TRAINING MANUAL

- ENVIRONMENTAL MANAGEMENT -

SUSTAINABLE WATER MANAGEMENT

COLEACP

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SUSTAINABLE WATER MANAGEMENT

SUSTAINABLE WATER MANAGEMENT PART I

Introduction

INTRODUCTION

Among the natural resources that contribute to the development of human activities, water has unique characteristics that distinguish it from all the others: it is indispensable to life; it is omnipresent (it makes up 65% of the human body, and covers 70% of the earth's surface); it is available in strictly fixed quantities, dictated by conservation laws and the water cycle. The fact that it is indispensable to life on earth makes it a coveted resource more than any other.

With 70% of world consumption, agriculture is undoubtedly the most water consuming sector. Since the beginning of the 20^{th} century, the area of cultivated land, especially irrigated land, has increased significantly in response to population growth and food needs. Thus, world water consumption for agriculture increased six-fold between 1900 and 1975.

The amount of water mobilized for food production is mainly supplied by rainfall. In addition to rainfed irrigation, farmers are organizing their farm to improve their water management and production conditions. Already used by the Egyptian and Mesopotamian civilizations, these improvements make it possible to increase yields and increase the length of the agricultural season. Still very often traditional, the irrigation devices have a very low yield and require improvements. It is estimated that 30-60% of the water is wasted due to poor control of irrigation techniques and non-compliance with good irrigation practices.

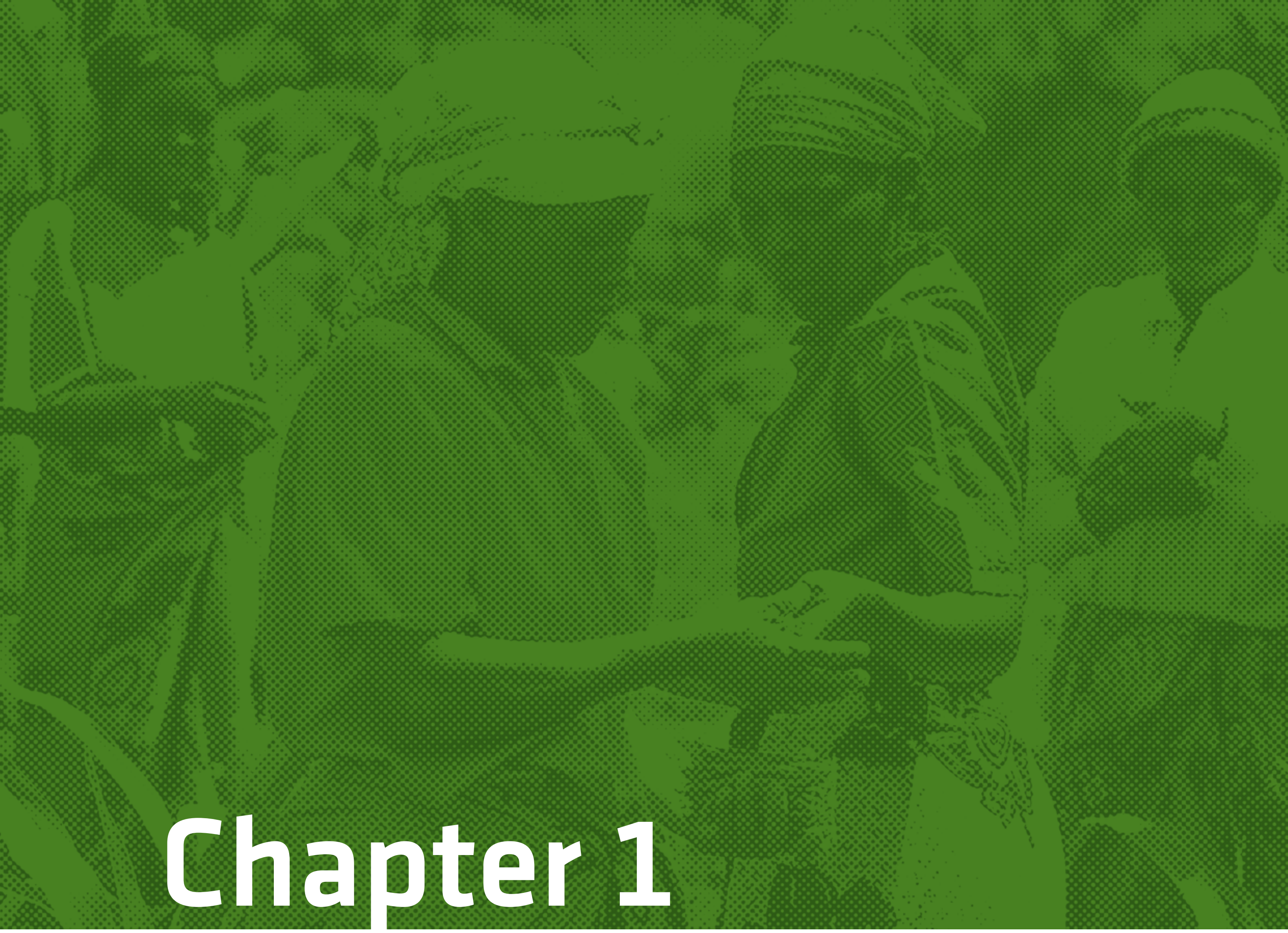
Even if multiple factors are to be taken into account, contemporary changes in agricultural production patterns have consequences for the natural water cycle, its quality and the balance of the resource. Rural land use and land-use processes influence the quantity and quality of water available in a catchment. The relationship between water and agriculture is therefore a major social challenge.

The objective of this manual is to provide responses to increase agricultural production, reduce the cost of inputs and increase resilience by improving the water management system. The first part of the manual presents all the theoretical and technical elements needed for sustainable water management: the importance of water for agriculture and the development of plants, both in quantity and quality, irrigation and its management principles, water in the post-harvest process, and finally all the legislative aspects related to its use.

The second part further illustrates the first and explains how a horticultural company, particularly in the countries in Africa, the Caribbean and the Pacific (ACP countries), can in practical terms implement a strategy for sustainable water management on its farm. This second part deals in detail with the following topics: water catchment, recovery, recycling, rational use, preservation of water quality, diverse types of irrigation, price of water, soil management to improve water retention, water-related risks, the water management plan and record keeping.

SUSTAINABLE WATER MANAGEMENT

PART I



Chapter 1

The context of water for horticulture

1.1. INTRODUCTION: AGRICULTURE, FOOD AND WATER

1.1.1. Agriculture

We all know that we need water to live. We use it daily at home to drink, to wash, to cook and to clean. Daily drinking water-requirements per person are 2-4 litres, but total water use for a household can vary between 47 litres/person/day in Africa, 95 l/person/day in Asia, 334 l/person/day in the UK and 578 litres/person/day in the USA.[1] Water is also needed to grow food; in fact most of the water we consume is embedded in the food we eat. For example, it takes between 1,000 to 3,000 litres of water to produce 1 kg of rice, and about 2,000 to 5,000 litres of water to produce the average daily food intake of one person. Agriculture is the largest consumer of freshwater, and accounts for 70% of the world's freshwater withdrawals from rivers, lakes and aquifers (and more than 90% in some developing countries), compared to 22% for the industrial sector, and 8% for the domestic sector.[2]

A summary of the most pressing global issues for agriculture are:

- **Growing demand for agricultural products:** World agriculture faces the enormous challenge in the coming years of producing almost 50% more food by 2030, and doubling production by 2050 (OECD, 2015), due to population growth and changing lifestyles.
- **Increased competition for land and water resources:** Other sectors of the economy, often with bigger economic returns, compete strongly with agriculture for access to water. This includes, for example, mining, tourism, and the energy sector. The latter can have a significant impact on food production in cases where country policies provide incentives for biofuels, increasing competition for both water and land.
- **Water scarcity:** Water is a finite resource. As competition for water increases, some parts of the world will become more water-scarce. Water scarcity poses a great challenge for the development of agriculture. UNESCO[3] foresees that, in 2030, 47% of the world population will be living in areas of high water stress. Most population growth will occur in developing countries (Figure 1), mainly in regions that are already experiencing water stress.
- **Climate change:** Agriculture both contributes to climate change and is affected by it. Climate change is significantly affecting water availability across the globe.
- **Degraded lands and ecosystems:** Soil and water require a minimum quality to provide suitable conditions for crop production. Due to water and soil pollution, agricultural water is often of poor quality, for example, when contaminated wastewater is used for irrigation. Degraded or saline soils also reduce agricultural productivity dramatically.

1 UNFPA, "Water: a critical resource", New York, 2002, lwvlaplata.org/files/unfpa_water_1_.pdf.

2 UNESCO, "World Water Assessment Program. Facts and figures", 2015, www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact2-agricultural-use.

3 *Ibid.*

- **Energy requirements:** Food production is not only water intensive, but also energy intensive. Energy is required for pumping, transporting and distributing water for irrigation, as well as for agricultural vehicles and machinery, and for processing. As energy prices increase, food prices are strongly affected.
- **Environmental impacts:** While increasing production to meet increasing demands, agriculture must also minimise any negative impacts on ecosystems and human health.

These global issues imply that agriculture needs to become much more resource efficient, particularly water efficient. This is relevant for all sectors of the economy, but especially for agriculture as the biggest water consumer globally.

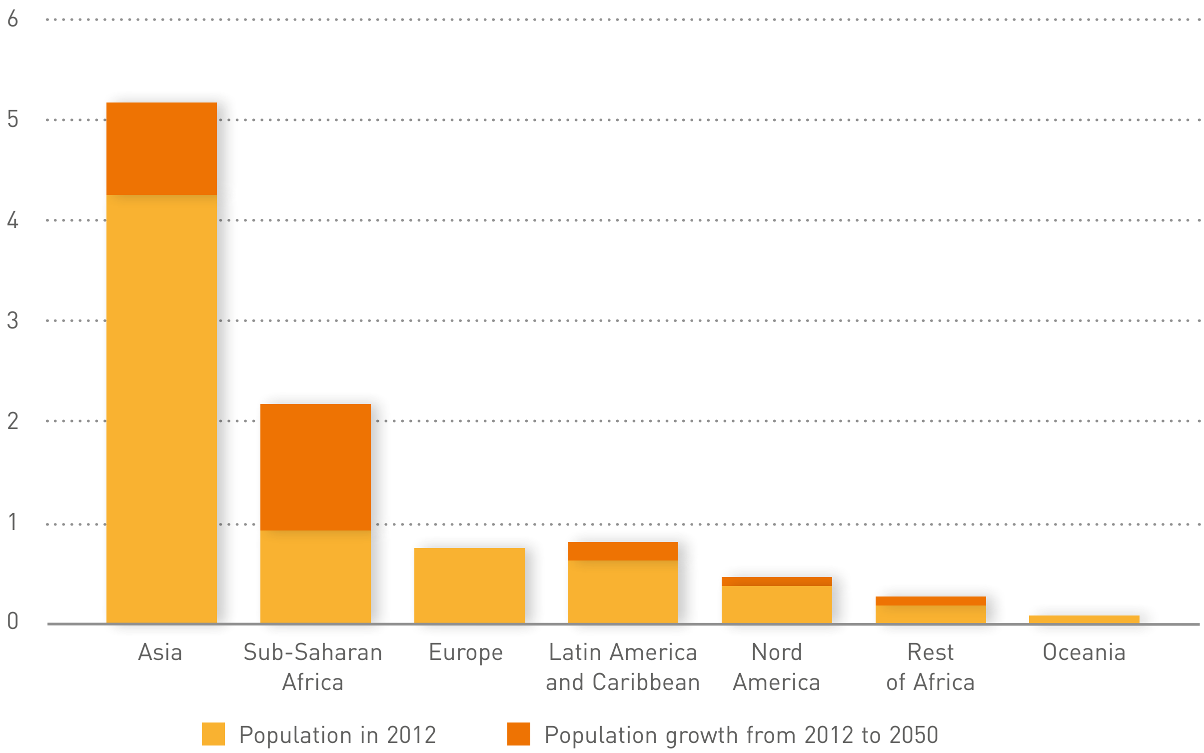


Figure 1 - Projected population growth (in billions).
Source: World Resources Institute[4] http://ow.ly/rpfMN

1.1.2. Food

Agriculture is defined by FAO as farming both animals (animal husbandry) and plants (agronomy, horticulture and forestry in part). It includes raising animals, and cultivation of plants (for food or medicinal purposes), fungi, fibre and bio-energy crops. Only a part of agriculture therefore involves food production. In the FAO policy brief on food security,[5] it is stated that "food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food

4 WRI, "The global food challenge explained in 18 graphics", 2015, www.wri.org/blog/2013/12/global-food-challenge-explained-18-graphics.

5 FAO, "Policy brief on Food Security", Iss. 2, Rome, June 2006, www.fao.org/forestry/13128-0e6f36f27e0091055bec28ebe830f46b3.pdf.

that meets their dietary needs and food preferences for an active and healthy life". FAO has published annual reports on the global state of food insecurity, where the goal was to evaluate progress in terms of the reduction of malnutrition, as well as achievement of the Millennium Development Goals with respect to hunger. In its 2015 report, FAO states that some 795 million people are undernourished globally, down 167 million over the last decade, and 216 million less than in 1990-92.[6] Some of its key findings are:

- **Economic growth is necessary** to sustain progress in efforts to reduce poverty, hunger and malnutrition, but alone is not sufficient.
- **Rural people make up a high percentage of the hungry and malnourished in developing countries.** Inclusive economic growth that provides opportunities for rural people is required in the fight against hunger and malnutrition.
- **Improving the productivity of resources held by family farmers and smallholders is an essential element** of inclusive growth and has broad implications for the rural economy. Well-functioning markets for food can help to integrate family farmers in the rural economy.
- **International trade**, in many cases, has an important potential to improve food security and nutrition by increasing food availability.

The global food security challenge is accentuated by a projected population growth from some 7 billion in 2012 to 9.6 billion in 2050, as well as by changing patterns of consumption. In particular, global per capita meat and milk consumption is growing (most notably in China and India) and is projected to remain high in the European Union, North America, Brazil, and Russia. These foods are very resource-intensive compared to plant-based diets. A shift in diet is one of the solutions proposed to tackle the food security challenge, together with a reduction in food waste, an increase in crop yields, improved land and water management, and an extension of agriculture into degraded lands.[7]

1.1.3. Water

Water is defined as a renewable resource since it circulates on the Earth's surface via the water cycle. Although renewable, it is a finite resource, which means that the amount of water on the planet is limited.

Freshwater is a vital productive factor for our economies and for all life, but is a resource that faces many current and future challenges. UNESCO[8] cites some important global facts and figures concerning water:

- By 2025, water withdrawals are predicted to increase by 50% in developing countries and by 18% in developed countries.

6 FAO, IFAD and WFP, "The State of Food Insecurity in the World, Meeting the 2015 international hunger targets: taking stock of uneven progress", Rome, FAO, 2015, www.fao.org/3/a-i4646e.pdf.

7 WRI, "The global food challenge explained in 18 graphics", *op. cit.*

8 UNESCO, "World Water Assessment Program. Facts and figures", *op. cit.*

- The world's seven billion people are using 54% of all accessible freshwater contained in rivers, lakes and groundwater. The volume of freshwater resources is around 35 million km^3, or some 2.5% of the total water volume on Earth (1.4 billion km^3).
- More than one in six people worldwide – 894 million – don't have access to the 20-50 litres of safe freshwater recommended by the UN per day per person for drinking, cooking and washing.
- Every day 2 million tons of human waste is discharged into water courses. In developing countries, 70% of industrial waste is dumped into waters where they pollute the usable water supply.
- On 28 July 2010, through Resolution 64/292, the United Nations General Assembly explicitly recognized the human right to water and sanitation.[9] It acknowledged that clean drinking water and sanitation are essential to the realization of all human rights. With this, all nations in the world acknowledged that water plays an essential role for all human societies.

Activities ranging from industrialization to tourism are expanding rapidly, all requiring increased water services. This is putting pressure on water resources and natural ecosystems[10] and leading to increased competition between water-using sectors.

Increasing agricultural output raises water consumption substantially, and can create competition between agribusiness and local communities. The Global Water Forum[11] reports that the growing use of water for export agriculture, for example, has affected ecosystems and local people, and accentuated water scarcity. That is the case for many developing and emergent economy countries. In these countries, there is an urgent need to better manage water, like the example of Lake Naivasha in Kenya shows. The area around the lake has become Kenya's most important horticultural region during the last three decades, with export cut flowers as the main economic activity of the region, using water from the lake for irrigation. At the same time, concern has grown mainly related to the decline of the lake's level and deterioration of water quality. The lake is also the primary source of potable water for a population of about 650.000 people.[12]

9 UN, Resol. 64/292, "The human right to water and sanitation", adopted by the UNGA, 28 July 2010, www.un.org/es/comun/docs/?symbol=a/res/64/292&lang=e.

