage (30 days): 21 August - 20 September
The crop coefficient curve is given in **Figure 4.10**

Month	**Decade**	**Eto mm/day**	Kc	**ETcrop mm/day**	**ETcrop mm/dec**
May	2	5.0	0.35	1.75	8.8
	3	5.3	0.35	1.86	18.6
June	1	6.0	0.40	2.40	24.0
	2	6.3	0.60	3.78	37.8
	3	6.8	0.80	5.44	54.4
July	1	7.0	1.00	7.00	70.0
	2	7.5	1.15	8.63	86.2
	3	7.5	1.15	8.63	86.2
August	1	7.0	1.15	8.05	80.5
	2	7.0	1.15	8.05	80.5
	3	6.5	1.00	6.50	65.0
September	1	6.5	0.80	5.20	52.0
	2	6.0	0.60	3.60	36.0

The potential crop evapotranspiration (ET_{crop}) of the season is 700 mm

5.5.6 The CROPWAT computer programme

The Land and Water Division of FAO (AGLW) has developed the CROPWAT computer programme to calculate crop water requirements and irrigation requirements from climatic and crop data. Furthermore, the program allows the development and evaluation of irrigation scjhedules for different management conditions and the calculation of scheme water supply for varying cropping patterns. In the CROPWAT programme, reference Evapotranspiration ETo is calculated by the Penman-Monteith equation, based on the climatic variables (temperature, air humidity, wind speed and daily sunshine) and the location of the meteo station.

See appendix A for cropwat practical guide.

6 PLANT - SOIL – WATER SYSTEM

The growth of the crop involves the plant itself, the water and the soil. Plant-water-soil relationships will be discussed here in as far as the soil is concerned. Main aspects considered are:

- How much water can be held by (or: stored in) the soil, and
- How much water stored in the soil is readily available for use by the crop.

6.1 The soil

a. Soil texture

The major part of (non-organic) soils consist of mineral soil particles: sand, silt and clay. The mineral soil elements can be classified according to their size. The size distribution of the ultimate soil particles is referred to as "texture". It can be estimated in the field or determined in the laboratory.

There are several textural classifications. The most commonly used for agronomic purposes is the classification of the USDA. The main particle size limits are given in **Table 6.1**.

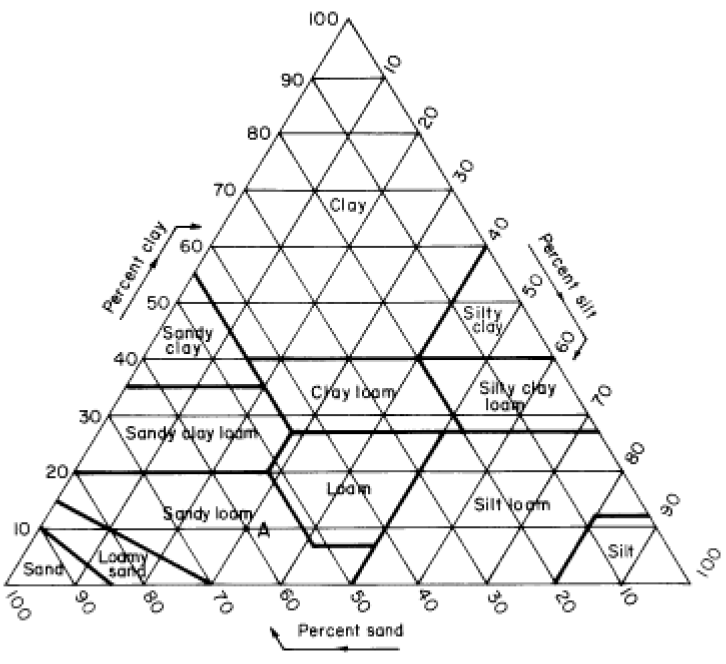


Figure 6.1: Textural Classification

Table 6.1: Praticle Size limits

Soil	Sub-class	Diameter (mm)	limits (mm)
Sand		2.00 - 0.050	
	Very coarse		2.00 - 1.00
	Coarse		1.00 - 0.50
	Medium		0.50 - 0.25
	Fine		0.25 - 0.10
	very fine		0.10 - 0.05
Silt		0.050 – 0.002	
	Coarse		0.050 - 0.020
	Fine		0.020 - 0.002
Clay		< 0.002	

The relative proportion of sand, silt and clay in a soil determine it's textural class. Evidently the number of possible combinations is infinite, but for practical purposes certain arbitrary divisions are made and a name is applied to those particle-size compositions. In **Table 7.2**, a 'soil-wise' and a 'texture-wise' description of the textural classes is given.

Table 6.2: Textural grouping

Textural term soil-wise	Alternative term Texture-wise	Textural classification
very heavy	very fine	heavy clay (more than 60% clay)
heavy	fine	clay, silty clay, sandy clay
moderately heavy	moderately fine	silty clay loam, clay loam, sandy clay loam
Medium	Medium	silt loam, loam, very fine sandy loam
Moderately light	Moderately coarse	fine sandy loam, sandy loam
Light	Coarse	loamy fine sand, loamy sand
Very light	very coarse	sand, coarse sand

b. Soil structure

The soil is a complex porous medium consisting of 4 components: mineral solid particles, organic matter, water with dissolved substances and air.

The solid mineral components consist mainly of various proportions of sand, silt and clay. Organic matter is usual about 5% or less (<1% in tropical and arid soils). There is also some living organic matter. The mineral particles and organic matter form a loosely packed matrix with spaces in between the particles.

The term "soil structure" refers to the three-dimensional arrangement of the primary soil particles (sand, silt, clay) and the secondary soil particles (micro-aggregates) into a certain structural pattern (macro-aggregates). The aggregates of textural elements are held together by colloids (mineral and organic) and separated from one another by cracks and large pores. Structure is not a plant-growth factor in itself, but it defines water retention, water movement, soil aeration, root penetration, micro-biological activities, resistance to erosion, etc.

c. Particle density

Particle density is the mass per unit volume of soil particles, usually expressed in grams per cm^3 of soil particles. Instead of "particle density" the term specific gravity (s.g.) is often used.

Average specific gravity of distinct soil components are: organic matter - 1.47 g/cm^3; sand - 2.66 g/cm^3; clay - 2.75 g/cm^3. For the soil as a whole the particle density varies from 2.6 to 2.9 g/cm^3 (2.65 g/cm^3 in average).

d. Bulk density

Bulk density is the dry weight of a unit volume of soil in its field condition, usually expressed in grams per cm^3. Bulk density is also known as "volume weight" or "apparent density". The bulk density of the soil is obtained by weighing an oven dry undisturbed soil sample of known volume. The bulk density, especially of the top soil, should be checked regularly. It usually ranges from 1.25 to 1.65 g/cm^3 (see **Table 6.6**). The finer the texture of the soil and the higher the organic matter content, the smaller the bulk density.

6.2 Soil moisture

A soil consists of mineral solid particles, organic matter and pore space. In the pore space, the space between the solid particles, water can be stored. The pore space varies from 30 % to 60 % of the total soil volume. Water and air exist in the pore space in varying proportions depending on the water status in the soil. In a dry soil, most of the pore space would be empty and filled with air, while in a wet soil, water would occupy most of the pore space.

The soil moisture content can be expressed in several ways. One way to express it, is on a dry mass basis. When examining water budgets, it is useful to express the water content on a volume basis or in terms of depths. When defining soil moisture content, it is useful to visualize the soil as a container in which water can be stored. In **Figure 6.2** a cubic soil sample is presented which contains a certain amount of water in the pore space. Consider that all of the solid particles could be compressed together without leaving any pore space between them. The soil water would settle above the solid and the soil air would occupy the space above the soil water.

a. *Dry Mass basis*

The dry mass moisture content is given by the ratio of the mass of soil water to the mass of dry soil (times 100 if expressed as a percentage) :

$$\theta_m = 100\,\frac{\textit{mass soil water}}{\textit{mass dry soil}} \qquad [\textit{mass}\,\%]$$

With reference to **Figure 6.3**, the dry mass moisture content is the ratio of (ρ_w bA) to (ρ_p cA) in which ρ_w is the density of soil water (1 g/cm^3) and ρ_p the density of the solid particles (2.65 g/cm^3) that constitute the soil.

Figure 6.2: Schematic presentation of a cubic soil sample with the three considered soil phases : solids, solution and air.

The gravimetric method is the standard method to determine the soil moisture content. The method consists in weighing, drying and reweighing a soil sample. By means of an auger a number of representative soil samples are taken. The difference in mass of the sample before and after drying gives the mass of water. If m_{s+w} is the wet mass (gram) of the sample and m_s the mass (gram) of the oven dry sample, the dry mass water percentage is :

$$\theta_m = 100 \frac{m_{s+w} - m_s}{m_s} \qquad [mass\,\%]$$

In order to remove all the water from the soil sample, the sample should be dried to constant weight during 24 hours in a oven set at 105°C.

b. Volume basis

The volume water content is the ratio of the volume of soil water to the bulk volume of the soil (times 100 if expressed as a percentage) :

$$\theta = 100 \frac{volume\ soil\ water}{bulk\ volume\ soil} \qquad [vol\,\%]$$

With reference to **Figure 6.3**, it is the ratio of (b A) to (B A).

Given the wet mass of the sample and the mass of the oven dry sample, the volume moisture percentage is given by :

$$\theta = 100 \frac{m_{s+w} - m_s}{\rho_w V_b} \qquad [vol\,\%]$$

where $(m_{s+w} - m_s)/\rho_w$ is the volume of water (cm^3), ρ_w the density of soil water (g/cm^3) and V_b the bulk volume of the soil sample (i.e. B A in **Figure 6.3**). For all practical purposes, soil water can be considered to have a density equal to 1 g/cm^3.

Measuring the volume water content of a soil sample, implies that the bulk volume of the sample is carefully preserved during sampling. Such undisturbed samples could be obtained with core samplers. However, if the natural soil structure can not be maintained during the sampling, the volume water content of the loose material can still be determined if the bulk density of the soil is known.

The bulk density ρ_b is defined as the ratio of the dry mass of a given sample to its bulk volume :

$$\rho_b = \frac{mass\ dry\ soil}{bulk\ volume\ soil} = \frac{m_s}{V_b} \qquad [g/\ cm^3]$$

With reference to **Figure 6.3**, it is the ratio between (ρ_p cA) to (BA).

Integrating the above equations yields :

$$\theta = 100\ \rho_b \frac{m_{s+w} - m_s}{m_s\ \rho_w} = \rho_b\, \theta_m \qquad [vol\%]$$

c. Equivalent depth

The water content can be expressed also as the equivalent depth of liquid water per unit soil depth. With reference to **Figure 6.3**, the equivalent depth for a soil depth of B, is b. If expressed in millimeter water per meter soil depth, the depth value is equal to 10 times the value of the volume water percentage :

$$S = \frac{1000\ b\,(mm)}{B\,(m)} = 10\ \theta \qquad [mm(water)/m(soil\ depth)]$$

The amount of water retained in a specified soil depth (e.g. the root zone), is consequently :

$$W = D\ S = 10\ D\ \theta \qquad [mm(water)]$$

where D is the effective rooting depth in meter of the crop and θ the volume water percentage (vol%). To express the water content as a depth of water is useful. It makes the adding and subtracting of gains and losses of water straightforward since the various parameters of the soil moisture budget are usually expressed in terms of equivalent water depth (**Table 6.3**).

Table 6.3: Soil moisture content

A representative soil sample is taken in the root zone (D = 0.60 m) of sugar beets cultivated on a loamy soil (bulk density ρ_b = 1.40 g/cm^3). The weight of the soil sample before and after drying is respectively 133 and 114 gram. Express the water content of the root zone as a depth of water.
Θ_m = 100 (133-114)/114 = 16.7 mass % Θ = 1.4 (16.7) = 23.3 vol % S = 10 (23.3) = 233.3 mm(water)/m(soil depth) W = 0.60 (233.3) = 140.0 mm
The root zone contains 140.0 mm of water.

Table 6.4: Adding and subtracting water in the root zone.

The root zone contains 140.0 mm of water. What will be its water content when 20 mm of water is added through rainfall and 15 mm subtracted by evapotrans-piration.	
Initial moisture content	140.0 mm of water
Rainfall	+20.0
Evapotranspiration	-15.0
The root zone will contain 145.0 mm of water	

6.3 Soil moisture constants

a. Water retention curve

Water is stored in the soil within the pore spaces between the soil particles. It is held to the particles by forces of attraction acting between the water molecules and the particles of the soil matrix. The closer a water molecule is to a matrix particle the stronger is the force of attraction binding it to the matrix. Water that is further away from the matrix is freer to move and be taken up by plants or be drained out of the root zone by gravity.

The forces holding water to the soil matrix are called matrix forces. The plant roots have to overcome these forces to extract water from the soil. Water in a completely saturated soil can be regarded as being free of all forces i.e. has a matrix potential of zero. As water is removed from the soil the remaining water comes under increasingly stronger matrix forces and will be held stronger by the soil.

There is therefore a relationship between soil water content and its matrix potential. This relationship can be shown in a socalled soil water retention or soil water characteristic curve, as shown in **Figure 6.2**. The y-axis of this graph represents the matric potential expressed as a tension or suction. The tension is expressed as a negative pressure (Pa, bar, cm water column, etc.), i.e. the pressure that would be required to remove water from the soil. It can also be given as pF which is the negative logarithm (pF) of the pressure expressed in cm water column.

The shape of the soil water retention curve is strongly affected by the texture and structure of the soil. It is normally determined experimentally using a pressure plate apparatus. Once the curve is made the water content of a soil sample can be estimated if its matrix potential is known.

b. ***Saturation water content***

When all the available pore space is filled with water, the soil is said to be saturated. Saturation conditions exist in the upper soil layers immediately after a heavy rain or irrigation, and also direct above the groundwater table.

Since at saturation water has filled up all the pore space, the saturation water content is equal to the porosity :

$$\theta_{sat} = 100\left(1 - \frac{\rho_b}{\rho_p}\right) \qquad [vol\%]$$

θ_{sat} = soil water content at saturation point (vol %)

ρ_b = soil bulk density (g/cm^3)

ρ_p = soil particle density, which is the mass per unit volume of soil particles. For the soil as a whole the particle density is about 2.65g/cm^3.