10 WBCSD, "Facts and Trends of Water", 2006, www.unwater.org/downloads/Water_facts_and_trends.pdf.

11 Global Water Forum, Vos, J., Boelens, R. and Mena, P., "From local to virtual water control: The globalization of water insecurity and water access conflicts", 2014, www.globalwaterforum.org/2014/05/13/from-local-to-virtual-water-control-the-globalization-of-water-insecurity-and-water-access-conflicts.

12 Mekonnen, M., Hoekstra, A. and Becht, R., "Mitigating the Water Footprint of Export Cut Flowers from the Lake Naivasha Basin, Kenya", *Water Resources Management*, No. 26, 2012, pp. 3725-3742.

Figure 2 - Flower farms around Lake Naivasha, Kenya
Source: Green Farming[13]

Water pollution aggravates considerably the pressures on the water sector. According to UNEP,[14] while surface water quality has improved in the developed world in recent decades, in many other parts of the world, trends are going in the opposite direction. This increase in water pollution poses a risk to public health, food security and livelihoods. Water quality has become a global issue, but UNEP remains positive and acknowledges that there are feasible options for dealing with this challenge, such as wastewater treatment and new forms of water governance.

In summary, water, food and agriculture are sectors under pressure, as well as the energy sector. This pressure is likely to increase in the coming years (Figure 3). As these sectors are closely interrelated, promoting dialogue between them at both local and global levels will be vital to address the challenges they increasingly face.

13 Green Farming, "Green Farming's hydroponic system in Kenyan flower farm to save 60% irrigation water and to produce 10% more roses", 2012, www.dutchwatersector.com/news-events/news/4017-green-farming-s-hydroponic-system-in-kenyan-flower-farm-to-save-60-irrigation-water-and-to-produce-10-more-roses.html.

14 UNEP, "Science in UNEP: about the global water quality challenge", 2015, www.unep.org/science/chief-scientist/Activities/EcosystemsManagementandAgricultureEfficiency/GlobalWaterQualityChallenge.aspx.

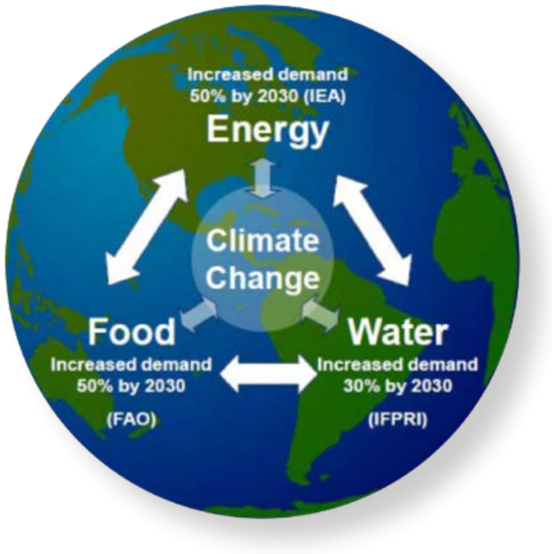


Figure 3 - Predicted water, food and energy needs for the year 2030
Source: Water Nexus Solutions, www.waternexussolutions.org/284

1.2. AGRICULTURE OF THE FUTURE

1.2.1. Principles

According to WRI[15], agriculture must perform a great balancing act in the coming years. It refers to achieving a sustainable food future and this will require meeting three needs simultaneously: closing the food gap to produce enough food for satisfying the needs of the population by 2050; supporting economic development; and reducing the environmental impact of agriculture. To achieve this balance, organizations such as UN DESA and FAO promote agricultural development that moves from being managed as an extractive industry to one that is more renewable. This is based on the following principles:

- **Inclusiveness:** Addressing issues facing medium and small-scale farmers and women farmers to ensure they are able to fully participate in agriculture and value chains
- **Climate-change resilience:** FAO proposed an approach to developing the technical, policy and investment conditions to achieve sustainable agricultural development for food security under climate change. This is not only with respect to climate resistant crop species, but also through application of the climate-smart agriculture (CSA) concept. It is composed of three main pillars:
  a. sustainably increasing agricultural productivity and incomes,
  b. adapting and building resilience to climate change,
  c. reducing and/or removing greenhouse gases emissions, where possible.[16]

15 WRI, "The global food challenge explained in 18 graphics", *op. cit.*
16 FAO, "Climate-smart agriculture source-book", 2013, www.fao.org/docrep/018/i3325e/i3325e.pdf

- **Increased water efficiency:** agricultural practices should be adapted towards increasing crop and water productivity. That means producing more food per drop of water. This requires the adoption of improved crop and soil management practices such as organic matter management for improving soil structure or soil coverage for reducing evaporation, in order to reduce irrigation requirements (these will be carefully explained in later chapters). Improving irrigation techniques is also an option to increase water efficiency, for example by using precision irrigation or deficit irrigation.
- **Pursue high yields through healthy agro-ecological systems** (UN DESA, 2015) specify investing in water-conscious agricultural systems to restore healthy soils, conserve natural habitats, and rehabilitate agricultural and pastoral habitats that have been degraded. Increased attention needs to be put to environmental impacts produced by fertilizer and pesticide use, which can be reduced by adopting integrated fertilizer and pesticide management practices. Technology also offers an option for optimisation of fertilizer and pesticide use, for example through precision farming, which tailors inputs according to crop needs, site and soil conditions (HGCA, 2002).[17] The challenge is to transfer this knowledge and technology to developing countries and take to scale.
- **Embed agricultural water management** into Integrated Water Resource Management (IWRM): IWRM is based on the principle that water is an integral part of the ecosystem, a natural resource, and a social and economic good which has to be protected. The integration of land and water-related management should be carried out at the level of the basin or sub-basin. Farmers and other stakeholders need to engage and cooperate at the geographical level of basin or sub-basin in order to manage water quantity and quality risks and to jointly develop strategies for developing and using water in a way that satisfies basic needs and safeguards ecosystems.[18] The ultimate goal of IWRM is the involvement of different institutions and policy measures into an integrated water management system.[19] **This can only** happen with adequate public policy support.

1.3. THE ROLE OF AGRICULTURAL PRACTICES

1.3.1. Impact

Agricultural practices can strongly impact efficiency in the use of resources such as water, land and other farm inputs. Before exploring technological options such as new irrigation techniques, it is worth reviewing agricultural practices in light of increasing resource efficiency. For this purpose, the farmer needs to have

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17 HGCA, *Home-grown cereals authority. Precision farming of cereals. Practical guidelines and crop nutrition*, London, 2002.

18 Ministry of Agriculture, Nature and Food Quality, *IWRM: for sustainable use of water. 50 years of international experience with the concept of integrated water management*, Wageningen, 2004.

19 OECD, "Sustainable Management of water resources in agriculture", 2010, www.oecd.org/tad/sustainable-agriculture/49040929.pdf.

an integrated overview of his/her farm and surroundings, taking into account location, climate, soil, crop, water quantity and water quality needs and availability, as well as fertiliser and pesticide needs.

A good knowledge of these issues will allow the farmer to plan and implement agricultural practices that are financially and operationally feasible and that will increase efficiency and profitability. These practices are described throughout this manual.

1.4. THE ROLE OF IRRIGATION

1.4.1. Scope

Crops need water to survive and grow, and this can either be received naturally (rain fed agriculture), or can be provided by human intervention (irrigated agriculture). Of the estimated 1.4 billion hectares of cropland worldwide, around 80% is rain fed and is responsible for some 60% of crop production. Irrigated agriculture covers the remaining 20% of cultivated land - around 280 million hectares –and accounts for 40% of global food production.[20] Higher cropping intensities and higher average yields account for the increased levels of productivity in irrigated agriculture. According to IFAD, irrigation multiplies yields of most crops by 2 to 5 times. Additionally, irrigation allows diversification into higher value, high input crops, where a reliable and flexible supply of water is vital.

FAO *et al.*[21] make a strong argument for irrigation as a central element in efforts to achieve food security. However, they also warn of two common undesirable side effects of irrigation projects. Results from a worldwide irrigation review show that:

1. They often tend to favour wealthier farmers, and are not inclusive of the poor. This happens because overall implementation, operation and maintenance costs increase with the irrigation project, and investments required are not affordable by the poor. This is contrary to the recommendations made by FAO itself on how best to tackle undernourishment and food insecurity globally. Including the poor in irrigation projects is described as a prerequisite to reinforce rural economies, increase access to food, and therefore reduce poverty and malnourishment.
2. Irrigation schemes sometimes upset the balance of local conditions, rights and customs, and devalue the environmental and agricultural knowledge and expertise that farmers have built up over generations.

Many global organizations work towards creating awareness of these issues and developing tools to support establishment of new irrigation projects that truly support

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20 FAO, "Save and Grow toolkit. A policymaker's guide to the sustainable intensification of small-holder crop production", 2011, www.fao.org/ag/save-and-grow.

21 FAO, IFAD and WFP, "The State of Food Insecurity in the World, Meeting the 2015 international hunger targets: taking stock of uneven progress", *op. cit.*

poverty reduction.[22] [23] [24] Small irrigation systems, in combination with ecological management of soil, organic matter and water, can play a key role to prevent the two issues mentioned above.

Irrigation can play a very important role towards achieving more resilient, efficient, and productive agricultural systems. The key is to develop irrigation systems within the framework of a sustainable management approach that takes into account the principles of 'Agriculture of the Future' described above; the global context described, and local realities and policies.

1.5. CONSIDERATIONS FOR HORTICULTURE

1.5.1. Global context

The general issues described for the entire sector of agriculture are also valid for the horticulture sector, but can be even more challenging in the case of high value, resource intensive crops that require consistent supplies of quality water during production, post-harvest and processing. The horticultural sector must address the risks and challenges associated with the efficient management and use of water, particularly in water sensitive zones. As an industry this means engaging in water management and policy both on farm, and beyond the farm gate at the community and basin or sub-basin level.

In the global context, the horticulture sector can play an important role with respect to the global food-water challenges:

- Vegetables and fruit are an important component of the human diet, in addition to cereals and other crops.
- The current global tendency towards increased meat consumption is a concern as livestock rearing has a very large water footprint compared to cereals or vegetables. A reliance on meat will thus not be sustainable (Hoekstra, 2013) in a resource-constrained world. With the future pressure to produce more food with less water, vegetables as a source of protein will become more relevant.
- The economic potential of fruit and vegetables per unit of land is generally higher than that for cereals or other crops. Economic returns in relation to water use (monetary units per cubic meter of water) from this sector are therefore high on average (Aldaya *et al.*, 2010).[25] Development of the sector can play an important role towards meeting the goals of poverty alleviation and food security, but this should be done through responsible water management, and in line with the principles of the agriculture of the future, as discussed above.

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22 FAO, "Economic and social development department. Water and people. Whose right is it?", 2015, www.fao.org/docrep/005/y4555e/y4555e00.htm.

23 WRI, "The global food challenge explained in 18 graphics", *op. cit.*

24 UNESCO, "World Water Assessment Program. Facts and figures", *op. cit.*

25 Aldaya, M. García-Novo, F. and Llamas, M.R., "Incorporating the water Footprint and environmental Water requirements into Policy: reflections from the Doñana region (Spain)", Papeles Agua Virtual, Observatorio del agua, Fundacion Marcelo Botin, Madrid, 2010, www.huellahidrica.org/Reports/Aldaya-et-al-2010-Donana.pdf.

The horticultural sector also faces many challenges, as described in previous sections. The African Farming Platform (African Farming, 2010) describes some specific challenges for horticulture in the African context: higher power costs, rising fuel prices, cost of inputs, foreign currency exchange rates, high transportation cost and poor infrastructure such as roads, higher water risks, obsolete technology and stringent international standards. Both the benefits and challenges of horticulture show that there is a true business opportunity in developing the sector while striving for resource efficiency and minimising impacts on the environment.

1.6. THIS MANUAL

1.6.1. Summary

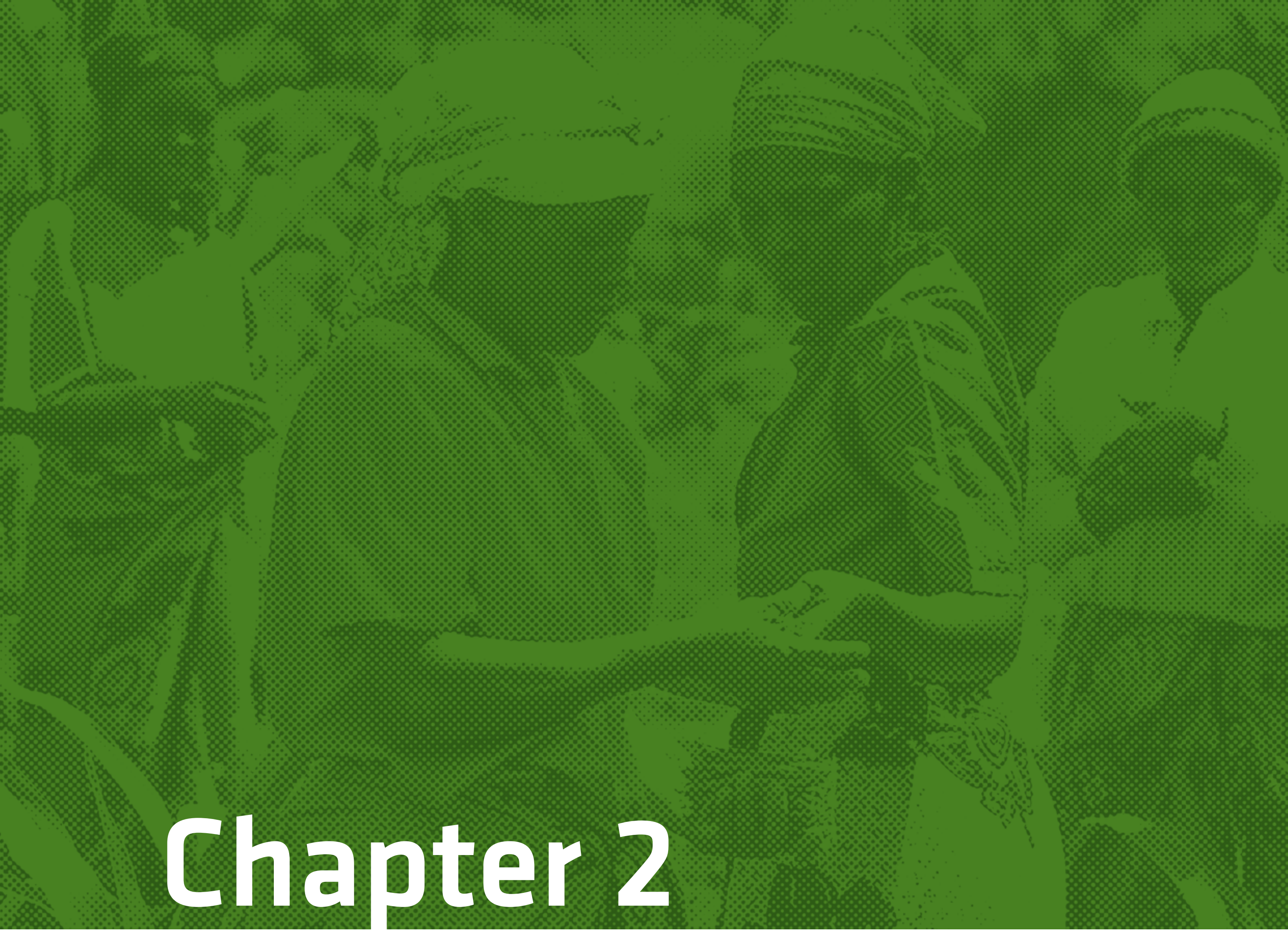
This manual is based on two underlying objectives:

1. to increase the availability of high quality and safe horticultural produce by supporting the development of improved crop management practices for sustainable and environmentally friendly horticultural crop production systems,
2. to support the transition from subsistence farming to income-generating agriculture by adding value to products through the more efficient, responsible and sustainable use and management of water.

The subsequent Chapters in this manual give a broad overview of the issues, and the current understanding of how these objectives can be achieved in the context of horticulture in Africa-Caribbean-Pacific countries. It targets service providers that support small and medium-scale horticultural enterprises whose activities cover both production and post-harvest. It covers basic background information on water management and irrigation in horticulture. We expect that with this manual, service providers will have the information needed to engage in water management, and to guide farmers in making decisions that fit the local productive and economic realities, with a general understanding of the most pressing global issues related to water and agriculture.

Chapters 2 and 3 introduce the theory of water as a dynamic resource, moving in space and time and through soil and plants. Chapter 4 introduces water quality in relation to agriculture. Chapters 5 and 6 present a broad outline on irrigation. The theory of irrigation systems is introduced, including engineering aspects (Chapter 5), followed by an introduction to irrigation management taking into account local considerations (such as legislation) as well as global issues (Chapter 6). Chapter 7 looks at water use in agriculture for post-harvest processing and washing. Chapter 8 considers water rights and legislation. Finally, a case-study is presented in Chapter 9.

We hope you enjoy the reading and wish you many new learning experiences!



Chapter 2

Foundations of the global water system

2.1. HYDROLOGICAL CYCLE

2.1.1. Water distribution on Earth

Water is the most important resource for life on Earth. Its molecule is composed of one oxygen and two hydrogen atoms connected by covalent bonds (Figure 1). In standard circumstances of pressure and temperature (1 bar at 20 °C.) water behaves as a liquid, but it can also be found on earth in solid and gaseous states. As a liquid, it is odourless, tasteless and transparent.

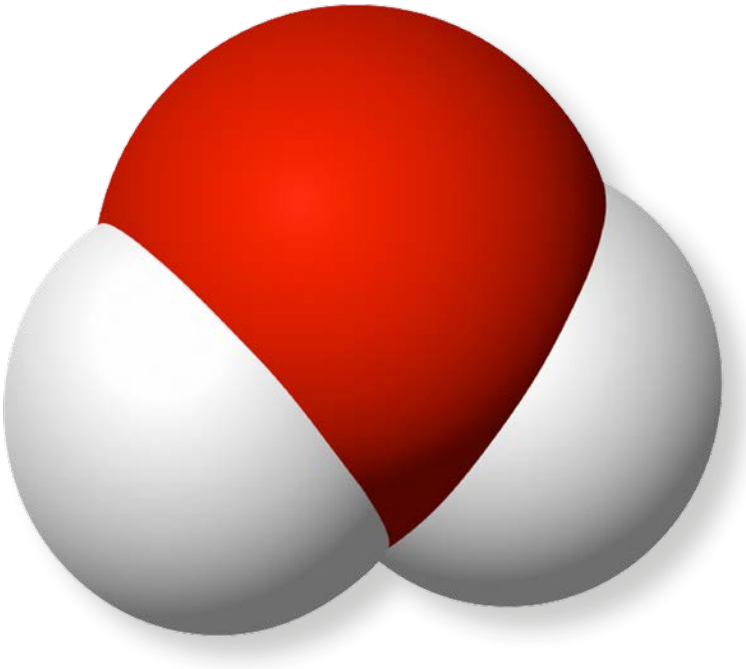


Figure 1 - Water molecule H_2O comprising two Hydrogen (depicted in white) and 1 Oxygen (depicted in red) atoms
Source: All-water.org[26]

The amount of water on Earth is approximately 1.386 million of km^3. Around 97% of this is saline water, contained in oceans. Only around 3% (about 35 million km^3) is freshwater, and not all of this freshwater is available for human consumption. About two thirds of the freshwater water is stored in icecaps and glaciers. The rest is stored in groundwater aquifers and surface water units, such as lakes, rivers and swamps. Less than 1% of total global water resources are directly available for human use (see Figure 2).

26 www.all-water.org/Chemistry.html.

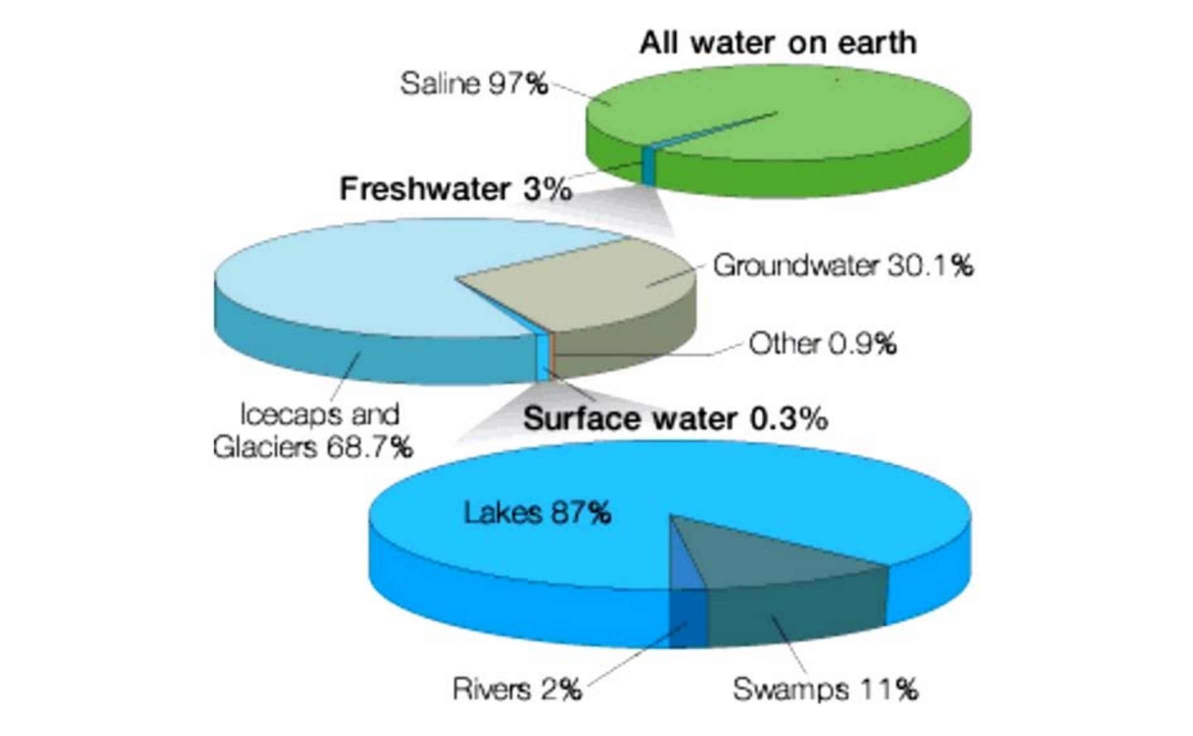


Figure 2 - Water directly available for human use in relation with total water on Earth
Source: pacificwater.org

The "less than 1%" of directly usable water is not evenly distributed across the globe. Today almost one third of the world's water resources are located in South America. Africa and Europe on the other hand, barely have 15% of the total available water resources (Figure 3).

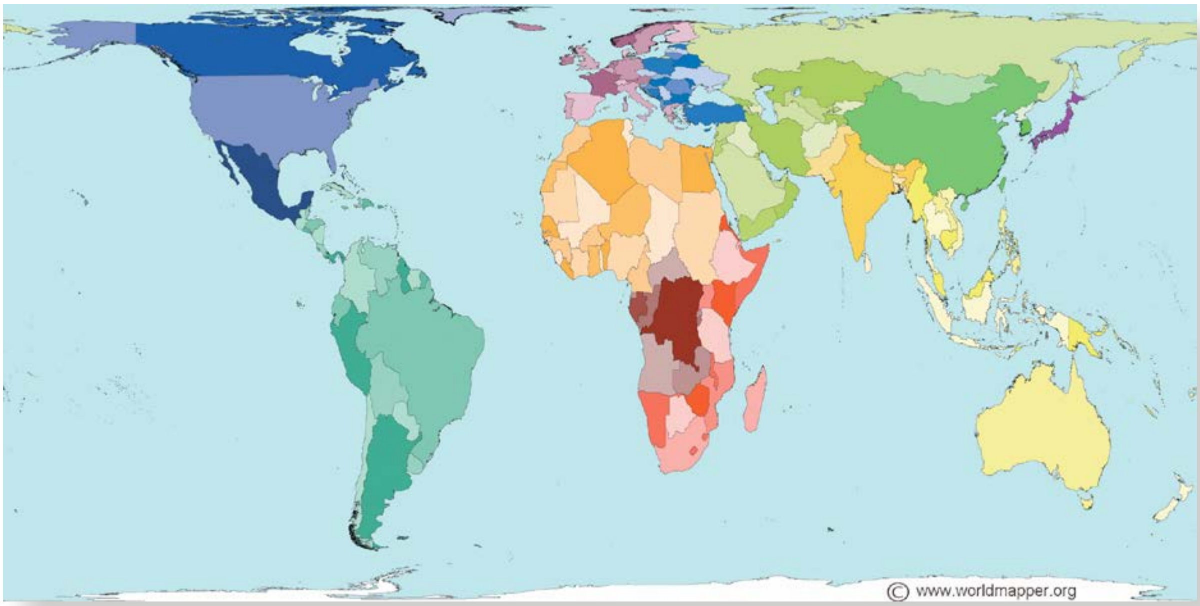


Figure 3 - Freshwater distribution on Earth depicted through territory size, showing the proportion of all-worldwide freshwater resources found there
Source: worldmapper.org

Water on Earth is highly dynamic. As a result of changing temperature and pressure in the Earth's environment, water changes state from gas to liquid to ice and vice versa. The diagram in figure 2.4 shows the phases of water at varying pressures and temperatures. At 1 bar (100 kPa) of pressure (atmospheric pressure) and 100 °C, liquid water changes into water vapour. At 1 bar and 0 °C, liquid (pure) water turns into ice. Water mobility is affected by its phase: ice is less mobile than liquid water; and liquid water is less mobile than water vapour. Earth's features such as gravity, topography, climatic zones, wind, temperature and pressure variability, not only make water change phase but also make it move across Earth in the different phases. This continuous change of phase of water, combined with its movement around the Earth is called the hydrological cycle.

2.1.2. Water vapour

To describe the hydrological cycle, we begin at the ocean. The sun heats the ocean surface. When the ocean surface tension is broken by wind, water evaporates. The water vapour is warmer than the ambient air above the ocean. As a result, the air containing water vapour rises. As it rises, air temperature and pressure become lower, so that the air becomes saturated. As a result of saturation, water vapour condensates into small droplets. Many of these small droplets together form clouds.

The oceans are not the only sources of water vapour; inland water bodies, evaporation directly from the soil, and plant transpiration, are also sources. Vapour can also be produced directly from ice through the process of sublimation.

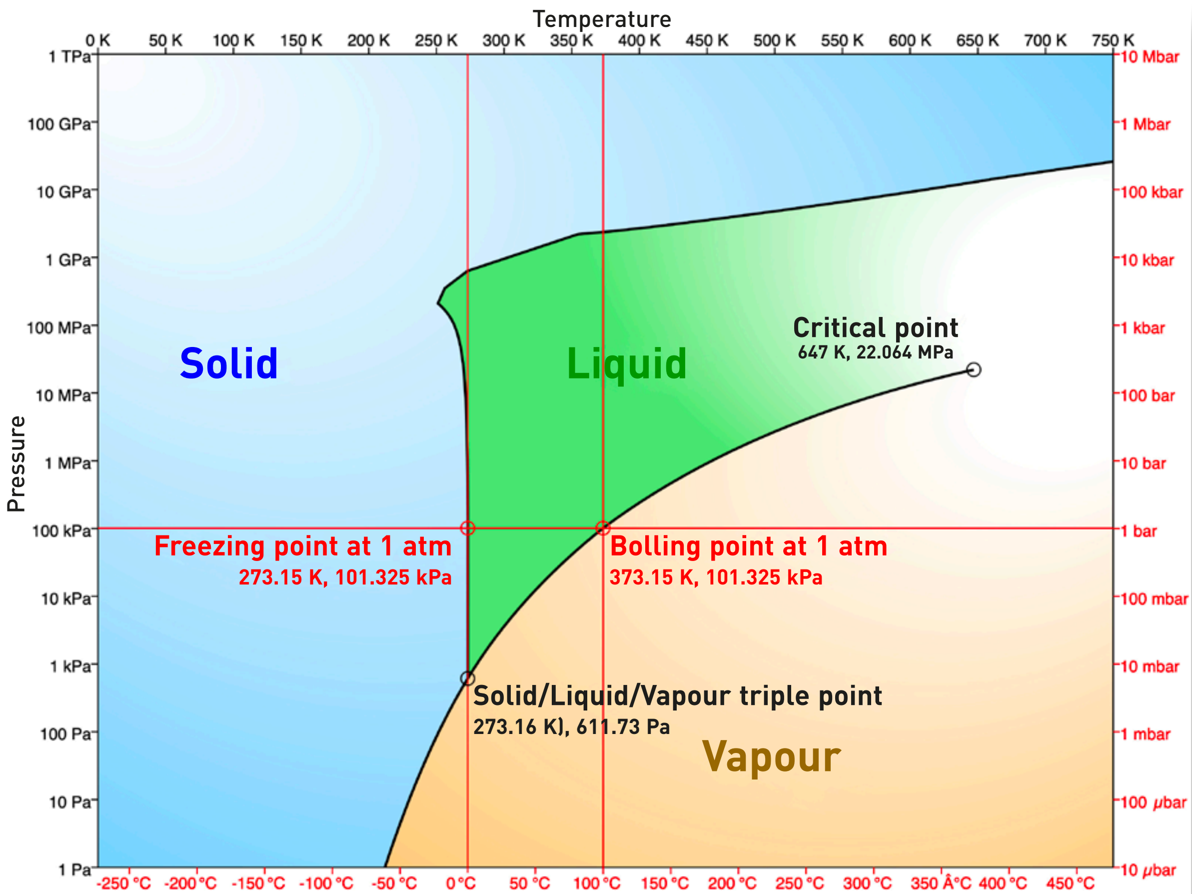


Figure 4 - Phase diagram of water. Source: Water structure and science, 2015

Clouds can be located at different heights depending on temperature and pressure. Air currents make clouds move across the globe. Clouds can travel long distances until the conditions are such that the small water droplets join together. Gravity makes the heavier droplets fall down as precipitation, which can be in the form of liquid rain, or solid as snow or ice. Through the process of precipitation, the water that left as vapour comes back to the Earth's surface. In the case of snow or ice, it can accumulate in ice caps or glaciers and remain there for thousands of years before it melts.

2.1.3. Groundwater

Water that has fallen as rain onto the Earth's surface flows as a result of gravity. It can flow in several directions depending on the physical characteristics of the soil, geomorphology and geology. Water can flow across the ground as surface runoff to enter streams and rivers, to lakes and other inland freshwater bodies, and back to the ocean. Water that does not run off can evaporate from the soil, or can infiltrate into the soil, where it can be used by vegetation in the process of transpiration. Water may also seep deeper into the ground to become groundwater.

Some groundwater bodies can store massive volumes of water for long periods of time. An example of this is the recently discovered aquifer in Turkana in Northern Kenya that is reported to hold sufficient water to supply the country for 70 years.[27] Water stored in aquifers may flow, but generally with very low flow rates. A flow of 30 cm per day is considered a high flow rate.[28] Groundwater flow can also re-appear at the surface, as freshwater springs. It can also flow beneath the soil surface to rivers, inland water bodies, or to the ocean. And with this, the whole water cycle can start again.[29] Figure 5 illustrates the complete hydrologic cycle.