Figure 6.3: Soil water retention curve for various soil types

c. Field capacity

If a soil is saturated, the water that is not very strongly held to the soil matrix drains freely under gravity. The water content at field capacity (θ_{FC}) is that soil water content, which is held by the soil matrix against the gravitational forces. Field capacity, which will be reached within 1 to 2 days after saturation, occurs around pF 2. The variation in suction depends on the soil type: clay or loam soil $\pm$ 0.3 bar (pF = 2.5); sandy soils $\pm$ 0.1 bar (pF = 2.0). Typical values of field capacity for different soil types are given in **Table 6.5**.

Table 6.5: Field Capacity

The root zone of sugarbeets (D = 0.6 m), cultivated on a loamy soil, contains 145.0 mm of water. What will be its water content, reached within 1 to 2 days, after a heavy rainfall of 60 mm. The field capacity of the loamy soil is 31 vol%.
The root zone contains 145.0 mm of water Rainfall +60.0 Total 205.0 mm of water Field capacity is 31 vol%. The corresponding equivalent depth is S_{FC} = 10 (31) = 310 mm(water)/m(soil depth). The amount of water retained in the root zone at field capacity is W_{FC} = 0.60 (310) = 186 mm. Hence, the root zone cannot contain more than 186 mm. The surplus (205-186 = 19mm) will drain freely out of the root zone under gravity.
After 1 to 2 days, the root zone will contain 186 mm of water.

d. Permanent wilting point

Plants extract water freely and easily from soil at field capacity. As water uptake progresses the amount of water in the soil decreases and the remaining water is held to the particles with greater force, making it more difficult for the plant to extract it. A point is reached when the plant can no longer extract water in sufficient quantities and rapidly enough to replace the water being lost by transpiration. Leaves begin to wilt during the afternoon but may still recover at night. Finally a stage is reached when the wilted plants do not recover at night, or even when water is added to the soil. The plants have permanently wilted and soil water content is said to be at the permanent wilting point (θ_{WP}). For most soils this happens when water is held at a suction of about 15 bars. Beyond the permanent wilting point water is no longer available to the plant. Typical values of the permanent wilting point for different soil types are given in **Table 6.7**.

e. Total available soil moisture

The amount of water held between field capacity and permanent wilting point is the total available soil moisture, i.e. the water available for the crop to use.

$$S_a = 10\,(\theta_{FC} - \theta_{WP}) \qquad [mm(water)/m(soil\ depth)]$$

The total amount of water that a crop can extract from its root zone of D meter is:

$$TAM = D\,S_a \qquad [mm(water)]$$

The magnitude of S_a for any soil is very important. It shows the capacity of the soil to supply water to the crop over time. A low value of S_a indicates early wilting of crops and a high frequency of irrigation will be required to keep soil moisture at acceptable levels.

The magnitude of S_a is a function of soil texture and structure. Coarse textured soils (sandy soils) have lower S_a than fine textured clays, while loams are intermediate. This is because the finer the particle size the larger is the surface area for water adsorption. Therefore, soils with fine particles will have higher water contents at both field capacity and wilting point than soils with coarser particles (**Table 6.6**).

Table 6.6: Average soil moisture constants and physical properties for different soil types

Textural Class	ρ_b g/cm^3	θ_{sat} (vol%)	θ_{FC} (vol%)	θ_{WP} (vol%)	S_a (mm/m)
Sand	1.65	38	15	7	80
Sandy loam	1.50	46	21	6	150
Loam	1.40	47	31	10	210
Clay loam	1.35	44	40	26	140
Silty clay	1.30	51	42	25	170
Clay	1.25	54	45	27	180

An example of the calculation of the total available water is given in **Table 6.8**.

Table 6.7: Total available soil moisture contained in the root zone

Calculate the total available soil moisture (TAM) contained in the root zone of soybeans (D = 0.6 m) cultivated respectively on a sandy, loamy and clay soil

soil type	FC (vol%)	WP (vol%)	S_a (mm/m)	TAM (mm)
Sand	15	7	10(15-7)=80	0.6(80)=48
Loam	31	10	10(31-10)=210	0.6(210)=126
Clay	45	27	10(45-27)=180	0.6(180)=108

6.3.1 The root system and rooting depth

The soil acts as a storage medium for water. Plants are anchored in the soil by their roots. The roots also act as the organs of water absorption.

The root zone is the effective area ramified by roots from which water uptake occurs. It defines the lower limit of the soil volume effective as water storage for the plants. The effective root zone depends mainly on crop type, its growth stage and the total depth of the soil available for rooting.

The effective root depth changes with crop growth (**Figure 6.3**). At sowing it is about twice the seeding depth i.e. the zone from which the germinating seed and the young seedling can extract water. Next, the depth increases until a maximum is reached at peak growth, usually at the end of the development stage. The rate of root depth increase can be assumed to be either linear or exponential with time depending on the crop. **Table 6.9** give the effective rooting depths of main crops, i.e. the soil depth in which the bulk of the roots are concentrated and which should be considered when designing irrigation systems. The base of the rooting zone might be deeper.

Root distribution is not uniform throughout the profile. Root density is highest at the top 5 - 20 cm and decreases to zero at the base of the root zone. Water extraction generally follows root distribution.

Figure 6.4: Effective rooting depth of maize crop

Figure {} represents the pattern of root distribution and water extraction in a graphical way. About 90% of the roots are within the upper 40% of the profile. The extraction of water follows a roughly linear pattern, with a maximum value at the top. Consequently the fraction of soil water available for plant growth (p) is not uniform throughout the whole profile. Its value is nearly 1.0 at the top and becomes 0.0 at the base of the profile. As the use of different values of p complicates water availability calculations, use is made of average (or mean) values, varying from 0.2 to 0.65 for most crops.

Figure 6.5: Soil moisture depletion pattern in the root zone.

6.3.2 Readily Available Moisture (RAM)

a - Critical moisture content

As has been pointed out earlier water uptake gets progressively more difficult as plants absorb water between field capacity and permanent wilting point. Although water is theoretically available up to wilting point the experience has shown that the evapotranspiration rate drops below its potential level ($ET_{act} < ET_{crop}$) and that growth reduction occurs before this point is reached (**Figure […]**). The soil moisture content is said to be at the critical moisture content ($\Theta_{critical}$) when the evapotranspiration starts to drop below ET_{crop}. Irrigation turns therefore should be planned before this point and rather much earlier to maintain full evapotranspiration and optimal growth.

Figure 6.6: Reduction in crop evapotranspiration due to water stress.

b - Depletion factor

Readily available soil moisture (RAM) is the fraction (p) of total available soil moisture (S_a) that a crop can extract from the soil without suffering water stress ($ET_{act} = ET_{crop}$).

$$RAM = p.TAM = p.D.S_a \quad \text{[mm(water)]}$$

Where:
TAM = total available moisture = $D.S_a$ in mm(water)
D = depth of the root zone in m

The critical moisture content is given by :

$$\theta_{critical} = \theta_{FC} - p\,(\theta_{FC} - \theta_{WP}) \qquad [vol\%]$$

Where:
Θ_{FC} = soil moisture content at field capacity (vol%)
Θ_{WP} = soil moisture content at wilting point (vol%)

Integrating above equations yields:

$$RAM = 10\ D\ (\Theta_{FC} - \Theta_{critical}) \quad \text{[mm(water)]}$$

RAM is a function of both the crop and the soil. It indicates the tolerance of the crop to water stress because it gives the fraction of S_a that can be safely removed before stress occurs.

If, in irrigation scheduling soil moisture is at field capacity just after the water gift, one can allow the crop to take up water equal to RAM before providing the next water gift. In this sense RAM is also called "allowable depletion".

Likewise, the fraction (p) of available soil water is known as the "depletion factor". The magnitude of p has to be decided for each crop in a given soil. Generally (p) is determined by the rooting characteristics of the crop (depth and volume of soil penetrated by the roots at a given growth stage). Thus the value of p is chosen to minimize risk. The higher the risk (i.e. sensitive crop or growth stage) the lower the value of p.

c - Effect of evapotranspiration rate

The value of p is not only a function of the crop, but also of the potential crop evapotranspiration (ET_{crop}). ET_{crop} expresses the potential rate with which the soil water can be depleted. It is dictated by the meteorological conditions and crop characteristics. During the ripening stage, when the crop evapotranspiration demand is lower, p will be larger (up to 20 %) than the listed values.

d - Effect of soil type

To express the tolerance of crops to water stress as a function of the fraction (p) of the total available soil water is not fully correct. The rate of root water uptake is in fact influenced more directly by soil matric potential than by water content. Since a certain soil matric potential corresponds in different soil types with different soil water contents (**Figure 6.3**), the value of p is hence also a function of the soil type. Generally it can be stated that for 'clayey' soils the presented p values in **Table 6.8** should be somewhat reduced, while for more 'sandy' soils they should be increased.

Table 6.8: Effective rooting depths (D) and fraction of available soil water (p) for different fully grown crops (ETcrop = 5-6 mm/day).

	Effective rooting depth, D(m)	P
1. Small vegetables	**0.40**	**0.25**
	0.30 - 0.50	0.25
- Onions	0.40 - 0.70	0.35
- Carrots	0.20 - 0.40	0.30
- Lettuce	0.30 - 0.50	0.20
- Celery	0.30 - 0.50	0.20
- Spinach	0.30	
- Radish	0.30 - 0.60	0.15
- Strawberry	0.40 - 0.60	0.40
- Cabbage		
2. Vegetables (Beets)	**0.50**	**0.40**
- Sugar beet	0.50 - 1.00	0.50
- Turnip	0.30 - 0.60	0.40
- Parsnip	0.60 - 0.90	0.40
- Beetroot	0.40 - 0.70	0.30
3. Vegetables (Leguminosae)	**0.50**	**0.50**
- Beans (green)	0.50 - 0.80	0.45
- Beans (pulses)	0.60 - 1.20	0.50
- Groundnut	0.50 - 1.00	0.40
- Peas	0.45 - 0.90	0.35
- Soya bean	0.60 - 1.30	0.55
- Broad beans	0.50 - 0.80	0.40
- Lentils	0.60 - 1.00	0.55
- Chicken peas		
4. Vegetables (Solananaceae)	**0.60**	**0.30**
- Tomatoes	0.60 - 1.20	0.40
- Potatoes	0.40 - 0.60	0.30
- Sweet peppers	0.50 - 1.00	0.25
- Eggplants	0.40 - 0.60	0.30
- Chilies		

	Effective rooting depth, D(m)	P
5. Vegetables (Cucurbiaceae)	**0.60**	**0.45**
- Cucumbers	0.50 - 1.00	0.40
- Squash	0.50 - 1.00	0.40
- Melon	0.60 - 1.00	0.35
- Water melon	1.00 - 1.80	0.55
- Pumpkin	0.90 - 1.20	0.40
6. Vegetables (Divers)		
- Artichokes	0.60 - 0.90	0.50
- Asparagus	1.50	0.50
- Pineapple	0.40 - 0.60	0.50
- Tobacco	0.50 - 1.10	0.35
7. Fiber crops	**1.20**	**0.60**
- Cotton	0.80 - 1.50	0.60
- Flax	1.00 - 1.50	0.50
- Sisal	1.00 - 2.00	0.80
8. Oil crops		
- Sunflower	0.80 - 1.50	0.60
- Safflower	1.00 - 1.50	0.60
9.Cereals	**1.20**	**0.55**
- Barley	0.90 - 1.20	0.60
- Oats	0.60 - 0.75	0.60
- Wheat	0.75 - 1.20	0.55
- Maize	0.60 - 1.00	0.50
- Sorghum	0.60 - 1.50	0.60
- Millet	0.60 - 1.20	0.60
10. Pasture & Fodder crops	**0.70**	**0.50**
- Pasture	0.40 - 0.80	0.50
- Alfalfa	1.00 - 1.50	0.40
- Clover	0.60 - 0.90	0.35
- Sudan grass	0.90 - 1.20	0.40
11. Sugar cane	**0.80 - 1.50**	**0.55**
12. Grapes & Berries		
- Grapes	1.00 - 2.00	0.60
- Coffee	0.80 - 1.50	0.40
- Tea	0.80 - 1.50	0.30
- Cacao	0.80 - 1.50	0.20
13. Fruit trees	**1.50**	**0.50**
- Dates	1.50 - 2.50	0.60
- Olives	1.20 - 1.70	0.65
- Citrus	0.60 - 1.50	0.50
- Deciduous trees	1.00 - 2.00	0.50
- Palm trees	0.70 - 1.10	0.65
- Avocado	0.80 - 1.20	0.40
- Banana	0.50 - 0.90	0.35

The readily and total available soil moisture contained in the root zone of the maize crop (**Figure 6.3**), cultivated on a sandy loam soil (S_a = 150 mm/m) is plotted in **Figure 6.6**. An example of the calculation of RAM is given in **Table 6.10**.

Figure 6.7: Readily (RAM) and total available (TAM) soil moisture of the root zone of maize cultivated on a sandy loam soil (Sa = 150 mm/m).

Table 6.9: Available soil moisture and critical moisture content

Calculate the critical moisture content and the readily available soil moisture (RAM) retained in the rootzone of sugarbeets (D = 0.60 m) cultivated on a loamy soil (Θ_{FC} = 31 vol %, Θ_{WP} = 10 vol %).
S_a = 10 (31 - 10) = 210 mm/m TAM = (0.60) 210 = 126.0 mm RAM = (0.50) 126.0 = 63 mm (depletion factor sugarbeets: 0.50, from table 7.8) $\Theta_{critical}$ = 31 - 0.5 (31-10) = 20.5 vol %
The readily available soil moisture is 63 mm. The critical moisture content is 20.5 vol%. The representative soil sample taken in the rootzone of the sugar beets, indicated that the moisture content was at 23.3 vol% which is slightly above the critical moisture content. To maintain full evapotranspiration and in the absence of rain, an irrigation will be soon required.

Figure 6.8: Schematic presentation of the available soil water in the rootzone.