27 BBC news, "Kenya aquifers discovered in dry Turkana region", 2013, www.bbc.com/news/science-environment-24049800

28 USGS, "General facts and concepts about ground water", 2013, pubs.usgs.gov/circ/circ1186/html/gen_facts.html.

29 USGS, "Summary of the Water Cycle", 2015, water.usgs.gov/edu/watercyclesummary.html.

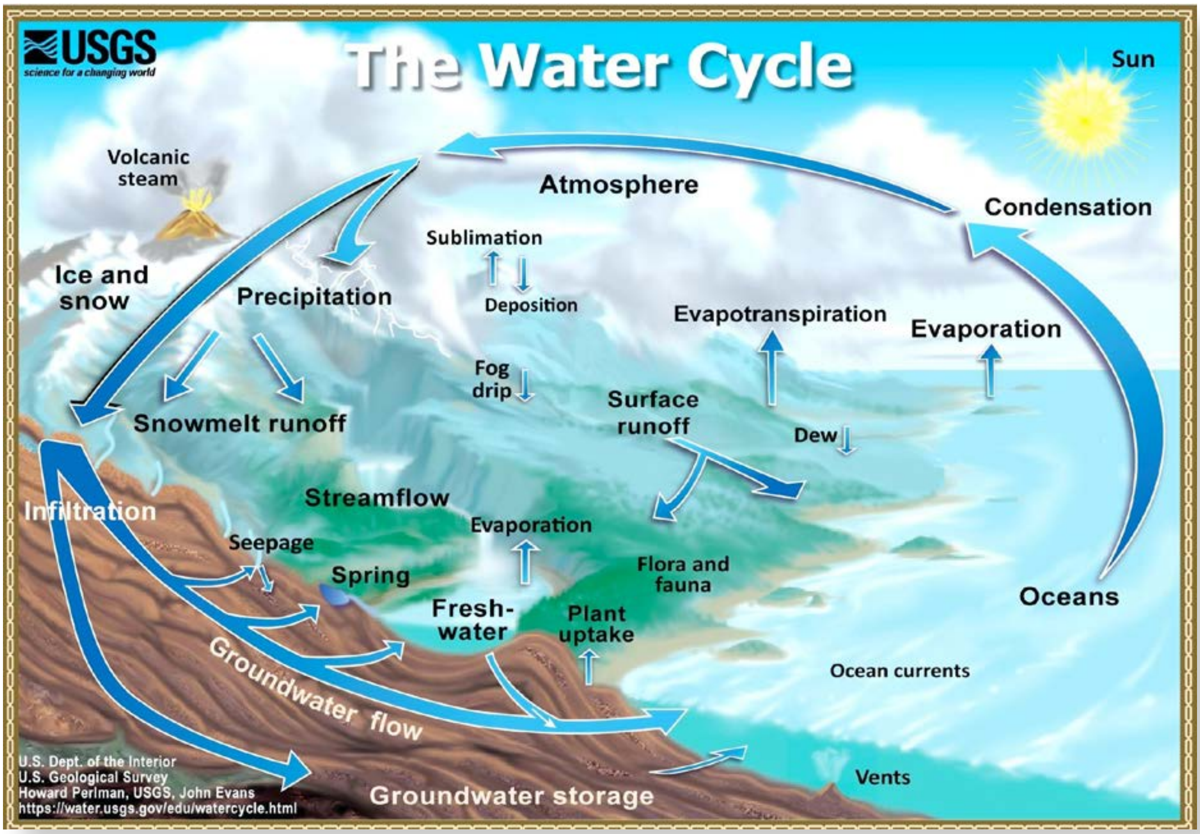


Figure 5 - The water cycle
Source: USGS

2.1.4. Water cycle

However, the water cycle is much more complex than the simple description given above. Recent research shows that precipitation over land in one part of the globe is highly dependent on evaporation of water from land in other regions. Moisture generated from land evaporation is an important contributor to rainfall. The average terrestrial rainfall coming from land evaporation is around 40%; and around 57% of terrestrial evaporation returns as rainfall over land.[30] Also, the water cycle connects different parts of the world that are vast distances apart. In the Río de la Plata for example, 70% of rainfall comes from moisture that originated in the Amazon rainforest. In Congo, most water has its origin in the eastern region of the Great Lakes.

Evaporation from land and plants is also very variable. Some plants and crops (e.g. maize or sugar cane) evaporate more water than others.

These facts illustrate three important points:

1. there is a close relationship between evaporation from land and rainfall;
2. the water cycle operates across vast distances;
3. there is a relationship between evaporation, humidity and plant production and health.

30 Van der Ent *et al.*, "Land use change influences continental water cycle", Delft University, 2013, tudelft.nl/en/current/latest-news/article/detail/ontbossing-beinvloedt-waterhuishouding-continenten.

This means that human activity and land use in one locality has a big impact on the conditions and water availability for agriculture, energy, livestock, industry and households in other locations.

2.2. HYDROLOGICAL UNITS, CATCHMENTS AND AQUIFERS

2.2.1. Hydrological units

As we all know, it is a basic fact that water flows by gravity to the lowest point of any surface. In a landscape this process of 'flowing to the lowest point' creates streams. The water in the streams originates from higher altitude areas. The whole area that feeds water to a river is called a surface drainage area or drainage basin. In a drainage basin, small streams join together to create bigger streams. These in turn join together to become rivers. The network of streams formed by the converging smaller tributaries finally flows into an estuary, a lake, the sea, or sometimes into underground water.

Hydrologists and hydro-geographers study and explain the movement and distribution of water in geographical units of varying scales. This is called a hydrological unit. A hydrological unit can be a geographical area representing part or all of a surface drainage basin, or a distinct hydrological feature such as a reservoir, lake, groundwater aquifer or artesian well (NOAA, 2015). We will come back to this in Chapter 5.

2.2.2. Water catchment

Water experts use varying terms to describe drainage basins. **The terms 'drainage basin', 'watershed', 'catchment' and 'river basin' are used interchangeably,** but generally are defined by scale. As a rule, basins are bigger than catchments, and catchments are bigger than watersheds. However, all of these hydrologic units are defined as a **geographically delimited area from which water from different sources drains toward a common watercourse or outlet point.**[31] The nature and shape of catchments is determined by the topography, geology, and water. A catchment that ends in the sea is known as an 'exoreic catchment'. If the river flow from a catchment ends into an inland water body, like a lake, it is called an 'endorheic catchment'.

31 NOAA, "Glossary of Hydrologic Terms", 2015, www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm.

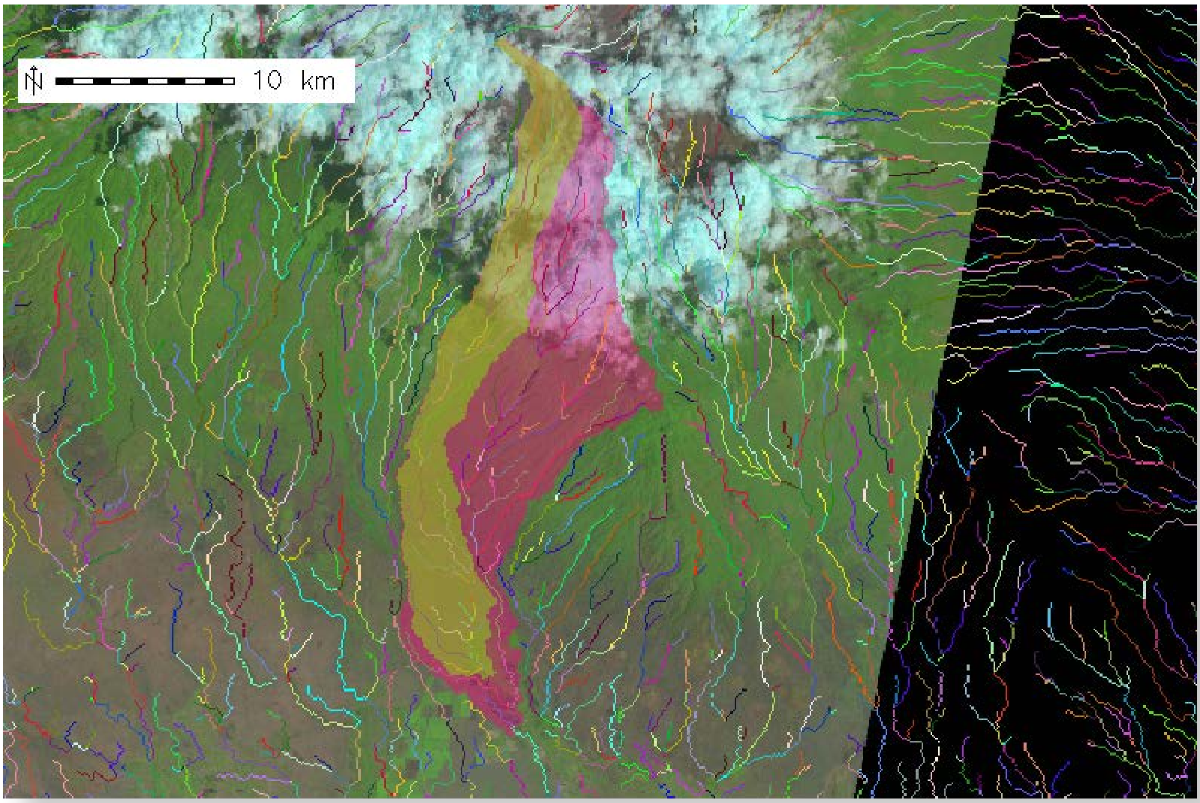


Figure 6 - Example of watershed based on a Digital Elevation model. Rau watershed, Moshi, Tanzania
Source: Good Stuff International

A catchment is always delimited by a drainage divider. This is an imaginary line that divides one catchment from its neighbouring catchments. Drainage dividers are the highest ridges, hills or mountains surrounding streams (Figure 6). A catchment has specific climatic, geological, soil, ecosystem and river characteristics. These characteristics in turn shape the (agricultural) production system, trade routes, and sometimes communities and cultures. Catchments played an important role in shaping ancient civilizations as in the case of the Yellow River in China, or the Tigris and Euphrates in the Middle East.

2.2.3. Aquifers

Water not only runs off from the surface, it also infiltrates into the ground and the rocks below. This process creates a hydrologic unit called a groundwater aquifer. An aquifer is an underground water body located in a water-bearing rock; these rocks have permeable structures that can hold or let liquids and gases pass through. Examples of these rock types are sedimentary rocks such as sandstones and gravels. Aquifers are often named according to the way they have been formed. An alluvial aquifer refers to an aquifer layer that is deposited by a river whereas a glacial drift aquifer refers to aquifers deposited by glacial action. An aquifer is filled with water by infiltration and permeation of rainfall, melted snow or ice that seeps into the ground and rock until it meets a less permeable rock type. Aquifers are the reservoirs for groundwater and as such they may store water for long periods of time, thousands and even millions of years.

Two different types of aquifer can be found:

- An **unconfined aquifer** is covered by permeable rock and can receive water from the earth surface. The highest water level in an unconfined aquifer is known as the water table or phreatic surface. The water table can rise or fall depending on the volume of water that enters or leaves the aquifer.
- A **confined aquifer** is an underground water body that lies between two layers of less permeable rocks. Water flows inside the confined aquifer through cracks in the layer of less permeable rock that is closer to a nearby water source, like an underground river or lake, or a nearby-unconfined aquifer. A special type of confined aquifer is the **artesian aquifer**. This is an aquifer that is under positive hydrostatic pressure as result of the non-permeable layer on top. If a well is drilled into the artesian aquifer, the pressure makes water flow upward to the Earth's surface (Figure 7).

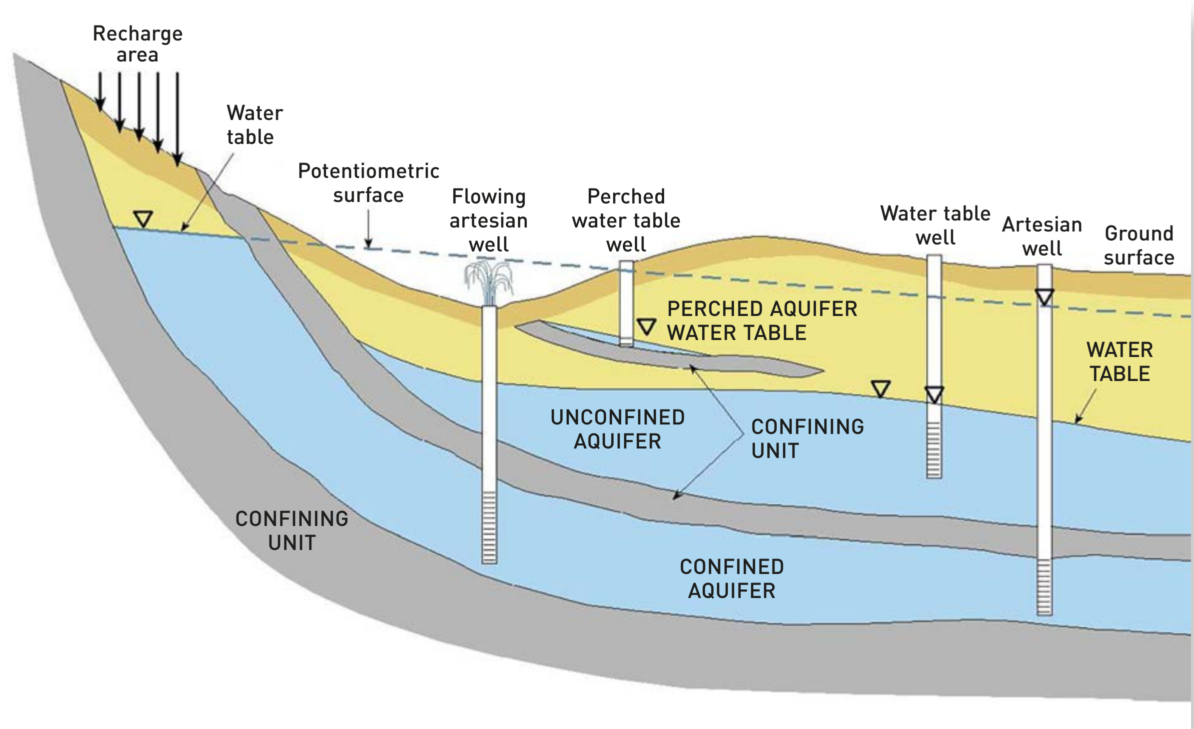


Figure 7 - Different types of aquifers
Source: Colorado Geological Society, 2015

Generally, aquifers are naturally recharged with water coming from surface water bodies, rain or melted ice or snow by the process of deep percolation. Water from aquifers can flow out in different ways. Water can flow from springs in a natural way and thus adding to surface water resources. It can also be extracted artificially by creating wells or boreholes to pump water for domestic, agriculture, or industrial uses. Human actions can change the recharge process. If more surface water is used for human activities, less water will be available to infiltrate, percolate and recharge groundwater aquifers. As a result, the groundwater levels may go down. If at the same time groundwater is extracted, this leads to a decline in the level of the groundwater table. For example, in India, 60% of irrigated farming depends on groundwater. A recent study shows that as a result, in Tamil Nadu, some 90% of open wells in the State have fallen dry.[32]

- For the sustainable management of groundwater, balancing extraction with groundwater recharge is essential. As a rule in good groundwater management, the volume of water abstracted from an aquifer should always be less than or at least equal to the volume that is recharged.
- Additionally, groundwater increasingly suffers from water quality issues. Groundwater can be polluted if water containing biological or chemical contaminants infiltrates into the aquifer. Also, a groundwater aquifer that is over-used can become saline as a result of salt-water intrusion. Groundwater management therefore involves taking care of not only water quantity but also water quality issues.[33]

2.3. WATER BALANCE OF A CATCHMENT

The basic method of understanding the water situation in any catchment is to produce a water balance. This is based on the principles of mass conservation, in this case for water. A water balance for a system (= catchment) over a given time period takes into account what enters the system, what leaves the system, plus any changes in water accumulation. An example of positive water accumulation for a catchment in a certain period of time can be an overall increase in soil moisture or in groundwater levels. A negative change in accumulation can be a decrease in groundwater levels. The concept of water balance provides an understanding of the hydrological behaviour of a catchment.

A simple equation[34] to describe the water balance of a catchment is:

$$P = ET + R + D + \Delta S \qquad \text{Equation 1}$$

where P is precipitation, ET is Evapotranspiration, R is surface Runoff, D is recharge to groundwater and ΔS is the change in soil water storage, or water stocks.

32 National Geographic, "India's Food Security Threatened by Groundwater Depletion", 2015, voices.nationalgeographic.com/2015/02/03/indias-food-security-threatened-by-groundwater-depletion.

33 *Ibid.*

34 Zhang, L., Dawes, W.R. and Walker, G.R., "Predicting the effect of vegetation changes on catchment average water balance", 1999, catalogue.nla.gov.au/Record/408538.

2.3.1. Green and blue water

The distinction between green and blue water was introduced in the 90's by Falkenmark[35] when trying to demonstrate the value of water stored in the soil as soil moisture, available for agriculture without additional engineering (irrigation).

Green water is the precipitation that falls on land but does not run off or recharge the groundwater, but instead is stored in the soil, or temporarily stays on top of the soil or vegetation.[36] Eventually, this portion of precipitation will evaporate or transpire through plants. Non-irrigated, rainfed agriculture only consumes green water, in other words, using only soil moisture derived directly from rain.

Blue water is the water that runs off towards streams and rivers, as well as water that infiltrates and percolates into groundwater aquifers. Blue water thus includes surface water (rivers and streams) and groundwater (aquifers). Using a variety of infrastructure, blue water is used by people on a large scale to satisfy our needs.

Irrigated agriculture may use both green and blue water if the crop uses soil moisture from rain and irrigation water from surface and/or groundwater sources. The need for blue water consumption (irrigation) mostly depends on the local climatic conditions.

In many cases, for example in protected systems in Israel, **grey water** is also used for irrigation. Grey water is the result of capture, recycling and reuse of green or blue water that has already been used for different purposes. Recycling and reuse of water is further addressed.

The water balance for a catchment (equation 1) is expressed in units of volume such as cubic meters (m^3) or million cubic meters (Mm^3). When possible, it should also differentiate between blue and green water.

An example of a water balance is shown in Table 1 for the Guadalquivir river basin in Spain. For the year 2003, from the 32 billion cubic meters of precipitation in this catchment, 90% returned to the atmosphere in the form of evapotranspiration (28.7 billion cubic meters), from both green and blue water. However, the blue water contribution to evapotranspiration (ET) is significantly smaller (2.8 billion cubic meters; about 9%) than the green water contribution (26 billion cubic meters, 81%). This illustrates the importance of green water.

35 Falkenmark, M. and Rockström, J., "The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management", 2006, appgeodb.nancy.inra.fr/biljou/pdf/falkenmark-and-rockstrom.pdf.

36 WFN, "Glossary of terms", 2015, waterfootprint.org/en/water-footprint/glossary.

Table 1. Example of water balance of Guadalquivir river basin, Spain. Assumptions: ΔS = 0, Losses to deep percolation are minimal. Base year is 2003[37]

		Mm³	
P	**Precipitation**		**32,042**
ET (green)	**Total Green ET**		**25,955**
	Non-irrigated agriculture	3,690	
	Irrigated agriculture	1,190	
	Pastures	1,930	
	Forests	19,145	
ET (blue)	**Blue ET Surface water**		**1,981**
	Blue ET Groundwater		**770**
	Agriculture	2,290	
	Domestic	96	
	Industry, Energy	50	
	Reservoirs	315	
ET (total)	**Total Green + Blue ET**		**28,706**
R	**Runoff**		**3,337**
D	**Recharge to groundwater**		**770**
ΔS	**Soil water storage**		**0**

2.3.2. Environmental flow requirements

"(Blue) Environmental Flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). This definition is part of the Brisbane declaration, which highlights the fact that freshwater ecosystems are seriously impaired, and continue to degrade at alarming rates. In order to address this degradation, and to maintain rivers as well as the productivity and biodiversity of their ecosystems, the declaration commits to the establishment of environmental flows for all rivers globally, and to working on its inclusion into water management frameworks and approaches.

Blue water environmental flow requirements play an essential role in the generation and maintenance of a wide variety of ecologically important natural habitats. For example, in the Doñana national park in Southern Spain, there is a direct relationship between the depth of the groundwater table and the type of vegetation.[38] It also shows the need to manage water and land, and in this the case water management authorities have a key role in water allocation.

37 Aldaya, M.M., Garrido, A., Llamas, M.R., Varelo-Ortega, C., Novo, P., and Casado, R.R., "Water footprint and virtual water trade in Spain", in *Water policy in Spain* (A. Garrido and M.R. Llamas eds), Leiden, CRC Press, 2010, pp. 49-59.

38 *Ibid.*

The science of environmental flow assessment is still relatively young, with methodologies ranging from very simplistic hydrologic approaches to highly sophisticated holistic approaches. Generally the water management authority sets the environmental flow requirements as part of its water management mandate. They can thus not be seen as separate from integrated water resource management (IWRM). In the Guadalquivir example of Table 1, the environmental flow is accounted for within the Runoff values. The environmental flow requirement is allocated by the Guadalquivir water management authority to maintain the ´good environmental status´ that is required by the European water policy, the Water Framework Directive.[39]

In the case of green water, **the environmental green water requirement is defined as** *"the quantity of green water from lands that need to be reserved for nature and biodiversity preservation and for human livelihoods that depend on the ecosystems in the natural areas"* (Water Footprint Network, 2015).[40] The environmental green water requirement is also part of the IWRM framework, although in a slightly different manner. The green environmental requirement instead of a water allocation issue, is more of a land allocation issue that goes beyond the water management authority. To ensure green water for the environment, a sufficient amount of land in the catchment needs to be reserved for natural ecosystems. **The green environmental flow requirement shows clearly the need to manage land and water in an integrated and holistic way.** To set a target for green environmental flow requirements at the catchment level, target 11 of the Convention on Biological diversity can be used. This target aims that by 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas,[41] are protected and integrated into the landscape management policies.

Blue and green environmental flow requirements are important concepts when assessing the sustainability of water consumption at a certain catchment. Both concepts come from the basic concept of sustaining freshwater and estuarine ecosystems for the purpose of assuring the watershed services that we as humans require. This means, using water in that catchment in a sustainable way. If agreed environmental flows are violated, i.e. if more water is consumed in the catchment than the water that is actually available for human use (deducting environmental flows), we can say that water consumption in that catchment is not sustainable.

39 EC, "Water Framework Directive objectives", 2015, ec.europa.eu/environment/water/water-framework/index_en.html.

40 Water Footprint Network, "Glossary of terms", *op. cit.*

41 www.cbd.int.

2.4. HUMAN CONSUMPTION AND POLLUTION OF WATER

2.4.1. The water footprint and virtual water concepts

The water footprint is an indicator that was first proposed by Hoekstra[42] as an indicator of human water appropriation and use.[43] Nowadays it is commonly used to assess human consumption and pollution of water.

The water footprint has three components: the green, the blue and the grey water footprints.

- Blue water footprints refer to the volume of surface and groundwater consumed as a result of the production of a good or a service. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water abstracted from surface water or groundwater in a catchment and returned to another catchment or the sea. It is the amount of water abstracted from groundwater or surface water that does not return to the catchment from which it was withdrawn.
- The green water footprint refers to the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products.
- The grey water footprint refers to water pollution in the form of the volume of freshwater required to dilute a given load of pollutants, based on specific natural background and ambient water quality standard concentrations. The grey water footprint will depend on the pollutant used for the calculation. Water quality experts deem the notion of expressing pollution in volumes as contentious. However, using a volumetric measure for pollution does bring together the quantity and quality issues related to water use in one framework.

The global annual average water footprint in the period 1996-2005 was 9,087 Gm^3/year (74% green, 11% blue and 15% grey - with grey water footprint referring to nitrogen). The global water footprints of the agriculture, industrial and domestic sectors are 92%, 4.4% and 3.6% of the total, respectively. The global blue water footprint of agriculture, water consumed by irrigation, is 10% (945 Gm^3/year) of the global total water footprint.[44] China, India and the United States are the countries with the largest total water footprint within their territories.

Main freshwater uses vary from country to country.[45] In an industrialized country such as Belgium, the industrial sector is responsible for 80% of the use of freshwater resources,[46] whereas agriculture is undoubtedly the biggest water user in South Asia, Africa, or central and South America. Taking a closer look at the ACP region, agriculture uses more than 85% of the water abstracted.

42 Hoekstra, A., *The Water Footprint of Modern Consumer Society*, London, Routledge, 2013.

43 WFN, "Glossary of terms", *op. cit.*

44 Hoekstra, A.Y. and Mekonnen M.M., "Water Footprint of Humanity", *PNAS*, vol. 109, No. 9, 28 February 2012, www.pnas.org/content/109/9/3232.full.

45 UNEP, "Freshwater use by sector at the beginning of the 2000s", 2008, www.unep.org/dewa/vitalwater/article48.html.

46 Worldometers, 2015, www.worldometers.info/water.

The virtual water content of a product refers to the volume of freshwater 'embodied' in the product, not in real sense, but in virtual sense. It refers to the water consumed or polluted to produce the product, including the evapotranspiration from crops and fodder. It is basically calculated in exactly the same way as the water footprint. The main difference between both concepts is that the water footprint is a multi-dimensional indicator, spatially and temporally explicit, whereas the virtual water content refers to a volume only. Both are expressed in water units, but the water footprint also refers to where and when these volumes of water were abstracted or polluted, and addresses its impact in space and time.

In a globalized world, both concepts gain importance. We talk about importing or exporting virtual water to explain that if a nation imports or exports a product, it imports or exports water in a virtual form as the water that was required for the production of the product. Virtual water import/export has been depicted as a potential solution in a given water-scarce region in order to alleviate the pressure on local water resources. It concretely refers to import/export of agricultural products, which are water-intensive. In line with this notion, in water-scarce places, the prioritization of water allocation could be given to domestic purposes and for activities with higher economic return than agriculture. Although trade is seen as a potential solution to partially face the agriculture and water-related future challenges, it needs to be considered with care because of its side impacts, such as additional carbon emissions due to transport, impacts on ecosystems and livelihoods in the producing countries, usually developing countries with weak governance, and finally, the political-dependency it would generate on those regions with respect to food.

2.4.2. Water scarcity across the globe

As we have seen, not all parts of the world are similarly endowed with freshwater resources. **Water scarcity is defined as a situation where the ratio between water use and water availability exceeds a certain threshold.** For example, in India's river basins, severe water scarcity (>200%) takes place, meaning by that monthly blue water footprint exceeds 40% of natural runoff. Runoff is seriously modified and thus environmental flow requirements are not met.[47] Modern water scarcity indicators try to incorporate environmental flow requirements as well in the water scarcity indicators. As a result of the geographical differences in availability and use, a distinct pattern of water scarcity exists across the globe (Figure 8).

47 Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E. and Richter, B.D., "Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability", *PLoS ONE*, vol. 7, No. 2, 2012, journals.plos.org/plosone/article?id=10.1371/journal.pone.0032688.

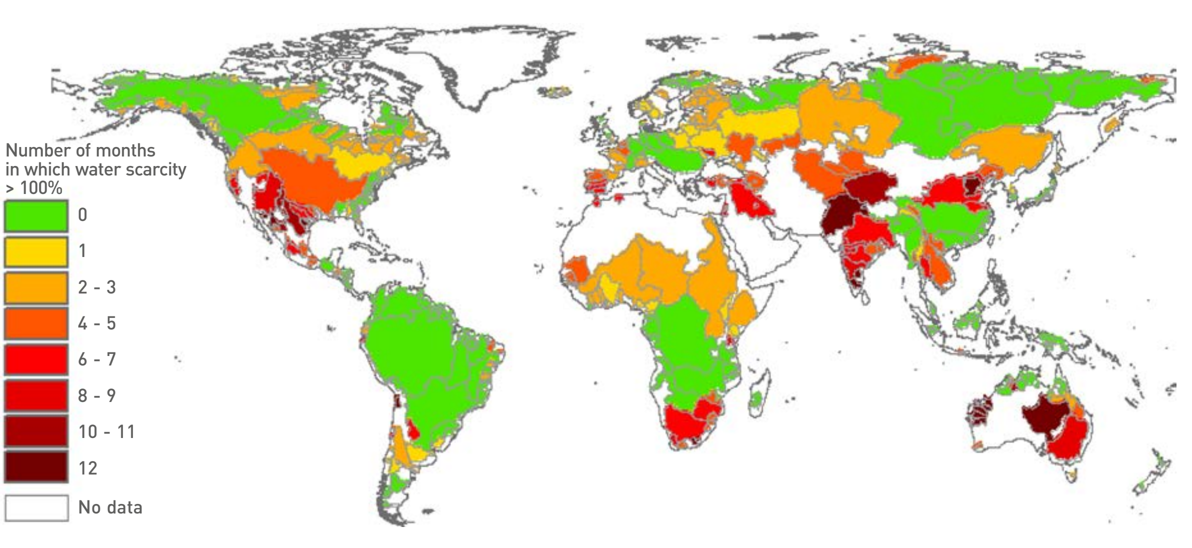


Figure 8 - Number of months during the year in which water scarcity exceeds 100% for the world's major river basins. Period 1996-2005[48]

Almost 1.2 billion people live in areas of physical scarcity. **Physical water scarcity** means that there is not enough water to meet all demands, such as those required by an ecosystem to function effectively. 600 million people extra are expected to live in this situation by 2025. Also, another 1.6 billion people, currently face **economic water shortage** (faced in countries that lack the necessary water infrastructure to satisfy the water needs of the population).[49] Water scarcity is one of the main problems faced by the world in the 21st century.

Many countries suffer water scarcity and their situation can be aggravated by weak policy, institutions and financing frameworks for water management and development. In other countries there might not be water scarcity but weak policies may result in low water use efficiency and/or pollution, resulting in undesired environmental, social or economic impacts. Climate, policy, and the way water resources are distributed around the globe all have an impact on water scarcity.

Climate change, land use change such as deforestation and wetland conversion all have increasing impact on the local water situation. Increases in temperatures will lead to higher evapotranspiration in agriculture. Decreases and more erratic rainfall will lead to higher insecurities in water availability, especially for rainfed agriculture. As an example, in the Sahel, temperatures are expected to increase by 1.4 °C by 2050 and rainfall, while in some parts increasing and in other parts decreasing, will become more erratic.[50] As a result, traditional rainfed agriculture is becoming less reliable leading to changes in the patterns of agricultural, and migration of people from the Sahel to the more humid South. Even where the total amount of rainfall is projected to stay the same, water availability will drop in many places as rainfall

48 Hoekstra, A.Y. and Mekonnen, M.M., "Global water scarcity: monthly blue water footprint compared to blue water availability for the world´s major river basins", *Value of Water Research Report Series*, No. 53, Delft, UNESCO-IHE, 2011.

49 UN, "Water for life decade", 2006, www.un.org/waterforlifedecade/scarcity.shtml.

50 IPCC, *The Regional Impacts of Climate Change. Special reports*, 2015, www.ipcc.ch/ipccreports/sres/regional/index.php?idp=11.

patterns move towards fewer, more severe rainfall events, which tends to increases the proportion of surface runoff that that ends up as blue water.

The loss of natural forests and wetlands decreases the water holding capacity of landscapes; on top of this evaporation is generally higher from the new land uses that replace them (such as intensive agriculture, plantations). This result in a big change in local water cycles. Together with the overarching impacts of climate change, this is affecting water systems around the world.

2.4.3. Water quality standards and water pollution levels

Access to clean water for drinking and sanitary purposes is a precondition for human health and well-being. Similarly, clean unpolluted water is essential for our ecosystems.

Water quality is defined as the *"physical, chemical, and biological characteristics of water necessary to sustain desired water uses"*.[51] Water quality refers to all aspects of the quality of water to sustain ecosystems, biodiversity and human well-being such as health, food production and economic development. Water quality therefore has a strong influence over human poverty, wealth and educational levels.[52]

Almost all human activities have an impact on the quality of water, be it surface or groundwater. Two sources of pollution are commonly recognized: point and diffuse sources of pollution:

- Point sources, such as discharges from the treatment of urban wastewater, industry and fish farms, are defined as "*stationary locations or fixed facilities from which pollutants are discharged*".[53] Pollutants that are normally associated with point sources include oxygen consuming substances (with high biological or chemical oxygen demand) and hazardous chemicals.
- Diffuse pollution can be caused by a variety of activities that have no specific point of discharge. Agriculture is a key source of diffuse pollution, but urban land, forestry, atmospheric deposition and rural dwellings can also be important sources.[54] Key pollutants that come from diffuse polluting sources such as agricultural or urban activities include: nutrients, pesticides, sediments, parasites, toxins, viruses, human drugs (chemicals and medicines), oil, detergents, heavy metals and faecal microbes.

From a management perspective, water quality is defined by its desired end use. Water for recreation, fishing, drinking and habitat for aquatic organisms requires higher levels of purity, whereas for hydropower, for example, water quality standards are less important. Depending on the use, different types of standards exist. For instance, there are drinking water standards, irrigation quality standards, emission (or effluent) standards, and ambient water quality standards. The latter are defined as the maximum allowable amount of a substance in rivers, lakes or groundwater,

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51 www.unwater.org/wwd10/faqs.html.

52 *Ibid.*

53 EEA, "Water pollution – overview", 2008, www.eea.europa.eu/themes/water/water-pollution.

54 *Ibid.*

given as a concentration. Standards are set to protect against anticipated adverse effects on human health or welfare, wildlife or the functioning of ecosystems,[55] and can be issued for a specific state, country or group of countries.[56]

The Water Pollution Level (WPL) is defined as the degree of pollution of the runoff flow, measured as the fraction of the waste assimilation capacity of runoff actually consumed (Hoekstra *et al.*, 2011). A water pollution level of 100 per cent means that the waste assimilation capacity of the runoff flow has been fully consumed. When the water pollution level exceeds 100 per cent, ambient water quality standards are violated. WPL can give insight in the level of pollution globally. Liu *et al.*[57] analysed the Nitrogen loads for more than a thousand rivers of the world (Figure 9). For the year 2000, 66% of the river basins analysed had a WPL for N higher than 1, indicating serious pollution problems.