6.3.3 Yield response to water

With increasing water stress the yield starts to decrease. For many crops ET_{crop} shows a direct relationship with dry matter production or yield. When ET_{act} = ET_{crop}, water supply is optimum. No stress exists and the crop produces an optimum yield. On the other hand when ET_{act} is reduced by stress, the yield will be less than optimum. This forms the basis of yield prediction based on the level of water supply. The relation is:

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y \left(1 - \frac{ET_{act}}{ET_{crop}}\right)$$

where:
Y_a = actual harvested yield

Y_m = maximum possible yield
ET_{act} = actual crop evapotranspiration
ET_{crop} = potential crop evapotranspiration
k_y = yield response factor (= relative yield decrease/relative evapotranspiration deficit)

This relationship applies for healty, well developed crops grown under optimal conditions, water being the only constraint. Under the restrictions mentioned, the presented relationship is applicable to the total growing period of a crop and to individual development stages. Y_m is determined through experiments. ET_{crop} is the total seasonal evapotranspiration that can be obtained by a disease free crop with optimum water supply. It is either experimentally determined with a lysimeter or estimated from ET_o and k_c. ET_{act} is the actual evapotranspiration, which is either measured using any of the soil moisture measurement techniques or estimated by a soil water budget analysis. Finally, k_y expresses the effect of water deficit on yield for the given crop. It depends on the drought resistance of the species and its growth stage (k_y<1, more resistant; k_y>1, less resistant)

Figure 6.9 and **Figure 6.10** are graphical presentations for the determination of k_y.

A yield reduction in an individual development stage is causing a cumulative yield reduction in the next development stage:

$$\left(1 - \frac{Y_a}{Y_m}\right)_{cum} = 1 - \left(\frac{Y_a}{Y_m}\right)_1 \bullet \left(\frac{Y_a}{Y_m}\right)_2 \bullet \ldots\ldots.$$

Further reading and reference:

FAO Irrigation and Drainage Paper Nr. 33, Yield response to water.

Figure 6.9: Generalized relationship between relative yield (Ya/Ym) and relative evapotranspiration (ETact/ETcrop) for the total growing season.

(I. alfalfa, groundnut, safflower, sugarbeet; II. alfalfa, cabbage, citrus, cotton, grape, sorghum, soybean, sugarbeet, sunflower, tobacco, wheat; III. bean, citrus, onion, pea, pepper, potato, tomato, water melon, wheat; IV. banana, maize, sugarcane)

Figure 6.10: Generalized relationship between relative yield (Ya/Ym) and relative evapotranspiration (ETact/ETcrop) for the individual growth periods.

6.4 Soil water balance

To generate or evaluate irrigation schedules, information of the moisture content in the rooting zone is required. This moisture content is simulated by means of a water balance model. Such a model keeps track of all inputs of water through rainfall, irrigation and capillary rise and of all withdrawal of water through run-off, soil evaporation, crop transpiration and deep percolation. The moisture content of the rooting zone is affected by these processes and consequently the water balance can be written as :

$$W_{i+1} = W_i + P + I + G_e - ET_{act} - RO - DP \quad \text{(mm)}$$

where:

W_{i+1} = the soil water content in the rootzone at time i+1 (mm)
W_i = the soil water content in the rootzone at time i (mm)
P = rainfall (mm)
I = irrigation (mm)
G_e = capillary rise from the groundwater (mm)
ET_{act} = actual crop evapotranspiration of the crop (mm)
RO = runoff from rainfall or irrigation (mm)
DP = deep percolation of rainfall or irrigation water (mm)

P, I, G_e, ET_{act}, RO and DP indicate or represent rainfall, irrigation, capillary rise, surface run-off and deep percolation occurring between time i and time i+1.

If the soil water content at the start of the irrigation season (W_0) is known (by measurement) and the changes in all factors are continually measured or calculated, then the water balance equation can be used to calculate the soil water content at the subsequent intervals: i = 1, 2, 3, ..., n = last. Depending on the required accuracy, the interval i may be one day, one week, one decade or even the interval between two irrigations. An example of the calculation of the water balance is given in **Table 6.10** and its graphical presentation in **Figure 6.11**.

Table 6.10: Soil water balance

Calculate the daily water balance of the rootzone of sugarbeets (D = 0.60 m, p = 0.5) cultivated on a loamy soil (Θ_{FC} = 31 vol%, Θ_{WP} = 14 vol%) for a 10-day period.
- At the start of the 10-day period, the rootzone is at field capacity
- At day 2, a shower of 50 mm is observed (10% is lost by surface run-off)
- The mean potential crop evapotranspiration is 6 mm/day
- At the end of the 10-day period, an irrigation refill the rootzone up to field capacity

$W_0 = W_{FC} = 10\ D\ \Theta_{FC} = 10\ (0.6)\ 31 = 186$ mm
As long as the soil moisture content in the rootzone is larger then $\Theta_{critical}$, the actual evapotranspiration is equal to ET_{crop} = 6 mm/day

$$\Theta_{critical} = 31 – 0.50\ (31\text{-}14) = 22.5 \text{ vol\%}$$

Or the water content of the rootzone may not drop below :

$$W_{critical} = 10\ D\ \Theta_{critical} = 10\ (0.6)\ 22.5 = 135 \text{ mm}$$

Day	W_i (mm)	P (mm)	I (mm)	G_e (mm)	ET_{act} (mm)	RO (mm)	DP (mm)	W_{i+1} (mm)
1	186	-	-	-	-6	-	-	180
2	180	50	-	-	-6	-5	-	219
Since the water content is above field capacity (219 mm > W_{FC}, water will drain out of the rootzone till field capacity is reached								
							-33	186
3	186	-	-	-	-6	-	-	180
4	180	-	-	-	-6	-	-	174
5	174	-	-	-	-6	-	-	168
6	168	-	-	-	-6	-	-	162
7	162	-	-	-	-6	-	-	156

8	156	-	-	-	-6	-	-	150
9	150	-	-	-	-6	-	-	144
10	144	-	-	-	-6	-	-	138
To refill the rootzone up to field capacity, (186-138) = 48 mm is required								
			48					180
The results are graphically presented in **Figure 7.11**.								

In stead of calculating water contents, one can also express the results as a water shortage versus field capacity, i.e. root zone depletion. At field capacity, the root zone depletion is zero. If water is consumed by evapotranspiration, the depeletion increases. If water is added by rainfall or irrigation, the depletion decreases. This is illustrated in **Table 6.11**

Table 6.11: Soil water depletion

RAM = p D TAM = 0.5 (0.6 m) (170 mm/m) = 51 mm.
As long as the root zone depletion (Depl) is smaller then RAM the actual evapotranspiration is equal to ET_{crop} = 6 mm/day.

Day	$Depl_i$ (mm)	P (mm)	I (mm)	G_e (mm)	ET_{act} (mm)	RO (mm)	DP (mm)	$Depl_{i+1}$ (mm)
1	0	-	-	-	6	-	-	6
2	6	-50	-	-	6	5	-	-33
The depletion becomes negative (i.e. surplus of water above field capacity). Since the water content is above field capacity, water will drain out of the rootzone till field capacity is reached.								
							33	0
3	0	-	-	-	6	-	-	6
4	6	-	-	-	6	-	-	12
5	12	-	-	-	6	-	-	18
6	18	-	-	-	6	-	-	24
7	24	-	-	-	6	-	-	30
8	30	-	-	-	6	-	-	36
9	36	-	-	-	6	-	-	42
10	42	-	-	-	6	-	-	48
To refill the rootzone back to field capacity, 48 mm is required								
			-48					0
The results are graphically presented in **Figure 6.9**								

Figure 6.11: Daily water balance of the root zone of sugarbeets (Example 7.11).

Figure 6.12: Depletion in root zone of sugarbeets (Example 7.11).

Schematically (**Figure 6.11**) the rootzone can be presented by means of a container in which the moisture content may fluctuate. After irrigation (I) or heavy rainfall (P), which thoroughly wets the rooting zone, the moisture content may be close to saturation. The moisture content above field capacity however cannot be held against the forces of gravity and will drain out of the rooting zone (Drain). After some time, which depends on the drainage ability of the soil, field capacity will be reached. Crop evapotranspiration will further deplete water from the rootzone. As discussed before, between field capacity and the critical moisture content the water extraction by plant roots is at the potential rate as dictated by the climatological demand (ET_{act} = ET_{crop}). If the moisture content in the rootzone drops below the critical moisture content, the actual evapotranspiration rate will be smaller than the potential rate. Furthermore, the less water in the rootzone, the more the actual evapotranspiration rate will deviate from the potential rate. In the end the rate becomes zero when wilting point is reached (see **Figure 6.12**). The moisture content below wilting point can not be extracted by the plant roots.

Figure 6.13: Schematic presentation of the water balance of the rootzone

To avoid any water stress and to maintain full production, an irrigation should be considered before the actual crop evapotranspiration (ET_{act}) drops below the potential level of ET_{crop}. This answers the question when to irrigate.

The amount of water to apply is given by the rootzone depletion, i.e. the amount of water required to refill the rootzone up to field capacity. Any surplus water will be lost by deep percolation, since this water is not strongly held to the soil matrix and will drain freely under gravity. The planning of the timing and depth of irrigation is discussed in the next chapter.

The representation of the rootzone as one bulk volume describes the system very roughly and may be inappropriate for many purposes. The fluxes in and out of the rootzone can be described much more precisely if the distribution and movement of water inside the profile is considered. Therefore the total soil profile is divided in a number of horizontal compartments. Water flow and uptake between and in each of these compartments is solved numerically in water balance models.

Figure 6.14: Crop evapotranspiration as function of soil moisture content in the rootzone

7 IRRIGATION REQUIREMENT

This chapter provides guidelines for the estimation of the irrigation water requirement. The requirement is the amount of water to be supplied to the plants to prevent stress and yield reduction. Seasonal and short term irrigation requirements for fields, farms and the entire irrigation scheme are needed for the design and operation of an irrigation system. Knowledge of the peak irrigation requirement is needed in determining the size of main canals, pipe networks and pumping stations. Information on the seasonal irrigation requirement is needed when designing water storage reservoirs and distribution systems or in determining the size of the irrigation scheme given a limited amount of water. Short term irrigation requirements, when combined with soil water holding characteristics, enables to specify when and how much water to apply.

The calculation of the irrigation water requirements consists in determining, in a first step, the net irrigation requirement of each of the crops cultivated. The requirement is obtained by subtracting the expected gains of water from the crop water requirement (ET_{crop}). The first gain to be considered is rainfall, but water transported to the root zone by capillary rise from a shallow groundwater table may also contribute to the crop water requirement. Part of the crop water requirement may also be met by stored soil water at the start of the growing season.

In addition to meeting the net irrigation requirements, water may be required for leaching accumulated salts out of the root zone and for cultural practices. Since irrigation is never 100 percent efficient, allowance must be made for losses during conveyance and application of water. The gross irrigation requirement of the scheme is finally obtained by adding up the individual irrigation requirements of each of the crops.

7.1 Crop Irrigation requirement

It is the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given environment.

The *net irrigation requirement* (I_n) is obtained by subtracting from the crop water requirement (ET_{crop}) the expected gains of water. The gains include effective rainfall (P_{eff}), groundwater contributions (G_e) and stored soil water (W_b). To avoid any water deficit during the season, the estimations are made with rainfall amounts that can be expected 3 out of 4 years or 4 out of 5 years.

In the calculation of the *gross irrigation requirement*, the amount of water needed for leaching accumulated salts from the root zone and to compensate for water losses during conveyance and application are included. The leaching requirement (LR) and irrigation efficiency (E) are expressed as a fraction of the net irrigation requirement.

7.2 Scheme Irrigation requirement

The scheme irrigation requirement is the sum of the individual irrigation requirements of each of the crops.

7.3 First assessment of the net Irrigation Requirement

a. Seasonal and monthly net irrigation requirements

For (preliminary) planning purposes, monthly data are normally used to determine the seasonal irrigation requirement. The water requirements for the different months are computed by taking into account on the one hand the mean crop water requirement (ET_{crop}) and on the other hand the dependable effective rainfall (P_{eff}). No other gain of water is considered.

Mean monthly evapotranspiration values are generally used. By nature evapotranspiration is much more conservative for a given time period in the year and at a given location than precipitation, which usually exhibits large variations. Hence, rather than using mean monthly rainfall data, a dependable level of rainfall should be selected, eg. 75 or 80 %, i.e. the monthly rainfall that can be expected 3 out of 4 years or 4 out of 5 years. A higher level of dependable rainfall (say 9 out of 10 years, i.e. 90 %) may need to be selected during the period that crops are germinating or are most sensitive to water stress and yields are severely affected. An example of the calculation of the seasonal net irrigation requirement is given in **Table 8.1**.

Table 7.1: First estimate of monthly and seasonal net irrigation requirements of corn

Location : Oran (Algeria) – mediterranean climate
Season : spring – summer
Corn – Length of growing season : 150 days, Sowing date : 1 March
Soil : sandy loam

	March 31 days	April 30 days	May 31 days	June 30 days	July 28 days	Total
ET_o (mm/day)	2.4	3.7	4.6	4.9	5.5	-
k_c	0.40	0.68	1.15	1.15	0.88	-
ET_{crop} (mm/day)	1.0	2.5	5.3	5.6	4.8	-
ET_{crop} (mm)	30	75	164	169	136	574
Rainfall^{*1} (mm)	14	15	0	0	0	
P_{eff}^{*2} (mm)	8	10	0	0	0	18
I_n (mm/period)	22	65	164	169	136	556

^{*1} i.e. 80 % dependable rainfall
^{*2} Table 3.8

Seasonal ET_{crop}	574 mm
Seasonal Effective rainfall	-18 mm
Seasonal Net irrigation requirement	556 mm or 5,560 m^3/ha

b. Peak irrigation requirement

For preliminary planning, the capacity of the engineering works can be obtained from the supply needed during the month of peak water use. In selecting ET_{crop} in the months of peak water use, knowledge should be obtained on level and frequency at which high demands for water can be expected. When sufficiently long climatic records are available (10 years or more) a frequency analysis can be made similar to that given for rainfall. The value of ET_{crop} selected for design can then be based on a probability of 75 or 80 percent or highest ET_{crop} value out of 4 or 5 years.