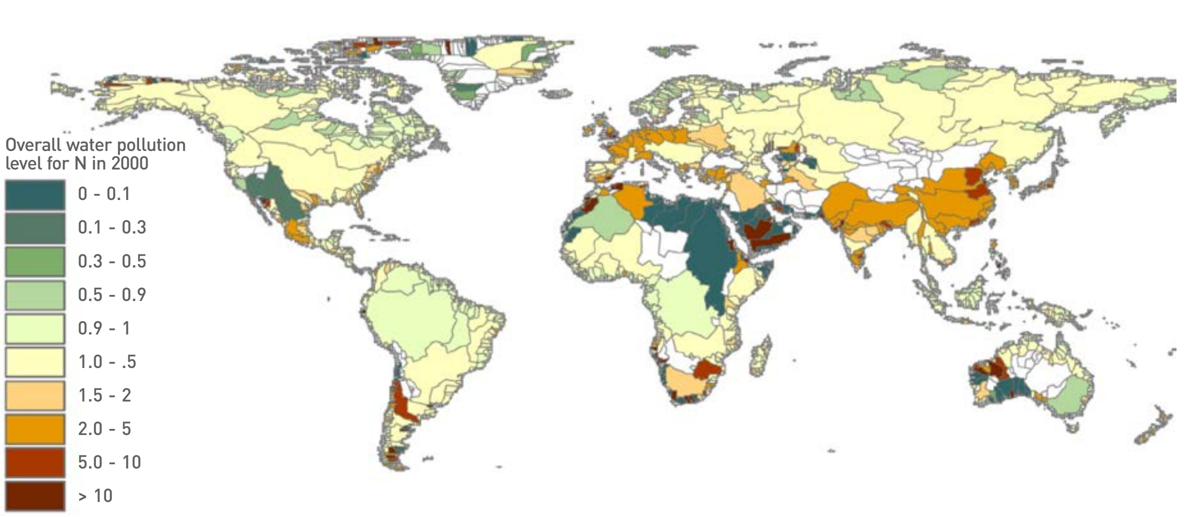
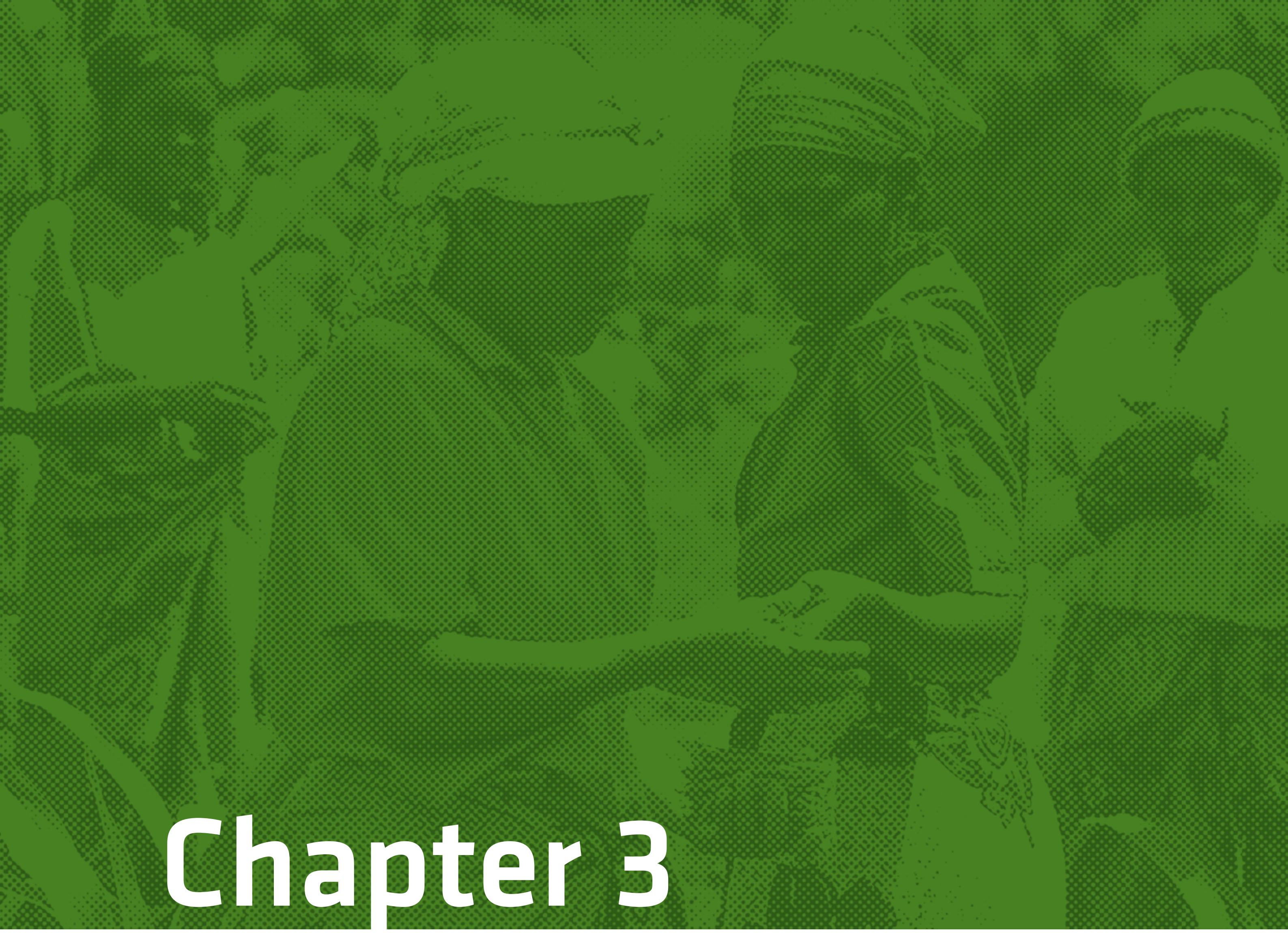


Figure 9 - Water pollution level for Nitrogen in the world's river basins for reference year 2000

55 Hoekstra, A.Y. and Mekonnen, M.M., "Global water scarcity: monthly blue water footprint compared to blue water availability for the world´s major river basins", *op. cit.*

56 COLEACP, *Training manual. Sustainable and responsible production*, 2017.

57 Liu, C., Kroeze, C., Hoekstra, A.Y. and Gerbens-Leenes, W., "Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers", *Ecological Indicators*, No. 18, 2012, pp. 42-49.



Chapter 3

Water for plant development

3.1. THE ROLE OF WATER IN PLANTS

Water is the foundation of the many physiological processes that are required for plant growth.

3.1.1. Transpiration

The main process that drives water movement in plants is transpiration, which is the process of water loss from plants in the form of vapour (evaporation). Around 95% of water absorbed from soil by plants is used for transpiration. Only a small part of it, around 5%, is used in the process of photosynthesis to produce carbohydrates, needed for plant growth.

Transpiration occurs through the stomata in the leaves of the plant. The result of transpiration is a water potential gradient from leaves to root. The air around the leaves has low water potential and the soil (when enough water is available) high potential. Water moves from high to low water potential. The water thus moves from soil to root to leaves to the air.

The transpiration rate of plants depends on water availability within the plant, the soil and on the available energy to vaporize water from the leaves of the plant. Transpiration also varies with the development stage of the plant (see Section 3.3). In full maturity, the plant transpires most. Most of the energy used for transpiration comes directly from the sun through solar radiation. The transpiration rate of plants in sunny and hot areas is therefore higher. As a result, the water requirement of plants in hot areas is also higher. Growth in hot areas thus generally requires more water to be available to plants.

3.1.2. Turgor

Plant tissue mass is made up of around 85-90% of water in the growing period. In the mature stage of woody plants, the range is around 50%, whereas it can go up to 95% in some herbaceous plants. Water allows the plant to keep erect by building up turgor pressure within cells. Turgor provides the mechanical stability of non-woody plant tissue. Without the stability that turgor provides, many plants would just collapse and physiological processes would be inhibited. These processes include: cell enlargement (or plant growth), exchange of gases in the leaves, water and sugars transportation through the plant, as well as many others.

As a result of low water content in the soil, plants may not be able to maintain turgor. When this occurs the plant has reached its **wilting point** (WP). WP is the level of soil water content where the plant cannot take up water from the soil and subsequently wilts. Wilting can be reversed when the plant receives water again if the plant has not reached **its permanent wilting point (PWP). PWP** is the point at which the continuous thread of water through the plant xylem and tissue is interrupted. A plant cannot recover once its PWP is passed, and it dies.

3.1.3. Nutrition

Water is the carrier of sugars, nutrients and sometimes systemic pesticides through the plant. As we have seen water enters a plant through the root system, largely due to the difference in water potential between the root and the soil. Water helps nutrients to be taken up by the root through a variety of complex processes, including active transport. Once taken up they become available for the physiological processes in the plant as a result of water movement from the roots to other parts of the plant. Water movement through the plant is due to two processes: the most important process is transpiration from the leaves (see above). The second process, which happens at a smaller scale, occurs when water is driven up from the roots to the leaves due to a high concentration of solutes in the root. As a result the water pressure in the roots increases, and water is pushed up through the plant and pushed out through the leaves in the process of guttation.

3.2. CROP WATER REQUIREMENT

3.2.1. Principles

FAO[58] defines crop water requirement as "the depth (or amount) of water needed to meet the water loss of a crop through evapotranspiration (ET_c = Evapotranspiration for a specific crop)". **The crop water requirement is thus completely dependent on the evapotranspiration of the crop.**

Evapotranspiration (ET) is the sum of transpiration from leaves of plants and evaporation from the soil surface.[59] Evaporation is a term that covers all processes in which liquid water is transferred as water vapour to the atmosphere.

There are various ways to estimate ET. It can be obtained from remote sensing data. ASTER and MODIS datasets can be used to generate detailed ET estimations.[60] Remote sensing methods can also be combined with equations to estimate evaporation. CGIAR CSI (2015) developed this for its global databases on evaporation and aridity. These databases were created by coupling remote sensing elevation data,[61] global climate databases[62] and the standard evaporation equation of FAO.[63] ET can also be experimentally derived from lysimetric data or evaporation pan data.

58 Brouwer, C. and Heibloem, M., *Irrigation water management: Irrigation water needs*, Rome, FAO, 1986.

59 Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., "Food and Agriculture Organization of the United Nations. Crop evapotranspiration", Guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56, Rome, FAO, 1998.

60 French, A.N., Schmugge, T.J., Kustas, W.P. and Prueger, J.H., "Evapotranspiration Estimation Using Multispectral Thermal Infrared Data from ASTER and MODIS", American Geophysical Union, Fall Meeting 2009, abstract #U32A-08, 2009.

61 Jarvis, A. *et al.*, "Hole-filled SRTM for the globe Version 4", available from the CGIAR-CSI SRTM 90m Database, 2008, srtm.csi.cgiar.org.

62 Hijmans, R.J. *et al.*, "The WorldClim interpolated global terrestrial climate surfaces", version 1.3. 2004.

63 Zomer, R.J. *et al.*, "Food and Agriculture Organization of the United Nations. Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation", *Agric. Ecosystems and Envir.*, FAO, No. 126, 2008, pp. 67-80.

Most field level crop water requirement calculations are done by estimating the ET through equations that use local climate, crop and soil data. A number of equations have been developed including: Penman, Penman Monteith, Priestley Taylor and FAO 56 Reference Crop Equation.[64] A full overview of the different methods to estimate ET is given by McMahon *et al.*[65]

For the calculation of ET_c in this manual we follow the FAO 56 Reference report[66] as this is the standard accepted method of calculation.[67]

This uses the Penman Monteith equation to calculate ET for a hypothetical reference crop in a given location. This ET is called the Reference Evapotranspiration or ET_0. It uses standard parameter values: height = 0.12 m, surface resistance = 70 s m/1, and albedo = 0.23. It estimates the daily ET_0 (expressed in mm/day) based on the following climate parameters: sunshine hours or solar radiation, maximum air temperature, minimum air temperature, relative humidity, wind speed and elevation. The reference evapotranspiration can be calculated for different time periods (monthly, weekly, daily and hourly). The resulting ET_0 values can subsequently be used to calculate crop water requirements for different crops. Different crops have different levels of evapotranspiration. In order to calculate Crop Water Requirement (ET_c) of any crop a crop specific coefficient K_c is introduced (equation 1).

$$ET_c = K_c * ET_0 \qquad \textit{Equation 1}$$

Crop coefficient values vary between crops and between the growth stages of a crop. Figure 1 gives an overview of the variation of K_c values for a variety of agricultural crops. Looking at the K_c values of the various crops, it is clear that maize (K_c=1.2) will have a higher ET_c then pineapple (K_c 0.3) under the same climatic conditions.

64 Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., "Food and Agriculture Organization of the United Nations. Crop evapotranspiration", *op. cit.*

65 McMahon,T.A. *et al.*, "Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis", *Hydrol. Earth Syst. Sci.*, No. 17, 2013, pp. 1331–1363, www.hydrol-earth-syst-sci.net/17/1331/2013/hess-17-1331-2013.pdf.

66 Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., "Food and Agriculture Organization of the United Nations. Crop evapotranspiration", *op. cit.*

67 McMahon, T.A. *et al.*, "Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis", *op. cit.*

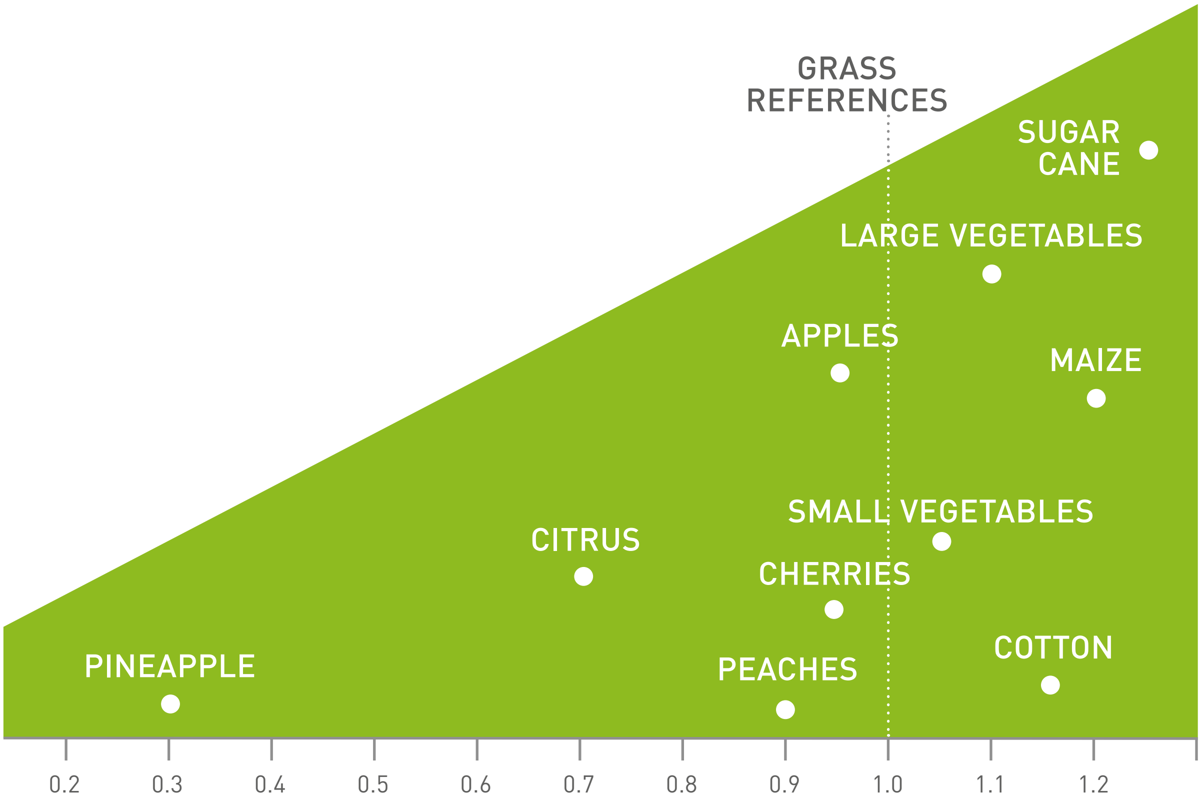


Figure 1 - Mid-season K_c values for a variety of agricultural crops.
Source: Allen *et al.*[68]

During plant growth, evapotranspiration varies, mainly due to changes in leaf area. Four growth stages can be roughly identified: initial, crop development, mid-season and late season.

1. In the initial stage, due to small leaf area of the crop, evaporation occurs mainly from the soil. The soil evaporation is a function of the wetness of the soil and thus K_c is high when the soil is wet and low when the soil is dry.
2. As a crop develops it can increase from 10% ground cover to 100% – full cover of the ground by the crop. Although K_c depends on the type of crop and wetness of the soil, it generally ranges from 0.5 for 25-40% to 0.7 for 40-60% ground cover.
3. The mid-season stage occurs from the start of full maturity to the beginning of aging (yellow leaves). At mid-season the crop reaches its maximum K_c value.
4. The late season stage ends when the crop is harvested. The K_c value at the end of the late season stage (K_c end) reflects crop and water management practices.

Figure 2 displays the typical ranges of K_c values for the four different growth stages. Please refer to Annex to this Chapter for the K_c values for various crops.

68 Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., "Food and Agriculture Organization of the United Nations. Crop evapotranspiration", *op. cit.*

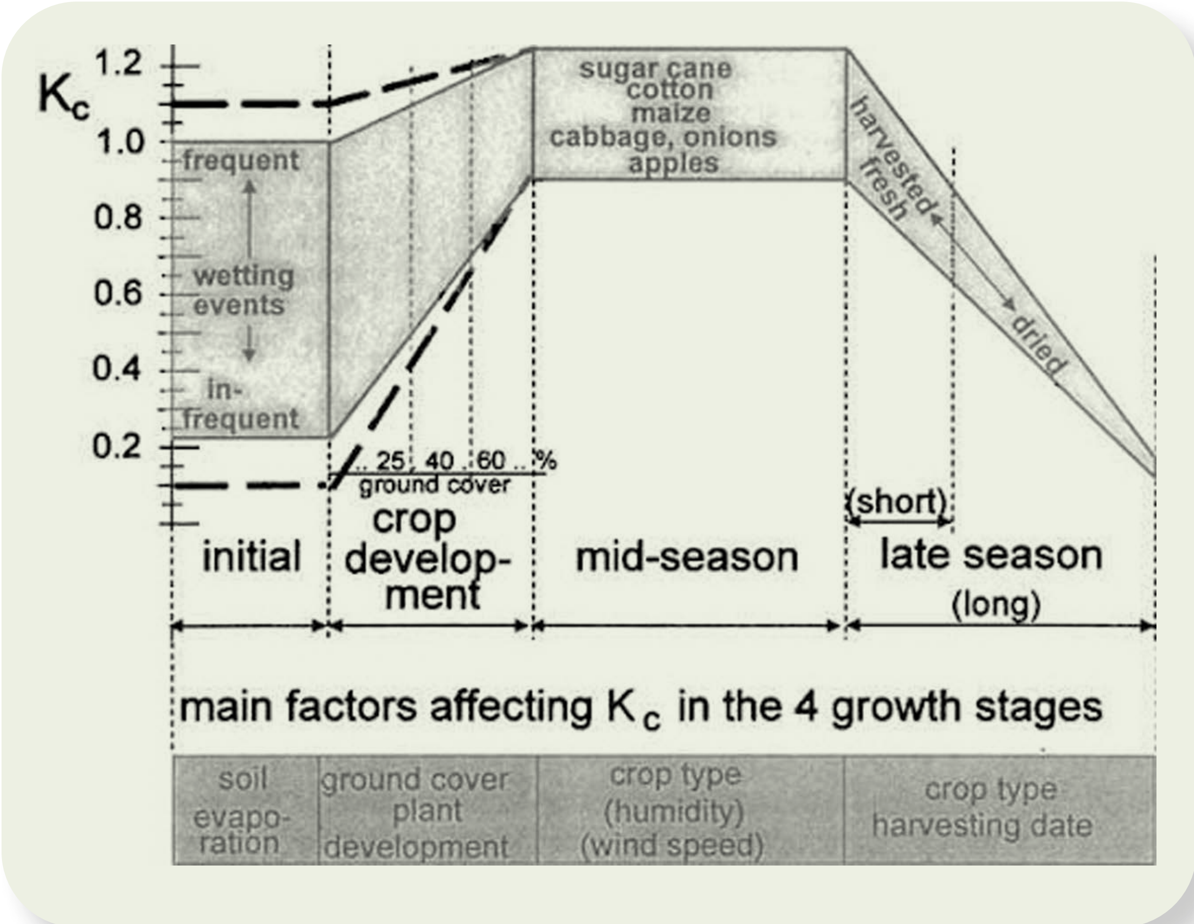


Figure 2 - Typical ranges of K_c for the four growth stages
Source: Allen *et al.*[69]

The ET of a crop also varies according to the water conditions in the soil and the ability of the plant to take up water from the soil. With sufficient water, the ET of the crop varies according to the crop coefficients in the four crop stages. When insufficient water is available to the crop, a condition of water stress exists. In water stress conditions, the ET of the crop will be reduced. The result is that the crop is unable to evaporate fully, inhibiting crop growth. For irrigators it is important to understand how low the water availability in the soil can get before negative impacts from water stress start to occur.

Not all water in the soil is available to plants. Only soil water content in the root zone of the plant between field capacity (FC) and the permanent wilting point (PWP) can be used by the plant. This is referred to as the Total Available Water or TAW. TAW is therefore the difference between the water content at field capacity (FC) and the permanent wilting point (PWP). TAW is crop specific due to rooting depth. Theoretically, there is water available until wilting point but, as water content decreases in the soil a situation of water stress occurs. Crop water uptake reduces before wilting point has been reached.

69 *Ibid.*

The fraction of TAW that a crop can deplete from the root zone before crop water stress occurs is called the Readily Available Water (RAW) to the plant, and is given by a factor p (RAW = p * TAW). Again, p is crop specific. For example, cabbage has a larger p value than onion and can thus withstand lower soil water content before water stress occurs.

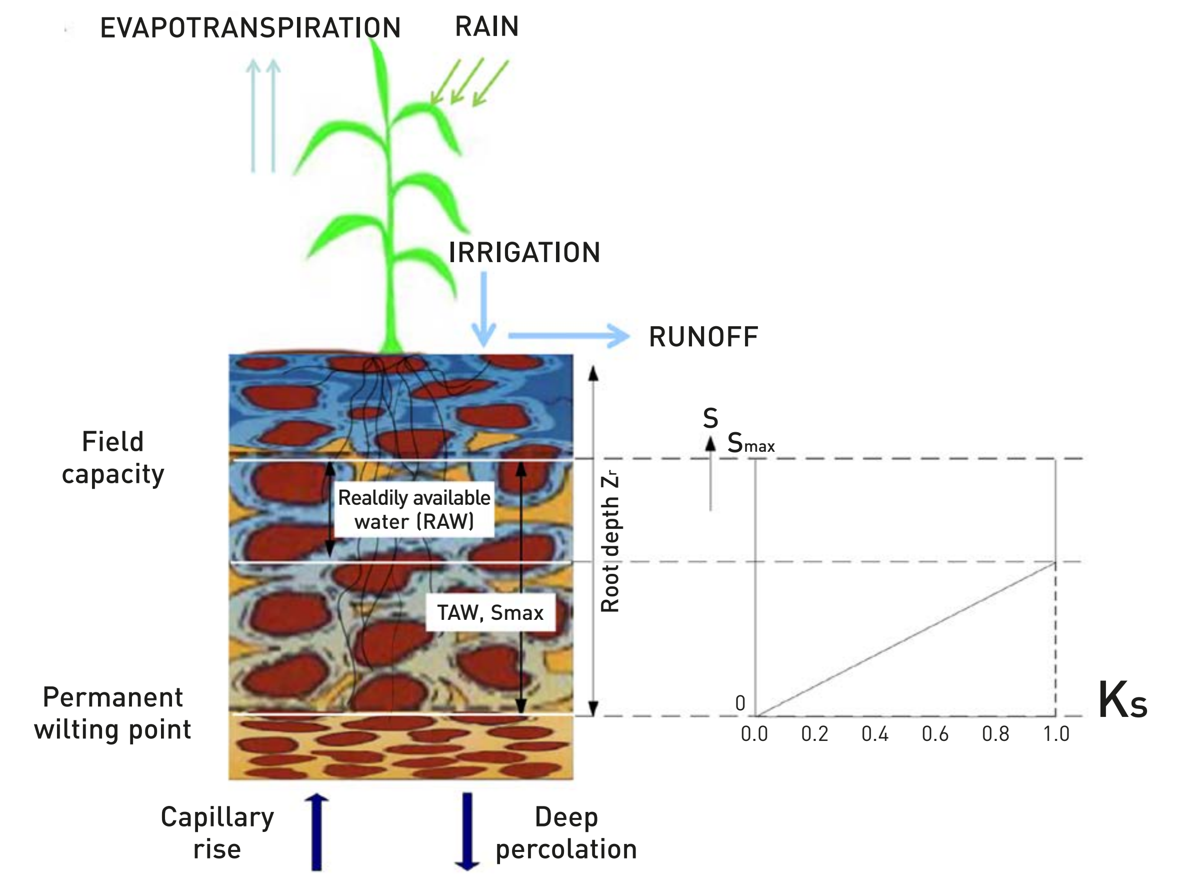


Figure 3 - Total available water in the soil (TAW) between field capacity and wilting point and Readily available water (RAW). On the right, the development of the Ks when soil water content is lower than RAW
Source: retrieved from Water Footprint Network training materials.

When in water stress, crops can evaporate less. As a result, we cannot use ET_c which is crop evapotranspiration under standard conditions. Instead we use ET_c, adj. crop evapotranspiration under non-standard conditions (of water stress). To calculate the evaporation of a crop ($Et_{c,\ adj}$) in water stress conditions, the crop coefficient K_c in equation 1 is multiplied by a stress coefficient Ks. The stress coefficient K_s is crop specific. By definition, K_s is 0 at wilting point and 1 at field capacity (figure 3).

Following equation 1, by knowing the ET_0 and crop coefficients for the various growth stages, we can calculate the Crop Water Requirements at different times depending on the time resolution of the data available (Figure 4).

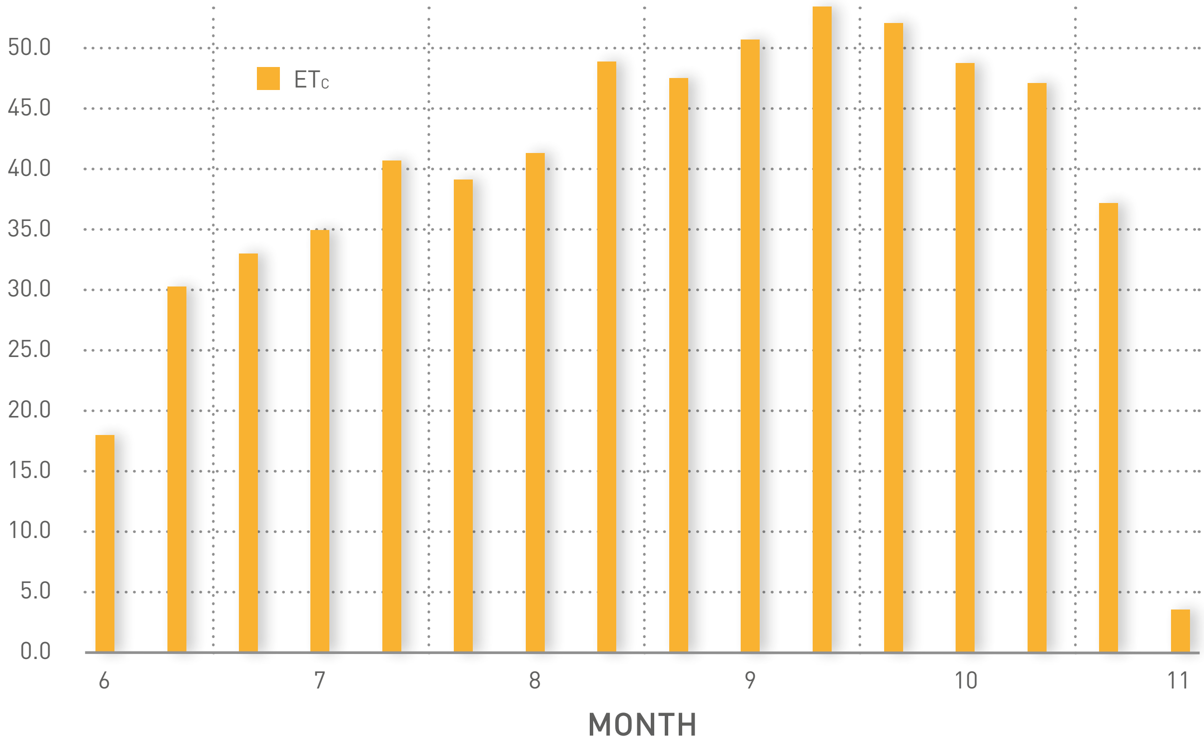


Figure 4 - Crop water requirements in mm per 10 days, for an example crop during the entire growing season (modelled using CROPWAT)[70]

3.3. SOIL AND WATER

The water availability to the roots is determined by the moisture content of the soil and the water retaining characteristics of the soil around the roots. Obviously if the soil does not have enough water available for the plant, there will be reduced transpiration, which results in the loss of cell turgor. The decrease of stability in plant causes wilting and subsequently impeded growth and death of the plant. In order to understand the soil water availability for crops we need to understand more about the soil-water related processes and water requirements of plants.

The background on soils is explained in the COLEACP Manual[71] on *Sustainable and Responsible Production*. This section will address soil and soil processes mainly from the viewpoint of water for plant development.

70 FAO, CROPWAT model, 2010, www.fao.org/nr/water/infores_databases_cropwat.html.

71 COLEACP, Training manual, *Sustainable and responsible production*, 2017

3.3.1. Soil characteristics

Soil is a complex of minerals and dead and living organic matter. Soil consists of a solid element of minerals and organic matter that is complemented by a porous element that holds gases and water. Soil forms under the influence of five major factors:

- parent material,
- climate,
- living organisms\ -especially native vegetation,
- topography,
- time.

Soils changes as a result of physical, chemical and biological processes such as weathering, oxidation, reduction, clay formation, erosion, decomposition of organic matter by bacteria, fungi and invertebrate (e.g. insects, worms) and vertebrate organisms (e.g. mice and moles). Soils provide plants with: physical support, air, water, temperature moderation, nutrients, and protection from toxins (by soil organisms that decompose organic toxins), ventilation, and suppression of toxin producing organisms. Natural soils provide nutrients to plants and animals by converting dead organic matter into various nutrient forms.[72]

Soils can be characterized according to their physical, chemical and biological properties that all influence the water holding capacity of soils.

The physical properties of a soil are determined by soil texture and soil structure. Texture and structure of soils have a direct relation to the porosity of the soil and with that the ability of a soil to hold water. Soil texture is determined by the proportion of the three types of soil particles: sand, silt, and clay. These soil particles are mainly distinguished on the basis of size (Table 1). The texture can be determined by a sensory test by a trained person or by measuring the percentage of the three soil particle sizes.

Table 1. Soil particles and their sizes[73] (FAO, 1998)

Soil particle	Size (mm)
Gravel to coarse sand	2-1
Coarse to fine sand	1-0.05
Silt	0.05-0.002
Clay	<0.002

72 Jenny, H., *Factors of Soil Formation: A System of Quantitative Pedology*, New York, Dover, 1994, www.soilandhealth.org/01aglibrary/010159.Jenny.pdf, extracted from www.soilandhealth.org/01aglibrary/01aglibwelcome.html.

73 FAO, "Simple methods for Aquaculture", FAO training series, Rome, FAO, 1998, ftp.fao.org/fi/CDrom/FAO_Training/FAO_Training/ENG_MENU.htm.

Soil structure refers to the way soil particles (clay, silt, sand) and organic matter are grouped in compounds and aggregates.[74] Organic matter (OM) plays a central role in this by creating clay-OM complexes. Through biological processes, OM binds to minerals, particularly clay particles.[75] These structural aggregates, unlike texture particles, are not permanent. The soil structure continually alters by natural, chemical and physical processes. These processes include cultivation practices.

Aggregates can be arranged in different ways: massive, prismatic, blocky and granular. Farming practices usually try to find a granular structure for the topsoil, as it helps water flow and consequently, better seed germination and plant growth. Soil structure affects aeration, water movement, conduction of heat, plant root growth and resistance to erosion.[76]

As a living complex, soil has certain **chemical properties** that are relevant for any farmer, especially those related to water. Knowledge and management of these chemical properties is fundamental to provide the best conditions for crop growth. The most important chemical properties of soils in relation to water are outlined in Table 2.

Table 2. Selected Chemical soil properties related to water issues[77]

Property	Use
Cation Exchange Capacity (CEC)	Used as a measure of fertility and nutrient retention capacity. Affected positively by soil carbon content.
pH	Affects the availability of ions in soils. Highly acidic soils (pH <5.5) tend to be toxic, highly alkaline soils tend to disperse and swell strongly when wet thus restricting water and air movement in the soil. Most crops do best with a pH of 6.5.
Plant nutrients	Nutrients are essential for plant growth and living organisms in the soil. These fall in two different categories namely macro- and micronutrients. The most important macronutrients include Carbon (C taken up from the air, not the soil), Oxygen (O), Hydrogen (H), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S). Next to this plants need micro-nutrients as well (presented in detail in Chapter 4).
Organic carbon	Soil organic carbon improves the physical properties of the soil. It increases Cation Exchange Capacity, the soils ability to hold nutrients and the water-holding capacity. It contributes to the structural stability of clay soils by helping to bind particles into aggregates.

74 FAO, "Soils portal, physical properties", 2015, www.fao.org/soils-portal/soil-survey/soil-properties/physical-properties/en.

75 COLEACP, Training manual. *Sustainable and responsible production*,

76 FAO, "Soils portal, physical properties", *op. cit.*

77 *Ibid.*

Soil salinity	Salts can be transported to the soil surface by capillary transport from a salt laden water table and then accumulate due to evaporation. Salinity can be the result of irrigation practices without proper drainage (described in detail in Chapter) 4
Soil sodicity	Refers to an excess of exchangeable sodium in the soil. These soils tend to occur in arid to semiarid regions and often have poor physical and chemical properties, which impede water infiltration, water availability, and ultimately plant growth.