A first estimate of meeting ET_{crop} three out of four years, but still using mean ET_{crop} data can also be obtained using **Figure 7.1**. Degree of weather variations for different types of climate is important. However, available soil water has a balancing effect in meeting high ET_{crop} values during short periods. This effect is smaller for shallow, light soils than for deep, fine textured soils. Readily available soil water should therefore be considered. An example is worked out in **Table7.2**.

Figure 7.1: Ratio peak and mean ETcrop for different climates during month of peak water use [1. Arid and semi-arid (clear sky); 2. Sub-humid to humid (higly variable cloudiness); 3 and 4. Mid-continental with mean ETcrop of 5 and 10 mm/day respectively (variable cloudiness)]

Table 7.2: Peak irrigation requirement

Data from previous example (Table 8.1) Location : Oran (Algeria) – mediterranean climate Semi-arid : Predominantly clear weather conditions during month of peak ET_{crop} RAM = 42 mm	
Peak month	June
ET_{crop} (mm/day)	5.6
Correction peak (Figure 6.1)	1.12
ET_{crop} corrected (mm/day)	6.3
P_{eff}	0
Net irrigation requirement (mm/day)	6.3
Net irrigation requirement in peak period is 6.3 mm/day or 0.73 l/s.ha	

7.4 Groundwater contribution (G_e)

Groundwater, if not too far below the root zone, may add water to the root zone by capillary rise. The extent of capillary rise depends on:

- the depth of the groundwater table below the root zone,
- the soil type, i.e. its capillary properties. Capillary rise will be much higher in clay(ey) soils than in sand(y) soils,
- the soil water content in the root zone i.e. the difference in water content at the groundwater table (saturation) and in the root zone. The larger the difference, the larger the upward transport of water.

An estimation of the contribution of the groundwater table to the root zone of an irrigated crop for different soil types is given in **Figure 7.2**. Capillary rise plays only a role if the groundwater table is within one meter or less of the lower limit of the root zone, except for fine to very fine sandy loams. An example of the calculation of the net irrigation requirement taking into account the groundwater contribution is worked out in **Table 7.3**.

Figure 7.2: Contribution of groundwater to moist root zone

Table 7.3: Calculation of seasonal net irrigation requirement of corn, considering groundwater contribution.

Data from previous example (Table 8.1)
Soil : sandy loam
Groundwater depth below root zone is 1.5 m in spring (March - April)

	March 31 days	April 30 days	May 31 days	June 30 days	July 28 days	Total
ET_{crop} ^{*1} (mm)	30	75	164	169	136	574
P_{eff} ^{*1} (mm)	8	10	0	0	0	18
G_e ^{*2} (mm/day)	0.5	0.5	0	0	0	-
(mm)	16	15	0	0	0	31
I_n (mm/period)	6	50	164	169	136	525

Seasonal ET_{crop}	574 mm
Seasonal effective rainfall	-18 mm
Seasonal groundwater contribution	-31 mm
Seasonal Net irrigation requirement	525 mm or 5,250 m^3/ha

7.5 Soil water contributions (W_b)

Abundant rainfall during the wet season may bring the soil profile near or at field capacity at the start of the growing season. The amount of water may be equivalent to one full irrigation and hence should be deducted when determining the seasonal irrigation requirements. An example of the calculation of the net irrigation requirement taking into account the soil water contribution is worked out in **Table 8.4**.

If no water is stored in the root zone, it should be checked if no extra water is required to replenish depleted soil moisture prior to sowing/planting. Soil moisture depleted by the preceding crop may not have been replenished and should preferably be brought to an acceptable level, for instance up to field capacity level. This "filling up" prior to sowing/planting constitutes an extra water requirement.

For rice soil moisture even must be brought up to saturation level before puddling of the soil and transplanting of the rice plants.

Table 7.4: Calculation of seasonal net irrigation requirement of corn, considering available soil water at start of season.

Data from previous example (Table 7.1 and 7.3)	
Available soil water (winter rain) at start of season 25 mm	
ET_{crop}	574 mm
Effective rainfall	-18 mm
Groundwater contribution	-31 mm
Soil water contribution	-25 mm

Net irrigation requirement	500 mm or 5000 m^3/ha

7.6 Irrigation requirement of rice

Irrigation of rice shows some specific characteristics, which deviate from irrigation of other crops :

- Land preparation at the start of the irrigation period requires the saturation of the soil. During this period, the irrigation requirement per unit time are at its maximum.

- The soil is usually kept submerged during the total growing season.

7.7 Seasonal requirement

There are various elements to be considered in determining the irrigation requirement for rice : saturation of the field prior to transplanting or sowing, water for establishing a water layer in the field, water for evapotranspiration and for percolation and effective rainfall.

a - Saturation of the soil

Depending on soil type and initial soil moisture content, the water required to saturate the root zone at the beginning of the season varies from 100 to 300 mm. During the saturation of the soil, the water-loss through cracks to the subsoil might be large and extra water should be allowed for this.

b - Water for establishing a water layer in the field

Lowland rice is inundated. There is no evidence with regard to the optimum depth of the water layer in the field, but adequate water during the total growing period is needed for vigorous growth and high yield. The water layer also decreases weed growth and acts as a temperature regulator. Often a water depth of 10 to 20 cm is maintained throughout the growing period. In order to maintain a more shallow water depth, the land must be carefully levelled, which requires considerable investment and labour. At the end of the season, fields are drained to facilitate the harvest operations. If the management involves periodical drainage, the water layer has to be established several times throughout the season, and allowance should be made for the replacement of the water layer.

c - Water for evapotranspiration

Rice evapotranspiration is obtained by multiplying ET_o with the crop coefficient. ET_{crop} includes water transpired by the crop plus water that evaporates directly into the air from the standing water layer in the fields. Hence, the k_c factor is large throughout the season. Values of the k_c factor are given in Chapter 4.

d - Water for percolation

The amount of water which drains out of the root zone varies with soil type and the existence of an impermeable or compacted layer below the bulk of the root mass. Percolation is most of the time not negligible and could be as high as evapotranspiration. Its rate averages from 1 to 6 mm/day. In rice fields terraced against mountain slopes, percolation losses may be even several times greater than the amount of water used for evapotranspiration.

e - Effective rainfall

Effective rainfall is defined as total rainfall minus rainfall that cannot be stored in the fields and subsequently used in rice production. Hence, the efficiency is determined by the in-field storage capacity for rainfall i.e. the height of the bunds, the depth of the water layer maintained in the fields and rain intensity. In the *FAO Irrigation and Drainage Paper Nr.25* different evaluation methods are reviewed. Depending on the rainfall intensity, 65 % to 90 % of the total rainfall can be generally considered as effective.

An example of the calculation of the seasonal net irrigation requirement of rice is worked out in **Table 7.5**.

Table 7.5: Seasonal net irrigation requirement of rice

Location : Podor (Senegal) – semi-arid climate
Season : wet season (July – October)
Rice variety : Jaya (medium cycle) - 114 days
Soil : Clay soil with a percolation rate of 3 mm/day

	July (31 days)	August (31 days)	September (30 days)	October (22 days)	Total
ET_o (mm/day)	8.3	7.4	6.9	6.5	-
k_c	1.15	1.30	1.30	1.05	-
ET_{crop} (mm/day)	9.5	9.6	9.0	6.8	-
ET_{crop} (mm)	296	298	269	150	1013
Rainfall[*1] (mm)	0	35	70	5	110
P_{eff} (P*0.85) mm	0	30	60	4	94

[*1] ie. 80 % dependable rainfall

Land preparation	175 mm
Water layer	200 mm
ET_{crop}	1,013 mm
Percolation	342 mm
Effective rainfall	- 94 mm

Net irrigation Requirement	1,636 mm or 16,360 m^3/ha

7.8 Peak Irrigation requirement

At the start of the irrigation period, most of the water supplied will be used to saturate the land and only a small part of the supply will go towards maintaining the water in the already saturated area. But, as the land preparation goes on, a smaller part of the water supply will go to saturate new land and a greater part will go to maintain the water in the already saturated fields, until, towards the end of the period, nearly all the water is used to maintain the water layer in the area. This process has been described mathematically by van de Goor and Zijlstra (1968) in *ILRI publication 14, Irrigation requirements for double cropping of lowland rice in Malaya.*

$$q = \frac{M\, e^{\frac{Mt}{S}}}{e^{\frac{Mt}{S}} - 1}$$

where:

q = supply required during land preparation [mm/day, m^3/ha.day or l/s.ha]

M = supply required for maintaining the water layer after saturation [mm/day, m^3/ha.day or l/s.ha]

t = duration of land preparation [day or second]

S = water required for saturation and establishing a water layer [mm, m^3/ha or l/s]

The required net water supply (q) corresponding to different lengths (t) of land preparation is shown in **Figure 7.3**. The figure is drawn for M = 12.5 mm/day and for S = 225 mm, i.e. the sum of water required for saturation (175 mm) and for establishing a shallow water layer of 50 mm at the beginning of the season. The water supply (M) for maintaining the water layer on the saturated fields, compensates the evapotranspiration (9.5 mm/day) and percolation losses (3 mm/day). No account has been taken of the possibility that rain may supply part of the water requirement.

Figure 7.3: Net irrigation requirement during the peak period in function of the length of land preparation.

Given the length of the period during which the land preparation should be completed, the required net water supply is selected from **Figure 7.3**. After land preparation, when only the water in the fields has to be maintained, the irrigation supply will be smaller. **Figure 7.4** gives the net irrigation requirement throughout the season for different lengths of land preparation.

Figure 7.4: Net irrigation requirement throughout the season for different lengths of land preparation (1 = 10 days, 2 = 20 days, 3 = 30 days).

7.9 Salinity Control

Accumulation of salts in the root zone is referred to as soil salinity. Salts contained in irrigation water are left behind when water is taken up by plants or lost by evaporation. As a result there is a gradual accumulation of these salts as the season progresses and from one year to the next year.

The level of salinity is affected by the quality (salt content) and quantity of irrigation water, by soil factors affecting drainage, by the availability of water (rainfall) to leach the profile, by the method of irrigation and by the prevailing cultural practices.

The <u>leaching requirement</u> is the minimum amount of irrigation water that must percolate below the root zone in order to maintain soil salinity at a given level. The level maintained usually corresponds to the salinity level at which the particular crop would not suffer an unacceptable reduction in yield level. The leaching requirement may be calculated by:

$$LR = \frac{EC_w}{5\,EC_e - EC_w}\,\frac{1}{E_l}$$

LR = Leaching requirement, expressed as the fraction of the total seasonal volume of irrigation water supplied, which should be used for the leaching of salts

EC_w = electrical conductivity of irrigation water [dS/m or mmhos/cm]

EC_e = electrical conductivity of the soil saturation extract corresponding to the yield level, that can be tolerated for the particular crop [dS/m or mmhos/cm].

E_l = leaching efficiency [fraction]

Leaching efficiency is a function of soil drainage characteristics. Well drained sandy soils have an E_l almost equal to 100%, while poorly drained heavy clays can have an E_l as low as 30%. Other soils fall within this range. An example of the calculation of the leaching requirement is worked out in **Table 7.6**.

Leaching of salts can be done before, during or after the irrigation season depending on when water is available and on the salt accumulation rate. For an accumulation rate creating intolerable salt levels in the root zone during the season, leaching has to be done concurrently with irrigation. If not, leaching can be done before or after the season, depending on the availability of water. Leaching is normally practiced outside the peak period, but when very saline water is used, this may need to be considered in the peak supply.

In case problems with salinity may be expected *FAO Irrigation and Drainage Paper Nr. 29 "Water Quality for Agriculture"* constitutes a good first reference on salinity.

Table 7.6: Estimation of leaching requirement

Location : Oran (Algeria) – mediterranean climate Corn (season : March – July) Soil : sandy loam (E_l = 0.9) Seasonal net irrigation requirement : 500 mm (Table 6.4) EC_w = 1 to 2.5 dS/m
For 100 % yield: if EC_w = 1 dS/m LR = $\frac{1}{(5*1.7-1)}\frac{1}{0.9}$ = 0.15 if EC_w = 2.5 dS/m LR = $\frac{2.5}{(5*1.7-2.5)}\frac{1}{0.9}$ = 0.46

7.9.1 Crop irrigation requirement

The irrigation requirement of a crop is given by:

$$\frac{I_n}{(1-LR)} \qquad mm$$

where
I_n = net irrigation requirement (mm/season)
LR = leaching requirement

The net irrigation requirement of the crop is obtained by subtracting the gains of water from the crop water requirement (ET_{crop}) :

$$I_n = ET_{crop} - (P_{eff} + G_e + W_b)$$

The gains of water include effective rainfall (P_{eff}), groundwater contributions (G_e) and stored soil water (W_b). All variables are expressed in units of depth of water (mm).

The amount of water to be supplied can be obtained from :

$$10 \frac{A\, I_n}{(1 - LR)} \qquad m^3$$

where:
A = acreage under the given crop (ha)
The factor 10 appears due to conversion of mm to m^3/ha.

Table 7.7: Crop Irrigation requirement

Data from previous examples. Location : Oran (Algeria) – mediterranean climate Mean annual rainfall (October - April) = 300 mm Seasonal net irrigation requirement : 500 mm (Table 6.4) For EC_w = 1 and 2.5 dS/m, the leaching requirements are respectively 0.15 and 0.46 (**Table 7.6**).
The irrigation requirement is : - for EC_w = 1 dS/m 500/(1-0.15) = 587 mm or 87 mm extra for leaching Note, that if no other crop is cultivated on the same land (cropping intensity is 100 %), the winter rains might be sufficient to leach the accumulated salts out of the rooting zone, and the extra 87 mm will not be needed. - for EC_w = 2.5 dS/m 500/(1-0.46) = 931 mm or 431 mm extra Whatever the cropping intensity, the winter rainfall is insufficient. Leaching should even take place during the crop season to avoid intolerable salt levels in the root zone.

7.10 Irrigation efficiencies

Water losses occur at different levels:

- at the level of the irrigated plot i.e. when applying water to the soil,
- at the level of the block i.e. after water has entered the block,
- at the level of the canals i.e. during conveyance of the water between the main scheme inlet to the block offtake

Water losses are normally expressed as irrigation efficiencies, whereby the concept "efficiency" denotes that fraction of the total amount of water, which will benefit the field respectively the crop.

a. Field application efficiency (E_a)

At the field level losses may occur due to deep percolation below the root zone and unwanted drainage (runoff) of water from the field. Deep percolation normally will occur as it is nearly impossible to achieve uniform water distribution within a field and the correct rate of water application at the crop level. Field application efficiency is defined as:

$$E_a = \frac{\text{Water stored in the root zone}}{\text{Water received at plot inlet}}$$

E_a is affected by the type of irrigation system, soil type and the skill of the farmer. **Table 7.8** gives indicative values of E_a.

b. Field canal efficiency (E_b)

The field canal efficiency is the efficiency of water conveyance in the canals within a sector, block or sub-unit. The unit may be the tertiary unit, but may also be the quaternary unit or even the sub-quaternary unit. The exact definition of the "field" unit depends on the definition of the scheme as well as on irrigation organizational aspects i.e. farmers groups or irrigation groups. The canals at this level are usually unlined and seepage losses along them are high. Field canal efficiency is defined as:

$$E_b = \frac{\text{Water received at plot inlet}}{\text{Water received at block inlet}}$$

c. Conveyance efficiency (E_c)

The conveyance efficiency is the efficiency of water conveyance in the (main) canal system, which transports i.e. conveys water from the scheme head works to the various sectors, blocks or sub-units. The scheme head works may be the intake at the river of the storage reservoir, but it may also be the head of a tertiary unit in case the tertiary unit is considered as the scheme.

Depending on the length of the canals and the porosity of the bed (lined, unlined, soil type) seepage and evaporation can be high. Conveyance efficiency is defined as:

$$E_c = \frac{\text{Water received at the block inlet}}{\text{Water received at the head works}}$$

d. Distribution efficiency (E_d)

The distribution efficiency is the efficiency of water conveyance and distribution between the head (inlet) of the scheme and the plot inlet. It covers all the losses inherent to the 'transport' of the water and is a function of lay-out of the system, water transport type (canals, pipes), nature of the canal bed, soil type, maintenance, irrigation method and scheme management. E_d is independent of crop type and crop stage (although these factors may influence the irrigation method).

$$E_d = E_c.E_b$$

e. Scheme efficiency (E_p)

The overall, scheme or project efficiency can be defined as:

$$E_p = \frac{\text{Water stored in the root zone}}{\text{Water received at the head works}}$$

The scheme efficiency can also be calculated as:

$$E_p = E_a.E_b.E_c$$

Irrigation efficiencies must be established through research i.e. monitoring of irrigation in the field. Not always such studies are or have been carried out, or adjustments in locally established values are necessary due to lining of the canals or improved performance of the farmers due to longer irrigation practice. If no values are locally available, use could be made of **Table 8.8** for an estimation of efficiencies.

Table 7.8: Conveyance, field canal, distribution, field application efficiencies

	ICID/ILRI
Conveyance efficiency (E_c)	
Continuous supply with no substantial change in flow	0.9
Rotational supply in projects of 3 000 to 7 000 ha and Rotational areas of 70 - 300 ha with effective management	0.8
Rotational supply in large schemes (>10 000 ha) and small Schemes (< 1 000 ha) with respective problematic communi-Cation and less effective management:	
- based on predetermined schedule	0.7

	- based on advance request	0.65
Field canal efficiency (E_b)		
Blocks larger than 20 ha	- unlined	0.8
	- lined or piped	0.9
Blocks below or up to 20 ha	- unlined	0.7
	- lined or piped	0.8
Distribution efficiency ($E_d = E_c.E_b$)		
Average for rotational supply with management and communi-Cation	- adequate	0.65
	- sufficient	0.55
	- insufficient	0.40
	- poor	0.30

Field application efficiency (E_a)

		USDA	US(SCS)	ICID/ILRI
Surface methods:				
- soil type	- light soils	0.55		
	- medium soils	0.70		
	- heavy soils	0.60		
- irrigation method	- graded border		0.60 - 0.75	0.53
	- basin and level border		0.60 - 0.80	0.58
	- contour ditch		0.50 - 0.55	
	- furrow		0.55 - 0.70	0.57
	- corrugation		0.50 - 0.70	
Subsurface			up to 0.80	
Sprinkler	- hot, dry climate		0.60	
	- moderate climate		0.70	
	- humid, cool climate		0.80	0.67
Rice				0.32

Table 7.9: Gross irrigation requirement of rice scheme

Data from previous example (Table 8.5)
Rice – Podor (Senegal)
Net irrigation requirement = 1,636 mm/season (Table 8.5)
Peak requirement in function of length of land preparation (Fig. 8.3)
Scheme : 350 ha

E_a : field application efficiency = 1.0 (losses are already considered as percolation losses)
E_b : field canal efficiency (unlined, well compacted) = 0.9
E_c : conveyance efficiency (continuous supply, no change in flow) = 0.9
E_p : scheme efficiency = 0.9 * 0.9 = 0.81

I_{season} = 1,636/0.81 = 2,020 mm/season
I_{peak} = (land preparation = 10 days) = 3.39/0.81 = 4.19 l/sec.ha
= (land preparation = 20 days) = 2.16/0.81 = 2.66 l/sec.ha
= (land preparation = 30 days) = 2.20/0.81 = 2.20 l/sec.ha

Seasonal gross irrigation requirement : 2,020 mm = 20,200 m^3/ha = 7,070,000 m^3
Gross peak supply (land preparation = 20 days) : 2.66 l/sec

7.11 Scheme water requirement

a. Seasonal requirement

Once the cropping pattern and intensity have been selected, the gross irrigation requirement of the scheme is obtained by adding up the individual irrigation requirements of each of the crops :

$$V = C\frac{10}{E_p}\sum(A_i I_{n,i})/(1-LR_i)$$

where:
E_p = scheme efficiency
for crop i = 1 to n
A = cultivated area (ha)
I_n = net irrigation requirement (mm/season)
LR = leaching requirement

An example of the calculation of the scheme water requirement is worked out in **Table 7.10**.

Table 7.10: Monthly supply requirements of a scheme

b. Peak supply

For a first estimate on capacity of engineering works, the peak supply can be based on project supply of the month of highest irrigation demands :

$$V_{\max} = C\frac{10}{E_p}\sum(A_i I_{peak,i})$$

where:
C = flexibility factor
I_{peak} = net irrigation requirement during peak month

To incorporate flexibility in the delivery capacity of the supply system as well as to allow for future intensification and diversification of crop production, a flexibility factor C is frequently added. This factor varies with the type of project and is generally higher for small schemes as compared to large schemes. For projects based on supplemental irrigation this factor is high. With monocultures such as rice, orchards and permanent pastures the factor is small. An example of the calculation of the peak supply of a scheme is given in **Table 7.11**.

Table 7.11: Yearly supply requirement of a scheme

Project size : 150 ha
Cropping intensity : 200 %
- winter : wheat (Area : 150 ha, I_n : 82 mm, LR : 0)
- summer : corn (Area : 90 ha, I_n : 500 mm, LR : 0.15) from previous examples
  cotton (Area : 60 ha, I_n : 650 mm, LR : 0.07)

Surface irrig., rotanial supply to irrigation blocks of 20 ha, lined canals (E_p : 0.5)

Crop

corn $\dfrac{10}{0.5}\dfrac{90\,.\,500}{(1-0.15)}$ = 1,058,824 m^3

cotton $\dfrac{10}{0.5}\dfrac{60\,.\,650}{(1-0.07)}$ = 838,710 m^3

wheat $\dfrac{10}{0.5}.\,150\,.\,82$ = 246,000 m^3

The yearly supply requirement : Vi = 2,143,534 m^3/year
Similarly the monthly supply requirements can be determined. The graphical output is given in Fig. 6.5.

Table 7.12: Peak supply requirement of a scheme

Data from previous examples
Peak irrigation month of the scheme is June (Fig 6.5)
Corn (I_n : 188 mm/month, A = 90 ha) Table 6.2
Cotton (I_n : 147 mm/month, A = 60 ha)
Wheat (not cultivated in June)
Scheme efficiency : E_p = 0.5
Selected flexibility factor is 1.2

$$V_{max} = 1.2\,\frac{10}{0.5}\,[188\,.\,90 + 60\,.\,147]$$

For the project acreage of 150 ha, the peak supply requirement of the main canal :
- without flexibility factor : V_{max} = 514,800 m^3/month = 199 l/sec
- with flexibility factor : V_{max} = 617,760 m^3/month = 238 l/sec

8 IRRIGATION SCHEDULING

8.1 Introduction

Irrigation scheduling means the planning of the timing and the depth of future irrigations. It deals basically with two questions: WHEN and HOW MUCH to irrigate. The primary objective is to apply irrigation water at the right period and in the right amount. At one hand there are many ways to do so, at the other hand, if water deliveries are untimely or not in the appropriate amount, irrigation efficiency decreases. Limited supply results in yield reduction due to water stress. Too much water may not only result in deep percolation losses which may leach relevant nutrients out of the rooting zone but might decrease the yield as well.

Figure 8.1 is a schematic representation of what irrigation scheduling is about. Starting with a soil at field capacity, water is extracted by the crop at a rate equal to ET_{crop}. As the uptake progresses the readily available moisture is depleted and actual crop evapotranspiration ET_{act} starts to fall below the optimal level of ET_{crop}. At this point one should irrigate and refill the profile up to field capacity.

This gives the irrigation interval and the amount of water to apply. Any delay results in a restricted water supply situation ($ET_{act} < ET_{crop}$) and increasing water stress, until at permanent wilting point the crop will no longer recover resulting in total crop failure.

In this chapter the general principles of irrigation scheduling based on crop evapotranspiration and the properties of the soil moisture reservoir are dealt with. However, specific crops could have for agronomic reasons particular water and irrigation scheduling requirements. For instance, irrigation of potatoes to control the disease common scab is as important in commercial agriculture than the increase of production (ref. *R. Bailey, 1990, Irrigated crops and their management*). More details concerning the irrigation of particular crops are found in many other documents. *FAO irrigation and drainage paper 33, Yield response to water,* constitutes a good first reference on irigation scheduling of specific crops

8.2 Definitions

a. Root zone depletion

Root zone depletion expresses the shortage of water in the root zone with respect to its maximum water holding capacity, i.e. field capacity. Any surplus of water will be lost through deep percolation. At field capacity the root zone depletion is 0 mm.

b. Maximum depletion

The maximum allowable root zone depletion is the maximum amount of water that a crop can extract from the soil without suffering water stress, i.e. the readily available soil moisture (RAM). If the root zone depletion is larger than RAM, the evapotranspiration drops below its potential level ($ET_{act} < ET_{crop}$) and water stress occurs.

Figure 8.1: Irrigation scheduling related to soil, crop and climate.

Figure 8.2: Graphical presentation of irrigation scheduling terminology

c. Water application depth (D_A)

The practice in on-farm irrigation is to express the amount of irrigation water applied in equivalent water depth (mm water). The depth is called the water application depth and denoted here as D_A.

Soil water holding characteristics determines how much water can be applied. If the actual soil moisture content at time i is equal to θ_i, then is the maximum water application depth equal to the root zone depletion. Indeed, irrigation should at maximum replenish soil moisture up to field capacity, as surplus water will be lost through deep percolation below the root zone.

$$D_A = 10 \ (\theta_{FC} - \theta_i) \ D \qquad [mm]$$

For rooting depth D :

where θ_{FC} and θ_i represent average values over the rooting depth (D) of respectively the moisture content (vol %) at field capacity and the actual moisture content (vol %).

For soil moisture content at time i equal to maximum depletion level, i.e. RAM, the

$$D_{A,n} = RAM = p \ D \ S_a \ \ (net) \qquad D_{a,g} = \frac{RAM}{E_u} = \frac{p \ D \ S_a}{E_u} \ \ (gross)$$

net and gross application depths are respectively :

Where:
$D_{A,n}$ = the net application depth (mm),
$D_{A,g}$ = the gross application depth (mm),
p = depletion factor (-),
D = depth of root zone (m),
S_a = total available soil moisture (mm(water)/m(soil depth)),
E_u = irrigation efficiency. The subscript "u" normally indicates field level, but could also taken at block level or even scheme or project level.

Application depths are normally adapted to the irrigation method. Indicative values for different irrigation methods are given in **Table 8.1**

Table 8.1: Typical application depths for different irrigation methods

Irrigation method		Application depth
Surface irrigation :	basin irrigation	50 - 150 mm
	furrow irrigation	30 - 60 mm
	border irrigation	40 - 80 mm
Sprinkler irrigation		30 - 80 mm

Drip irrigation	10 - 30 mm

d. Water application duration (WAD)

For the scheme management the application depth is useful, but what is of more interest to them is the time required to create this particular application depth i.e. the water application duration (WAD). Normally the application duration will be given per hectare per crop, but in the irrigation schedule this will finally be converted to the duration per field and/or farm and/or block. The application duration is basically expressed in seconds [sec] but may ultimately be expressed in minutes or in hours or in a combination of both.

For a water application depth of D_A mm ie. 10 D_A m^3/ha or 10,000 D_A l/ha, an area of A_u ha and a discharge (flow) of q_u l/sec, the volume of water (V) to be supplied and the water application duration (WAD) are respectively :

$$V = 10\, D_A\, A_u \qquad [m^3]$$

$$WAD = \frac{10{,}000\, D_A\, A_u}{q_u} \qquad [\text{sec}]$$

e. Unit flow (q_u)

The factor relating application duration and application depth is the unit flow (q_u) i.e. the flow received at the inlet of the unit, whether this is a field, a farm or a block of fields, having the same crops. Unit flow is expressed in liters per second [l/sec] . This unit flow is the flow that irrigators have to operate with. The size of this flow is very relevant: If the size is too low, more application losses (deep percolation) will occur and the irrigator stays iddle at his field; if the size is too large irrigation water will be spilled. In that respect, the ‘main d’eau’ is defined as the streamsize an irrigator can handle and with which he can perform the irrigation of his field in an effective and efficient way. This is principally dependent on the irrigation method and the skill of the irrigator.

f. Water application time (t_i) and Irrigation interval (INT)

The scheme management will be interested to know when to irrigate (t_i). The water application timing depends on the choice one makes; water application can be related directly to soil moisture content, which results in different intervals; but very often water application is done at fixed intervals and soil moisture content will then vary.

The time between successive water applications is called the irrigation interval (INT) and is measured from the start of one water application to the start of the next water application and therefore includes the water application duration (WAD). The irrigation interval is basically expressed in seconds [sec], but ultimately (in the schedule) will be expressed in hours or in days or in both.

For optimum water supply, soil moisture should not be depleted below its maximum depletion i.e. RAM, or the soil moisture content at the end of interval i (θ_i) should not drop below $\theta_{critical}$. Thus, the water application time here is determined by soil moisture. In reality there are several other ways for timing water applications and these will be discussed in more detail hereafter.

The net irrigation requirement when combined with soil water characteristics enables to specify when to irrigate. The maximum interval between successive water applications can be calculated as follows:

- If, after the previous water application (at time (i-1)) soil moisture content was equal to θ_{i-1} (which not necessarily was equal to field capacity θ_{FC}), and
- For I_n being the average net irrigation requirement over interval i, the maximum duration in days is:

$$INT_i = \frac{10\,(\theta_{i-1} - \theta_i)\,D}{I_n}$$

Where:

If $\theta_i = \theta_{critical} = \theta_{FC} - p\,(\theta_{FC} - \theta_{WP})$ i.e. maximum depletion,

and $\theta_{i-1} = \theta_{FC}$ i.e. maximum water application depth :

$$INT_i = \frac{10\,p\,(\theta_{FC} - \theta_{WP})\,D}{I_n} = \frac{p\,S_a\,D}{I_n} = \frac{RAM}{I_n}$$

Table 8.2: Water application depth and irrigation interval

Given the actual soil moisture content θ_i = 17.5 vol %, calculate the net application depth which replenish the soil up to field capacity. What is the maximum interval between successive water applications. The net irrigation requirement : I_n = 65 mm/decade Sandy loam soil (θ_{FC} = 21 vol %, θ_{WP} = 9 vol %) Maize (D = 0.8 m, p = 0.50)
D_A = 10 (21-17.5) 0.8 = 28 mm RAM = 0.50 (21-9) 10 (0.8) = 48 mm INT = 48/65 = 0.74 decade = 7.4 days
The net application depth is 28 mm. For the given net irrigation requirement and soil type, the maximum irrigation interval is 7 days.

8.3 Real time scheduling

In most scheduling methods climate data are used which are mean values calculated over a certain period in the past, i.e not taking into account the actual climate conditions. Under real time scheduling the climate conditions of the moment are taking in account. Several methods are used to determine the moment and the amount of irrigation.

8.3.1 Plant observation

This is probably the oldest method of irrigation scheduling. The crop will be irrigated, when individual plants start showing visible signs indicating that they are beginning to experience water stress. The signs range from colour changes and leaf curling to wilting during the afternoon.

The method is easy and requires no data gathering or computations, but it has the disadvantage, that by the time plants show symptoms of stress they have already suffered some growth and yield reduction.

More modern methods involve monitoring certain plant physiological states, such as stomatal closure using porometers, leaf water status using pressure bombs and leaf temperature using infrared radiation. These methods are not used on a routine basis.

8.3.2 Soil moisture meters

Notable among these instruments are tensiometers, resistance blocks and neutron meters. The principle of these instruments is, that they measure certain physical characteristics of the soil which depend on its moisture content. A calibration curve is then used to determine the corresponding soil moisture contents. When the reading indicates critical soil moisture content the crop should be irrigated. The disadvantages of the method include sensor breakdowns or malfunction and the fact that the method does not give the amount of water to apply at each irrigation.

a - Tensiometers

Tensiometers consist of a porous cup connected by a tube to a pressure gauge. Both cup and tube contain air-free boiled water. The cup is embedded to a required depth within the soil and maintained in water and temperature equilibrium with the soil. This allows the suction, with which water is being held in the soil, to be registered by the pressure gauge. The disadvantage of tensiometers is that they are reliable only up to about 0.7 bars. They are also very difficult to maintain in constant working state as any disruption of the equilibrium with the soil causes errors in the readings.

b - Electrical resistance blocks

Electrical resistance blocks are usually made of gypsum with two electrodes embedded. The block is buried at a required depth in the soil, where its water content equilibrates with the soil. Resistance to electricity flow between the electrodes is a function of the water content of the block and the surrounding soil. Resistance blocks are sensitive to a wider range of moisture contents than tensiometers, but they tend to deteriorate with time, especially in saline soils.

c - Neutron moisture probes

Neutron moisture probes uses a neutron scattering system to monitor soil moisture contents. It gives an easy method of measuring soil moisture. However, the equipment is expensive and can be hazardous if not handled with the recommended caution. The method is more widely used in agricultural research studies and cannot be recommended for individual small farmers, both for its cost and the skill required in handling the equipment.

8.3.3 Cumulative pan evaporation

This method is based on the cumulated pan evaporation (E_{pan}) starting from the last irrigation. It is based on the fact that E_{pan} is an estimate of ET_{crop}.

In a sense it is a version of the soil water budget method, because the value of cumulative E_{pan}, at which water should be applied is related to available soil moisture. When the value of cumulative E_{pan} is reached, the available water has been depleted to a level where irrigation is necessary.

The disadvantage of the method is that additions to soil moisture storage from precipitation or shallow groundwater table are not considered. It is therefore most appropriate at locations, where these additions do not occur during the irrigation season.

8.3.4 Soil water budget

This is the most complex, but in most cases, the most accurate of all the methods. Irrigation timing and depth of irrigation water are determined on the basis of the soil water balance. Information on the weather (ET_0 and rainfall) on a daily basis, the crop and the soil are required. The disadvantage is the large amount of data, which must be processed.

Water is added to the soil moisture in the profile by rainfall, irrigation or capillary rise from the groundwater table. Water is extracted from the soil moisture in the profile by evapotranspiration, run-off and deep percolation. If the soil water content drops below a critical value, the crop should be irrigated. The (net) volume of water to be given should be maximal equal to the amount required to bring the rooting zone back to field capacity.

8.4 Planning and evaluation of irrigation schedules

The soil water budget method is a powerful tool in planning and evaluation of irrigation schedules as well as in real time scheduling. The graphical presentation of the soil water budget as result of an irrigation schedule shows the variation of the soil moisture storage in the rootzone during the time period considered.

The soil water budget is based on the change of soil water content and consequently changes in available moisture in the rootzone between time i and i +1 (see also section 7.5):

Change of Available Moisture in Rootzone

$$\mathbf{AM_{rz,\,i+1} = AM_{rz,\,i} - ET - (DP) - (RO) + P_{eff}\ (+G_e) + I}$$

Where:

$AM_{rz,\,i+1}$	=	available soil moisture in the rootzone at time i+1	[mm]
$AM_{rz,i}$	=	available soil moisture in the rootzone at time i	[mm]
ET	=	crop evapotranspiration in the time period i,i+1	[mm]
DP	=	deep percolation in the time period i,i+1	[mm]
RO	=	runoff from rainfall or irrigation i,i+1	[mm]
P	=	rainfall in the time period i,i+1	[mm]
G_e	=	capillary rise in the time period i,i+1	[mm]

I = irrigation in the time period i, i+1 [mm]

If assumed:
CR = 0
In the time period between i and i+1 no irrigation will take place (I=0) then:

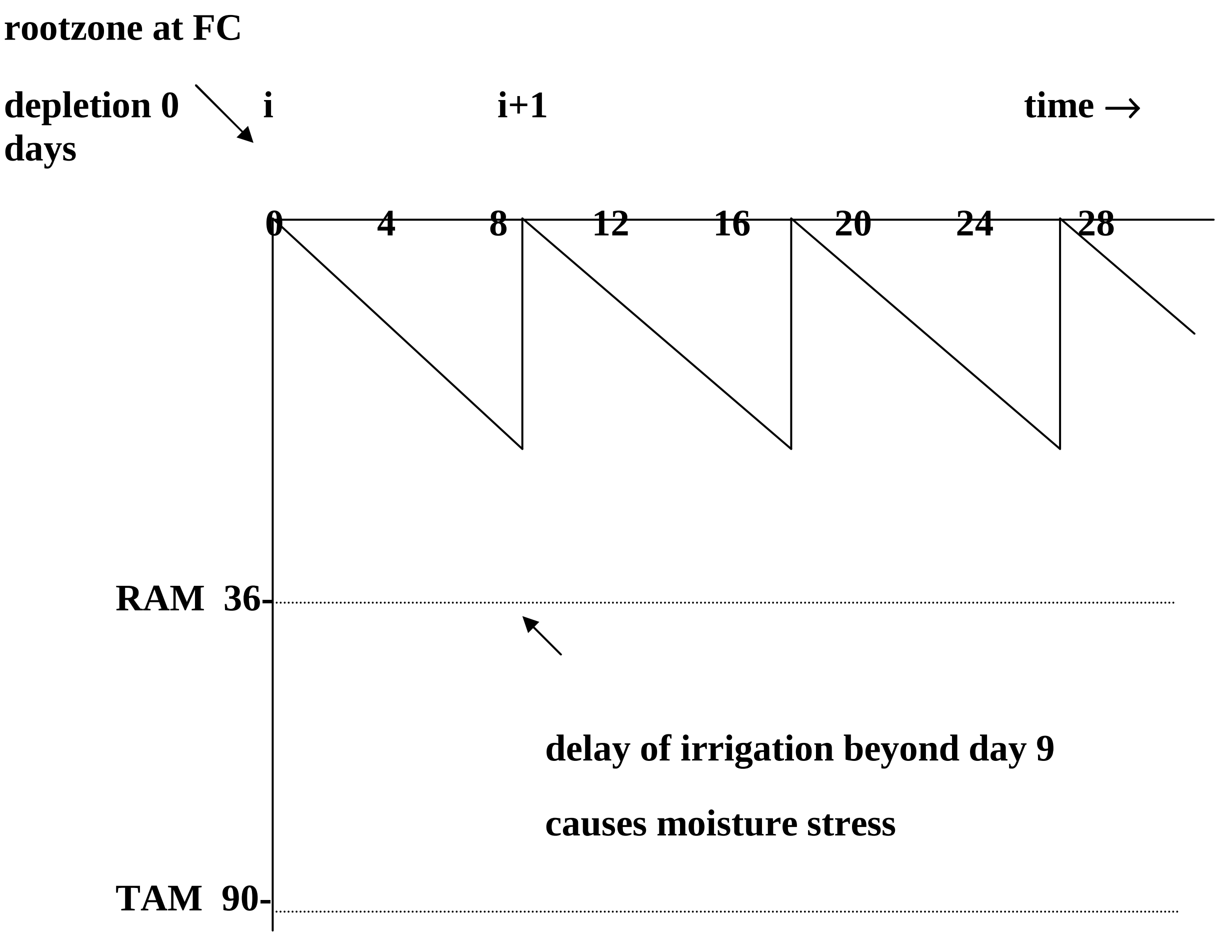
Water losses (DP and RO) between i and i+1 are accounted for in Peff (= P-DP-RO) and consequently:

$AM_{rz,\,i} - AM_{rz,\,i+1} = ET - P_{eff}$ = Net Irrigation requirement at time i+1 to bring available soil moisture in the rootzone back to $AM_{rz,\,i}$

The first term is equivalent to the **soil moisture depletion in the time period i, i+1**

This can be graphically presented in a soil moisture depletion diagram. An example of a soil moisture depletion diagram is given in **Figure 8.3**

Figure 8.3: Example of a Soil Moisture Depletion diagram



soil moisture

depletion mm ↓

Soil: medium

depth rootzone: 60 cm

TAM = total available moisture in the rootzone = (Θ_{fc} - Θ_{pwp}) D_{rz} =
(35% - 20%) 600mm = 90mm. Corresponds with a depletion of 0 mm.

RAM = readily avaible moisture in the rootzone= p TAM =0.4* 90 mm = 36 mm
Corresponds to a soil moisture depletion of 36 mm

ET - P_{eff} = 4 mm/d

After 9 days depletion is 9 * 4 = 36 mm and all readily available moisture is used → time to irrigate.

Irrigation interval (INT): 9 days

Net irrigation depth ($D_{A,n}$) of 36 mm brings rootzone again at Field Capacity.

8.5 Options in Irrigation Scheduling: Timing and Application Depths

In field irrigation, the objective is to maintain a favorable moisture regime for crop growth in the root zone. This implies that the variation of soil moisture in the root zone must be controlled within critical limits. But there are many ways to do so, for instance an irrigation water requirement of 100 mm in 20 days could be applied in one irrigation turn (INT = 20 days, $D_{A,n}$ = 100 mm) but also in five turns (INT=4 days, $D_{A,n}$ = 20 mm).

At the other hand, each irrigation system has its own operational and management characteristics and limitations. This has direct consequences for the most appropriate scheduling of irrigation turns. Irrigation scheduling at the field level and the operation/ management of the irrigation system need to be mutually adjusted.

The following **scheduling options** can be distinguished:

'Optimal' irrigation.

In this option the timing of water application is scheduled according to the depletion of soil moisture equal to the whole readily available moisture in the rootzone. Application depth will be equal to RAM so that the whole rootzone will be refilled to field capacity. **Figure 9.3** presents a graphical example of this scheduling option. Some variants of this option can be distinguished:

- irrigation water is applied whenever a certain soil moisture level is reached defined as percentage of RAM. Useful to set a safety level above critical soil moisture (for instance 80% RAM, no water stress) or to allow a certain stress level (for instance 120 % RAM).

- The application depth will bring soil moisture back to a fixed amount above (over-irrigation) or below field capacity. Useful to allow for leaching to control salts in the root zone (application larger than field capacity) or to accommodate possible rainfall (application below field capacity)

This option is the classical way to determine irrigation schedules, resulting in optimum irrigation efficiency and minimum irrigation turns but varying application depths and intervals over the season. At system level, this complexity couls still increase enormously assuming that various crops are grown on different soil types. To realize this scheduling option, the irrigation system and its management need to be structured in such a way that it can handle varying flows, water application times and intervals for delivering water at the different parts of the system. The operation of the irrigation system need to be highly flexible and the physical infrastructure designed accordingly. The water source(s) need to have an unrestricted water availability, supply characteristics that are adjusted to the varying irrigation requirements (peak demands and periods of low water requirements). The farmers and the scheme managers need to have considerable skills to ask respectively to deliver the right quantities of water at the right time (which implies for instance, knowing to work with the soil water budget), to work with varying flows, application times and intervals.

Figure 8.4: Irrigation schedule of sweet pepper in Jamaica, 'optimal' variant, Variation of soil moisture in the rootzone

(adapted from *M.Smith, 1990, scheduling of irrigation for vegetable crops under field conditions, Acta Horticulturae 278*)

<u>'Practical' irrigation</u>.

This option is the contrary of the 'optimal' scheduling. In the 'practical' option, water is applied at fixed intervals with fixed application depths (for examples, see **Figure 8.5** and **Figure 8.6**). This option is particularly suitable in a gravity system with rotational water distribution as found in many irrigation systems. Both the interval(s) and the amount(s) may not correspond to the soil moisture conditions, i.e. the amount may exceed or fall short of soil moisture depletion or the water requirements for the fixed interval may not correspond with readily available soil moisture. Although it may result in some over-irrigation in the initial stages and under –irrigation in the peak season, the fixed irrigation turns have great operational/management advantages both at the field and system level. Distribution infrastructure could be very simple.

In case of a variable water supply (for instance run-off-the-river schemes), some variants of this option in timing and application depths can be distinguished:

- Irrigation water applied on fixed interval turns but variable irrigation depths.
- A fixed application depth but variable intervals

Figure 8.5: Irrigation schedule of sweet pepper in Jamaica, 'practical' option, Variation of soil moisture in the rootzone

(adapted from *M.Smith, 1990, scheduling of irrigation for vegetable crops under field conditions, Acta Horticulturae 278*)

Figure 8.6: Irrigation schedule of Tomato in Pakistan, 'practical' option, Variation of soil moisture in the rootzone

(adapted from *M.Smith, 1990, scheduling of irrigation for vegetable crops under field conditions, Acta Horticulturae 278*)

Deficit irrigation.

Often water availability - actual water supply - is limited and below irrigation requirements. There is not enough water to replenish soil moisture up to field capacity and to irrigate before all of the readily available soil moisture (RAM) is depleted. Consequently the crop will experience water stress, to a degree depending on it's growth stage, its sensitivity to water stress and the seriousness of the soil moisture deficit.

In Chapter 7, section 7.4.3 information has been given on the reaction of the crop to water stress i.e. what will be the actual yield for the situation when actual crop evapotranspiration falls below (optimum) crop evapotranspiration.

The equation $(1 - \frac{Y_a}{Y_m}) = k_y (1 - \frac{ET_{act}}{ET_{crop}})$ can be rewritten as :

$$Y_a = \alpha \, ET_{act} + \beta$$

Where:

$$\alpha = k_y \frac{Y_m}{ET_{crop}}$$

$$\beta = (1 - k_y) Y_m$$

There is thus a linear relationship between actual yield and actual evapotranspiration, which can be established for known climate (ET_o), crop and crop stage (k_c and k_y factors, Y_m and ET_{crop}).

Options for irrigation scheduling under conditions of water stress are as follows:

- Accept a reduction in ET_{crop} ($ET_{act} = \xi.ET_{crop}$), which results in an acceptable Y_a value [$Y_a=\{1-(1-\xi).k_y\}.Y_m$]. Determine the irrigation schedule for the given conditions and evaluate water savings (Is the water availability covering the reduced water requirements)

- Accept an economically acceptable reduction in Y_a and calculate ET_{act}. Again check on the water savings

Strategies to reduce water stress and yield reductions are:

- Fill the soil profile up to field capacity over the maximum root depth + some 20 - 30 cm for capillary rise. This should be done prior to sowing or at the initial stage when water availability is still relatively high and crop water requirements relatively low.

- Make the irrigation interval as long as possible, even inducing slight water stress as this enhances root development by the young plant, looking for water ("growing after the water"). To enhance rapid and deep root growth a water deficit during the early growth periods can be advantageous for some crops (maize).

- For some crops the sensitivity to water stress during a sensitive period is less pronounced, when water deficit has been experienced during a preceding period (For instance maize, which is less sensitive to water stress during flowering when water stress has been experienced during the vegetative period).

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Appendix

Appendix I: Glossary of terms

Allowable depletion

- Portion of plant available water that is allowed for plant use prior to irrigation based in plant and management considerations.
- That part of soil moisture stored in the plant root zone managed for use by plants, usually expressed as equivalent depth of water in acre inches per acre, or inches.
- Is sometimes referred to as allowable **soil depletion** or **allowable soil water depletion**.

Aquifer

Underground geological formation, or group of formations, containing usable amounts of groundwater that can supply wells or springs for domestic, industrial, and irrigation uses. Removing more groundwater from an aquifer than is naturally replenished is called overdrafting, and can result in a dropping water table, increased pumping costs, land subsidence (which reduces the future recharge capacity), saltwater intrusion, reduced streamflows in interconnected ground- and surface-water systems, and exhaustion of groundwater reserves. Overdrafting groundwater occurs primarily in the Plains States and the West.

Available Soil Moisture: The difference in soil moisture content between Field Capacity and Permanent Wilting Point. This represents the moisture which can be stored in the root zone for use by crops, expressed as a depth of water in inches or feet

Blue water: available in rivers, lakes, and aquifers, and requiring technology to access it and move it

Chemigation: Application of chemicals (including fertilizers) to crops through an irrigation system by mixing them with the irrigation water.

Continuous-flow irrigation: System of irrigation water delivery where each irrigator receives the allotted quantity of water continuously.

Crop water stress index: Index of moisture in a plant compared to a fully watered plant, measured and calculated by a CWSI instrument. Relative humidity, solar radiation, ambient air temperature, and plant canopy temperature are measured.

Crop Root Zone: The soil depth from which a mature crop extracts most of the water needed for evapotranspiration. The crop root zone is equal to effective rooting depth and is expressed as a depth in inches or feet. This soil depth may be considered as the rooting depth of a subsequent crop, when accounting for soil moisture storage in efficiency calculations

Crop Water Requirement (CWR): The infiltrated water required to grow a crop, expressed as a depth of water in inches or feet

Deep Percolation (DP): The amount of irrigation water that flows below the crop root zone and is unavailable for evapotranspiration, expressed as a depth of water in inches or feet

Demand irrigation (system)(delivery): Procedure where each irrigator may request irrigation water in the amount needed and at the time desired.

Distribution Uniformity (DU): The ratio of the average low-quarter depth of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percent

Efficiency

- **application efficiency**
    - Ratio of the average depth of the irrigation water stored in the root zone to the average depth of irrigation water applied.
    - Ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied.
    - Amount of water stored in the root zone that is available for plant use divided by the average amount of water applied during irrigation.
    - Ratio of the average depth of irrigation water contributing to target, to the average depth of irrigation water applied.
- **(Water) application efficiency of lower half** [E_h,] Ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of water applied.
- **(water) application efficiency of lower quarter** [E_q,]
    - Ratio of the average low quarter depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied.
    - Ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of water applied.
- **Conveyance efficiency** [E_c] Ratio of the water delivered, to the total water diverted or pumped into an open channel or pipeline at the upstream end.
- **Irrigation efficiency*** [E_i, IE] Ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied.
- **potential application efficiency of Low Quarter** [PELQ] {%) low quarter application efficiency obtainable with a given irrigation system when the depth of irrigation water infiltrated in the quarter of the area receiving the least water equals some predetermined value of the soil moisture deficit.
- **project efficiency** Overall efficiency of irrigation water use in a project setting that accounts for all water uses and losses, such as crop ET, environmental control, salinity control, deep percolation, runoff, ditch and canal leakage, phreatophyte use, wetlands use, operational spills, and open water evaporation.
- **(Water) storage efficiency** [] Ratio of the amount of water stored in the root zone during irrigation to the amount of water needed to fill the root zone to field capacity.
- **Water use efficiency** [WUE] Ratio of the yield per unit area to the applied irrigation water per unit area.

Effluent irrigation: Land application of treated wastewater for irrigation and beneficial use of nutrients.

Evaporation is the loss of water by vaporization and the vapour removal from surfaces as soil surface, lakes, and rivers, wet vegetation (following rain, overhead irrigation, and dew)

Effective Precipitation (EP): That portion of rainfall that contributes to satisfying the evapotranspiration and/or leaching requirement of a crop, expressed as a depth of water in inches or feet

Evapotranspiration (ET): The amount of water loss over a period of time through transpiration from vegetation and evaporation from the soil, expressed as a depth of water in inches or feet

Evapotranspiration Potential (ETP): Evapotranspiration potential is a value calculated with a modified Penman equation and is equal to daily alfalfa evapotranspiration when the crop occupies an extensive surface; is actively growing, standing erect, and at least eight inches tall; and is well watered so that soil water availability does not limit evapotranspiration, expressed as a depth of water in inches or feet

Field capacity

- Moisture remaining in a soil following wetting and natural drainage until free drainage has practically ceased.
- Amount of water remaining in a soil when the downward water flow due to gravity becomes negligible.
- Depth of water retained in the soil after ample irrigation or heavy rain when the rate of downward movement has substantially decreased, usually one to three days after irrigation or rain, expressed as a depth of water in inches or feet

Full irrigation Management of water applications to fully replace water used by plants over an entire field.

Green water: Rainwater utilised by vegetation or lost through evaporation (i.e. used in evapotranspiration).

Hygroscopic water

- Water which is bound tightly by the soil solids at potential values lower than -31 bars.
- Water that is tightly held by soil particles. It does not move with the influence of capillary action or gravity, and it is normally unavailable to plants.

Infiltration

- Process of water movement through the soil surface into the soil matrix.
- The act of water entering the soil profile.

Infiltration rate

- Downward flow of water into the soil at the air-soil interface.
- Volume of water infiltrating through a horizontal unit area of soil surface at any instant.
- How quickly water moves into the soil.
- The rate of water entry into the soil expressed as a depth of water per unit of time in inches per hour or feet per day. The infiltration rate changes with time during irrigation

Irrigation is defined as "artificially supplying and systematically dividing of water for agriculture and horticulture in order to obtain higher or qualitatively better production."

Irrigation (water) requirement

- **net irrigation requirement**

    - Depth of water, exclusive of effective precipitation, stored soil moisture, or ground water, that is required for meeting crop evapotranspiration for crop production and other related uses. Such uses may include water required for leaching, frost protection, cooling and chemigation.
    - Difference between evapotranspiration and effective precipitation.
    - Quantity of water needed by the landscape to satisfy the evaporation, transpiration and other uses of the water in the soil.
- **gross irrigation requirement**
    - Total amount of water applied (or desired). See also **irrigation water requirement**.
    - Total irrigation requirement including net crop requirement plus any losses incurred in distributing and applying and in operating the system.
- **irrigation water requirement** [IWR]
    - Calculated amount of water needed to replace soil water used by the crop (soil water deficit), for leaching undesirable elements through and below the plant root zone, plus other needs; after considerations are made for effective precipitation.
    - Plant water requirement adjusted for application uniformity (and efficiency). (Same as **gross irrigation requirement**.)

Irrigation schedule
- Procedure of establishing and implementing the time and amount of irrigation water to apply.
- Determining when to irrigate and how much water to apply, based upon measurements or estimates of soil moisture or crop water used by a plant.
- Set of specifications identifying times to turn on and off water to various zones of an irrigation system.

Irrigation system
- Physical components (pumps, pipelines, valves, nozzles, ditches, gates, siphon tubes, turnout structures) and management used to apply irrigation water by an irrigation method.
- All equipment required to convey water to or within the design area.
- Set of components which includes (may include) the water source, water distribution network, control components and possibly other general irrigation equipment.
- **drip/trickle/micro**[]
    - Micro irrigation system (low pressure and low volume) wherein water is applied to the soil surface as drops or small streams through emitters. Preferred term is drip irrigation.
    - Method of micro-irrigation wherein water is applied to the soil surface (or below the soil surface) as drops or small streams through emitters. Discharge rates are generally less than 2 gph for single-outlet emitters and 3 gph per meter for line-source emitters.
    - Method of micro irrigation wherein water is applied to the soil surface as drops or small streams through emitters (preferred term is drip irrigation).
- **Bubbler irrigation** Application of water to flood the soil surface using a small stream or fountain. The discharge rates for point-source bubbler emitters are greater than for drip or subsurface emitters but generally less than 1 gpm. A small basin is usually required to contain or control the water.
- **surface**

- Type of irrigation where water is distributed to the plant material by a ground surface distribution network possibly including rows or dikes.
- Broad class of irrigation methods in which water is distributed over the soil surface by gravity flow.
- **Basin irrigation**: Irrigation by flooding areas of level land surrounded by dikes. Used interchangeably with level border irrigation, but usually refers to smaller areas.
- **Border irrigation**: Irrigation by flooding strips of land, rectangular in shape and cross leveled, bordered by dikes. Water is applied at a rate sufficient to move it down the strip in a uniform sheet. Border strips having no down field slope are referred to as level border systems. Border systems constructed on terraced lands are commonly referred to as benched borders.
- **Cablegation:** Method of surface irrigation that uses gated pipe to both transmit and distribute water to furrows or border strips. A plug, moving at a controlled rate through the pipe, causes irrigation to progress along the field and causes flow rates from any one gate to decrease continuously from some maximum rate to zero.
- **Check irrigation** Modification of a border strip with small earth ridges or checks constructed at intervals to retain water as the water flows down the strip.
- **Check basin irrigation:** Water is applied rapidly to relatively level plots surrounded by levees. The basin is a small check.
- **Corrugation irrigation:** Method of surface irrigation similar to furrow irrigation, in which small channels, called corrugations, are used to guide water across a field. No attempt is made to confine the water entirely to the corrugations.
- **Flood irrigation:** Method of irrigation where water is applied to the soil surface without flow controls, such as furrows, borders or corrugations.
- **Furrow irrigation:** Method of surface irrigation where the water is supplied to small ditches or furrows for guiding across the field.
  - **Alternate set irrigation:** Method of managing irrigation whereby, at every other irrigation, alternate furrows are irrigated, or sprinklers are placed midway between their locations during the previous irrigation.
  - **Alternate side irrigation**: Practice of furrow irrigating one side of a crop row (for row crops or orchards) and then, at about half the irrigation time, irrigating the other side.
  - **Cutback irrigation:** Reduction of the furrow or border inflow stream after water has advanced partially or completely through the field in order to reduce runoff.
  - **Surge** Surface irrigation technique wherein flow is applied to furrows (or less commonly, borders) intermittently during a single irrigation set.
- **Wild flooding** Surface irrigation system where water is applied to the soil surface without flow controls, such as furrows, borders (including dikes), or corrugations.

- **Sprinkler** Type of irrigation using mechanical devices with nozzles (sprinklers) to distribute the water by converting water pressure to a high velocity discharge stream or streams.
  - **continuous/self-move system**
    - Lateral, sprinkler (traveler), or boom that is continuous or self moving while water is being applied. Power for moving the facility is typically

provided by electric or hydraulic (water) motors or small diesel engines.

- **Boom** Elevated, cantilevered boom with sprinklers mounted on a central stand. The sprinkler-nozzle trajectory back pressure rotates the boom about a central pivot which is towed across the field by a cable attached to a winch or tractor. Can also be a periodic-move system.
- **Center pivot** Automated irrigation system consisting of a sprinkler lateral rotating about a pivot point and supported by a number of self-propelled towers. Water is supplied at the pivot point and flows outward through the pipeline supplying the individual sprinklers or spray heads.
- **Corner pivot** Additional span or other equipment attached to the end of a center pivot irrigation system that allows the overall radius to increase or decrease in relation to field boundaries.
- **Lateral (linear) move** Automated irrigation machine consisting of a sprinkler line supported by a number of self-propelled towers. The entire unit moves in a generally straight path perpendicular to the lateral and irrigates a basically rectangular area.
- **traveler (traveling gun) irrigation**
  - Large rotating sprinkler(s) mounted on a trailer to deliver water in a circle. The sprinkler and associated trailer are towed through the field by any of several means. ...
  - Travelers are also called **cable-tow, hard hose and hose drag**.

- **Periodic-move system:** System of laterals, sprinklers heads (gun types), or booms that are moved between irrigation settings. They remain stationary while applying water.
  - **Gun type** Single sprinkler head with large diameter nozzles, supported on skids or wheels. Periodically moved by hand or mechanically with a tractor, cable, or water supple hose.
  - **Portable (hand move) irrigation** Sprinkler system which is moved by uncoupling and picking up the pipes manually, requiring no special tools.
  - **Side move** Sprinkler system with the supply pipe supported on carriages and towing small diameter trailing pipelines each fitted with several sprinkler heads.
  - **Side role (wheel line)** Supply pipe is usually mounted on wheels with the pipe as the axle and where the system is moved across the field by rotating the pipeline by engine power.
  - **Towed sprinkler** System where lateral lines are mounted on wheels, sleds, or skids and are pulled or towed in a direction approximately parallel to the lateral. Rollers or wheels are secured in the ground near the main water supply line to force an offset in the tow path equal to half the distance the lateral would have been moved by hand.
- **Solid set/fixed** [] System of portable surface or permanently buried laterals totally covering the irrigated area or field. Typically several adjacent laterals or heads are operated at one time. Portable laterals are typically removed from the field at end of germination, plant establishment, or the irrigation season and are replaced the next irrigation system.

Management allowable (allowed) depletion (deficit)

- See similar term, **maximum allowable deficiency**.
- Desired soil moisture deficit at the time of irrigation.
- Portion of **available water** that is scheduled to be used prior to the next irrigation.
- Planned soil moisture deficit at the time of irrigation.

Lag time (flood irrigation) Period between the time that the irrigation stream is turned off at the upper end of an irrigated area and the time that water disappears from the surface at the point or points of application.

Moisture deficit, soil moisture depletion Difference between actual soil moisture and soil moisture held in the soil at field capacity.

opportunity time Time that water inundates the soil surface with opportunity to infiltrate.

Osmotic potential Potential attributable to the presence of solutes in the soil- in other words, to the soil solution.

(permanent) wilting point

- Moisture content, on a dry weight basis, at which plants can no longer obtain sufficient moisture from the soil to satisfy water requirements. Plants will not fully recover when water is added to the crop root zone once permanent wilting point has been experienced. Classically, 15 atmospheres (15 bars), soil moisture tension is used to estimate PWP.
- Moisture content of the soil after the plant can no longer extract moisture at a sufficient rate for wilted leaves to recover overnight or when placed in a saturated environment.
- Also known as wilting percentage, wilting coefficient or wilting point.

Potential

- **Soil water potential** Amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration.
- **Total potential** Sum of matric, pressure, solute and gravitational potentials.
- **Matric potential** Attraction of the solid soil matrix for water.
- **Pressure potential:** Potential caused by water pressure.
- **Solute or osmotic potential:** Potential caused by salinity.
- **Gravitational potential** Relative height of a point above or below a reference elevation.

Riparian

- Area of flowing streams that lies between the normal water line and some defined high water line.
- Pertaining to the banks of a body of water; riparian owner is the one who owns the banks.
- Riparian water right is the right to use and control water by virtue of ownership of the banks.

Effective root depth / zone: Depth from which roots extract water. The effective rooting depth is generally the depth from which the crop is currently capable of extracting soil water. However, it may also be expressed as the depth from which the crop can extract water when mature or the depth from which a future crop can extract soil water. Maximum effective root depth depends on the rooting capability of the plant, soil profile characteristics, and moisture levels in the soil profile

Root zone

- Depth of soil that plants roots readily penetrates and in which the predominant root activity occurs.
- Area of the soil from which the crop roots extract water and nutrients.
- Crop rooting depth is typically taken as the soil depth containing 80 percent of plant roots.
- (May also be used as a portion of the root zone in equations where soil characteristics change within the root zone.)

Runoff

- Portion of precipitation, snow melt or irrigation that flows over the soil, eventually making its way to surface water supplies.
- Surface water that leaves the subject region in liquid form.

Scheduling

- Procedure of establishing and implementing the time and amount of irrigation water to apply.
- Determining when to irrigate and how much water to apply, based upon measurements or estimates of soil moisture or crop water used by a plant.

Soil moisture (water) depletion (deficit)

- Difference between field capacity and the actual soil moisture in the root zone soil at any given time. It is the amount of water required to bring the soil in the root zone to field capacity.
- Amount of water required to fill the plant root zone to field capacity.

Sub-irrigation

- Application of irrigation water below the ground surface by raising the water table to within or near the root zone.
- Applying irrigation water below the ground surface either by raising the water table or by using a buried perforated or porous pipe system that discharges water directly into the plant root zone.

system capacity, Ability of an irrigation system to deliver the net required rate and volume of water necessary to meet crop water needs plus any losses during the application process. Crop water needs can include soil moisture storage for later plant use, leaching of toxic elements from the soil, air temperature modification, crop quality, and other plant needs.

Sustainable agriculture:*"Food production that can be continued indefinitely without destroying the natural bases which supports it"*

Tail water

- Water in a stream or canal, immediately downstream from a structure.
- Excess irrigation water which reaches the lower end of a field.
- Applied irrigation water that runs off the lower end of a field. Tail water is the average depth of runoff water, expressed in inches or feet.

Transpiration

- Process of plant water uptake and use, beginning with absorption through the roots and ending with transpiration at the leaf surfaces. See also **evapotranspiration**.
- Liquid movement of water from the soil, into the roots, up the plant stems, and finally out of the plant leaves into the air as vapor.

Underirrigation (UI): The difference between the water actually stored in the crop root zone during an irrigation (soil moisture replacement) and the water needed to refill the root zone to field capacity (soil moisture deficit) in all or part of the field, expressed as a depth of water in inches or feet.

Uniformity coefficient (Christiansen's) Measure of the uniformity of irrigation water application. The average depth of irrigation water infiltrated minus the average absolute deviation from this depth, all divided by the average depth infiltrated.

Water holding capacity Total amount of water held in the soil per increment of depth. It is the amount of water held between field capacity and oven dry moisture level.

Water window Time of day available for irrigation to occur

Appendix II: CROPWAT COMPUTER PROGRAM

For the practical we will use CROPWAT for calculation of crop water requirements and scheduling of irrigation.

CROPWAT is a software program designed by the FAO, which offers the possibility to calculate:

- ET_0 (Penman-Monteith)
- Crop water requirements
- Irrigation scheduling
- Scheme water supply

The program is used world wide in irrigation design. The software comes with a manual, which is available during the practical. Until now the most used version is the version 7.0, which is a DOS-based software package. Unfortunately this version does not work on windows versions higher as 98. The version 8 that will be used during the practical is a windows beta version. The manual and help function of this beta edition are not yet available. Any information and download possibilities are available at the FAO website: http://www.fao.org/ag/AGL/AGLW/cropwat.stm

Start CROPWAT from CD or hard disk. Go to the CROPWAT 8 directory and in the directory double click the CROPWAT application icon. When CROPWAT offers the possibility to SAVE data: do this. You will be able to restart with the data that you had already inserted.

In the file menu, you can open an existing session or create a new session.

Read the instructions on the screen and the exercises hereunder carefully. Read the whole exercise before starting one. When during exercise 1 CROPWAT requires data input, always select the option <open> and simply select one of the data files that is available.

During exercise 2, 3, and 4 you will be required to use your own data. Save them after input. After a while CROPWAT will prove to be a useful tool in irrigation design. You have 1 afternoon to do the exercises. A report on CROPWAT should contain the answers to the questions and for exercises 2,3 and 4 also the final CROPWAT output files.

<u>Exercise 1:</u> Getting to know CROPWAT

1. Which main program options exist?

2. Which climatological and geographical data are required for the calculation of the reference evapotranspiration according to Penman-Monteith? Also give unit specifications.

3. Which data are required to calculate the crop water requirements? Give the 3 main requirements.

3a. Which options does CROPWAT have to calculate the effective rainfall. Give 5 options and explain each option.

3b. Which detailed crop data are required (give 5 data types). In case you need these data what would be your information source.

3c. Which data are given in the output file "Crop evapotranspiration and irrigation requirements" (9 Columns).

4. Which data are required to calculate an irrigation schedule? Give the 6 main requirements.

4a. Which specific soil data are required? What is total available moisture? What is soil moisture depletion?

4b. Which Irrigation timing options does CROPWAT offer? What is RAM?

4c. What are the advantages and disadvantages of each timing options when used in an open canal small holders irrigation scheme of 150 ha with 300 plotholders and one water supply entry point?

4d. Which Irrigation application options does CROPWAT offer? What is field capacity? What is field application efficiency?

4e. The field application efficiency of a 70 mm application on a graded furrow plot, with furrow length of 100 m has been measured to be 70%. What happens to the field application efficiency when the application flow remains the same as in the above situation, but the furrow length is decreased to 60 m?

4f. Print one irrigation schedule output file. Which data are given in the Irrigation schedule output file. Explain the 3 different blocks, and give the 12 columns of block 1 (explain).

<u>Exercise 2:</u> Calculate an irrigation scheduling and corresponding yield reduction

(Describe all steps taken as well as any presumptions made during the calculation process; give the CROPWAT output = ET_0 calculation, crop water requirements and Irrigation scheduling)

1. Crop : Alfalfa, planting date 15 November

2. Soil : Coarse sand, Total available moisture (pF2 - pF4.2) = 8%

   No restricting layer observed within the rooting zone

3. Irrigation at fixed interval :

   April - October : 7 days

   November - March : 10 days

4. Fixed irrigation: 60 mm; field application efficiency 70%

5. Climatological data :

These data originate from Dégache meteorological station (Tunisia),

position: 8º East and 33º North at 51 m altitude; monthly averages over the period April 1992-May 1997.

60 % of the rainfall is effective; rainfall under 5mm should not be considered.

Month	Daily sunshine (h)	Av.temp. (º C)	Humidity (%)	Wind (m s^{-1})	Rain (mm)
January	9	13	77	0.3	6.5
February	10	13	64	1.5	12
March	11	15	70	1.0	29
April	11	25	22	0.6	0
May	12	25	40	0.4	0
June	12	27	37	0.8	0
July	12	28	34	1.0	0
August	12	37	30	1.5	0
September	11	27	50	1.5	0
October	10	21	40	1.5	0.4
November	10	17	48	0.2	0
December	9	15	76	0.5	1.0

Exercise 3: Analyzing the result obtained from assignment 2

a. What is

- the efficiency of the irrigation schedule
- yield reduction in each cropping stage
- total yield reduction
- total gross and net irrigation vs. actual and potential water use by the crop.

b. How could you improve the efficiency of the irrigation schedule. (which variable inputs could be changed and to what extend. Note: crop, planting date and crop stages are no variable inputs)

c. Change one (1) variable input : what effect does this have on the efficiency of the irrigation schedule and on the yield reduction? (give new data and CROPWAT output)

d. Change another variable input : same question

Exercise 4: Case Cascas, Senegal

Data available:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0	5.7	6.2	7.0	7.9	9.1	8.4	8.0	7.5	7.1	6.7	5.8	4.9
P	1	2	0	0	0	11	43	82	73	14	0	1

(ET_0 in mm d^{-1})

(P in mm $month^{-1}$)

Crop: Maize, growing period 130 days, November - February

Cropfactors: 0.5, 0.8, 1.1 and 0.6 resp.

Soil: loam

Total available moisture: 14 vol%

Allowable depletion: 50%

a. Calculate the crop water requirement

b. Set up the “ideal” irrigation schedule (max. efficiency with minimum yield reduction). Keep it practical.

Describe the steps and choices made during the calculation process.