The microbes living within the soil recycle nutrients such as carbon and nitrogen through the soil system (**biological properties**). Much of the organic material added to the litter (the accumulated material at the surface of the soil) or within the root zone each year, is almost completely consumed by microbes. Consequently, there is a reservoir of carbon with a fast turnover time of about 1 to 3 years in many cases. The by-products of this microbial consumption are CO_2, H_2O, and a variety of other compounds, collectively known as 'humus'.

Humus is a longer-lived reservoir of carbon in the soil with an age span of several hundreds to a thousand years. Both the fast and slower decomposition driven by microbial processes and climate conditions, lead to an average carbon residence time of around 20 to 30 years for most soils. The soil microbes respire faster at higher carbon concentrations, higher temperatures and in moister conditions. And, taken together, the fast decomposition of litter and the slower decomposition of humus form the soil organic matter (SOM). Soil organic matter is very beneficial for the retention of water in soils. SOM absorbs water directly but also indirectly contributes to the formation of soil aggregates improving the soil structure and with that, the water holding capacity.

Apart from the physical, chemical and biological properties, soils display a **vertical profile**. In the vertical soil profile of a well-developed soil a number of layers called "horizons" can be distinguished (Figure 5). Horizons are named with letters, O, A, E, B, C and R from top to bottom. See Table 3 for the characteristics of each horizon.

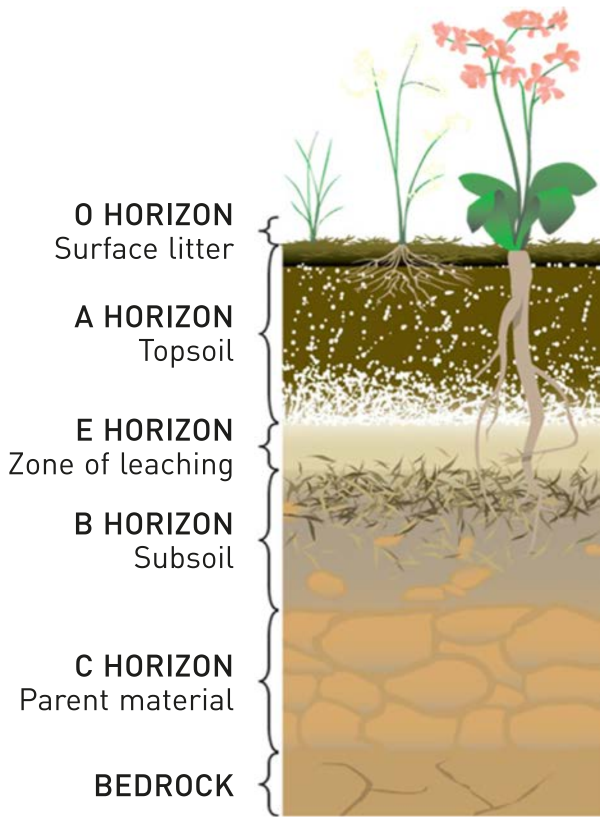


Figure 5 - A general profile of a well-developed soil displaying the division of the soil in main horizons, O, A, E, B, C and R
Source: img.sparknotes.com/figures/A/a4d938a405b10475f48eea440b31bab3/Soil_Horizons.jpg

Table 3. Soil horizons and their characteristics

Horizon	Characteristics
O	A layer of organic matter, containing fresh and decaying plant materials
A	A mainly mineral layer, darker than the horizons below as a result of mixing with and leaching of organic matter from the O horizon. When a soil is ploughed, the O and A horizons become mixed and are referred to as A_p (p from ploughing)
E	A layer with a generally bleached or whitish appearance thanks to leaching of soluble minerals and nutrients, as a result of water moving through
B	Subsoil, a lightly coloured, denser where leached materials accumulate, lower in organic matter than the A horizon
C	Horizon that consists of partly weathered parent material mixed
R	Bedrock (can be within cm or meters below the soil surface

3.3.2. Water in the soil

The pores in a soil, or soil porosity, determine the water holding capacity of a soil. It is calculated as a percentage of the soil volume. Porosity also determines the permeability of the soil, which refers to the movement of water into and through the soil. Permeability generally declines with processes of compaction, rainfall, irrigation, increased soil moisture content, decreased organic matter or amendments, and increased density. Permeability is also sometimes referred to as saturated hydraulic conductivity, and abbreviated as K_{sat}. Permeability is higher for sandy soils and smaller for clay soils (table 3.4). The porosity of a soil is determined by the combination of and interaction between physical, chemical and biological characteristics of a soil (see Tables 2 and 4).

Table 4. Average permeability (K_{sat}) in cm/hour for different soil textures[78]

Soil texture	Average permeability (K_{sat}, in cm/h)
Sand	5.0
Sandy loam	2.5
Loam	1.3
Clay loam	0.8
Silty clay	0.25
Clay	0.05

The soil moisture content is the amount of water that is retained by the soil. Soil moisture content can be expressed in various ways. It can be expressed as the amount of water (water depth in mm) in one meter of soil. It can also be expressed as a volume that 1m^3 of soil holds, e.g. 0.150 m^3; or as a percentage, in this case 15%. Saturation of the soil occurs when after rain or irrigation all soil pores fill with water. In saturated soils, the pores solely contain water. Air is not available in the soil. Plants and their roots need both air and water to grow. As a result many plants can only withstand 2-5 days of soil saturation in the root zone. Generally, situations of saturation will not last long. After the rain or irrigation stops, the water drains through gravity from the larger soil pores and is replaced by air. When the gravity-driven drainage from the soil stops, its field capacity is reached. **Field capacity** (FC) is the situation where the water and air content is said to be ideal for plant growth. At field capacity, large soil pores hold air and water and the smaller soil pores hold water. Water is also held in a thin layer around soil aggregates through adhesion.

FC can be determined by various methods. For example, USDA (1998) offers a simple method based on the ¨look and feel¨ of the soil in the root zone. A simple method for determining volumetric field capacity is demonstrated on: www.youtube.com/watch?v=Xfx3bhDd7YY. The amount of soil water available to plants is called the total available water content (TAW) and is the difference between the water content at field capacity (FC) and the permanent wilting point PWP.[79]

78 FAO, "Simple methods for Aquaculture", *op. cit.*
79 *Ibid.*

Available water content depends greatly on the type of soils (Table 5). The aim of applying irrigation water to crops is thus, to keep the total available water (TAW) between field capacity (FC) and wilting point (WP).

Table 5. Available water content (in mm water depth) ranges for sandy, loamy and clay soil types[80]

Soil	Water depth (mm/m)
Sand	25 - 100
Loam	100 - 175
Clay	175 - 250

3.3.3. Soil water content

In practical agricultural language, the change in Soil Water content (SWC) is often calculated using the concept of "**root zone depletion**", which refers to water shortage relative to field capacity. Mathematically, root zone depletion is expressed as D_r. At field capacity, the root zone depletion is zero ($D_r = 0$). If water is lost from the root zone, Dr increases. The reason for expressing SWC as root zone depletion is practical: Irrigators can directly use the depletion volume D_r to determine timing and amount of irrigation. Mathematically, SWC on day 1, assuming that the soil moisture is at Field Capacity (FC) can be expressed as:

$$SWC_{(1)} = FC - D_{r(1)} \qquad \text{Equation 2}$$

where:

$SWC_{(1)}$ = Soil Water Content end of Day 1

FC = Field Capacity

$D_{r(1)}$ = root zone depletion at end of Day 1

The change of water in the soil after day 1 and day 2 as root zone depletion can be written:

$$D_{r(1)} = FC - SWC_{(1)} \qquad \text{Equation 3}$$

$$SWC_{(2)} = FC - D_{r(2)} - D_{r(1)} \qquad \text{Equation 4}$$

$$SWC_{(2)} - FC = - D_{r(2)} - D_{r(1)} \qquad \text{Equation 5}$$

80 *Ibid.*

In equation 6 we can substitute FC - SWC in equation 5 as the difference between the **inputs or inflows** of water into the soil (FC) and the **losses (SWC)** of water from the soil. The inflows are: rain (P), irrigation (I) and groundwater contributions through capillary rise (CR). The losses are: evapotranspiration (ET), deep percolation (DP) and water that runs off (RO) (see Figure 6).

Finally, solving equation 5 for the root zone depletion on day 2, $D_{r(2)}$ we obtain:

$$D_{r(2)} = D_{r(1)} - P_1 - I_1 - CR_1 + ET_1 + DP_1 + RO_1 \qquad \text{Equation 6}$$

By convention, we assume that $D_{r(1)}$ corresponds to the initial conditions in the water balance, represented by day "zero" ($D_{r,0}$), and that $D_{r(2)}$ corresponds to the root zone depletion of day 1 ($D_{r,\,1,}$) (equation 7)

$$D_{r,1} = D_{r,0} - P_1 - I_1 - CR_1 + ET_1 + DP_I + RO_1 \qquad \text{Equation 7}$$

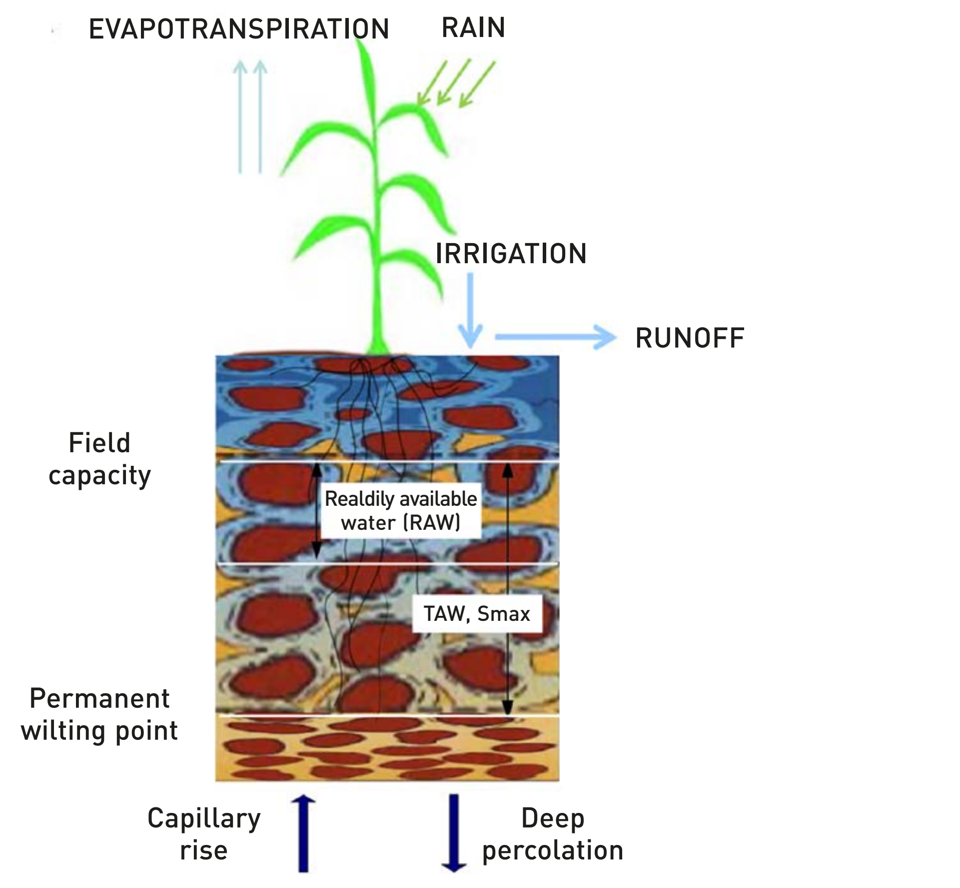


Figure 6 - Parameters in soil water balance: inputs or inflows: Rain (P), Capillary Rise (CR). Irrigation (I) and losses or outflows: Evapotranspiration (ET), Runoff (RO) Deep percolation (DP). Also the soil moisture content at Field Capacity (FC) and Permanent wilting point (WP) are presented. As well as Total Available water (TAW) and readily available water (RAW) (discussed below).
Source: retrieved from Water Footprint Network training materials

If we generalize equation 7 to calculate the development of root zone depletion through the growing season, we use the substitute ¨i-1¨ for ¨0¨ and ¨i¨ for ¨1¨. The root zone depletion at day i is then expressed as:[81]

$$D_{r,i} = Dr_{,i-1} - (P_i - RO_i) - I_i - CR_i + ET_{c,i} + DP_i \qquad \textit{Equation 8}$$

where:

$D_{r,i}$ root zone depletion at the end of day i [mm],

$D_{r,i-1}$ water content in the root zone at the end of the previous day, i-1 [mm],

P_i precipitation on day i [mm],

RO_i runoff from the soil surface on day i [mm],

81 *Ibid.*

I_i net irrigation depth on day i that infiltrates the soil [mm],

CR_i capillary rise from the groundwater table on day i [mm],

$ET_{c,i}$ crop evapotranspiration on day i [mm],

DP_i water loss out of the root zone by deep percolation on day i [mm].

The root zone depletion water balance method is specific for the type of soil. Once the soil water balance is known, the risk of applying excessive water, with consequences like deep percolation or runoff will be reduced. Thus more efficient and effective irrigation can be ensured to avoid crop stress and decrease water consumption. This process of applying the right amount of water at the right time, according to the different factors involved, is known as irrigation scheduling.

3.4. CROP WATER REQUIREMENT AND IRRIGATION

3.4.1. The CROPWAT model

To understand if a crop requires irrigation and especially how much and by when, we need to understand if the changes in soil water content are such that they inhibit crop growth. In other words the soil water balance needs to be established. There are many ways to get an idea of the SWC. Here we use the approach employed by the CROPWAT model of FAO.[82] The CROPWAT model – in its schedule module – carries out the soil water balance on a daily basis prior to irrigation application. For this CROPWAT uses a slightly adapted equation from equation 9. Instead of using Et_y, $Et_{c,\ adj}$ (crop evaporation under non-standard conditions) is used. The reason for this is that when a crop is cultivated, the crop evapotranspiration often differs from crop evapotranspiration under standard conditions as a result of less optimal conditions (*i.e.* water stress, pests, salinity). To correct for this, $ET_{c,\ adj}$ is used. The equation used by CROPWAT is:

$$D_{r,i} = D_{r,i-1} - (P_i - RO_i) - I_i - CR_i + Et_{c,adj,i} + DP_i \qquad \text{Equation 9}$$

Where:

$D_{r,i}$ root zone depletion at the end of day i [mm],

$D_{r,i-1}$ water content in the root zone at the end of the previous day, i-1 [mm],

P_i precipitation on day i [mm],

RO_i runoff from the soil surface on day i [mm],

I_i net irrigation depth on day i that infiltrates the soil [mm],

CR_i capillary rise from the groundwater table on day i [mm],

82 FAO, CROPWAT model, *op. cit.*

$Et_{c,adj,i}$ crop evapotranspiration under non-standard conditions on day i [mm],

DP_i water loss out of the root zone by deep percolation on day i [mm].

In order to obtain the net irrigation depth *I* from equation 9, CROPWAT solves the equation through estimation of the other variables in the equation. Table 6 provides an explanation of how CROPWAT estimates the variables.

Table 6. Variables in the soil water balance as estimated by the CROPWAT model,[83] based on equation 9

Variable	Method of estimation
P	Total rainfall, obtained from climatic parameters.
ET_{adj}	Crop evapotranspiration, obtained from climatic and crop parameters (see Section 3.3.). Crop parameters used are: the crop coefficient K_c and the stress coefficient K_s. Et_{adj} = Ks * K_c * ET_0 (ET_0 is the potential ET).
RO	Runoff, estimated with the help of the Maximum infiltration rate of the soil (MIR). MIR, expressed in mm/day, represents the water depth that can infiltrate in the soil over a 24-hour period. MIR is a parameter that depends on the type of soil. It is assumed RO occurs each time P exceeds MIR.
DP	Deep percolation. Following heavy rain or irrigation, the water content in thesoil might temporarily exceed FC. It is assumed that the total amount of water above FC is lost the same day by deep percolation. As long as the soil water content in the root zone is below FC, the soil will not drain and DP will be zero.
D_r	Root zone depletion, water shortage relative to Field capacity (FC). The root zone is assumed to be at FC following heavy rain or irrigation, therefore D_r = 0. As a result of ET, the water content in the root zone gradually decreases, thus D_r increases. In the absence of any wetting event, the water content will steadily reach its minimum value at Wilting Point. At that moment no water is left for ET, and D_r has reached its maximum value, equal to the total available water. $0 \leq Dr \leq TAW$. Dr is calculated prior to irrigation application, if any. Initial depletion To initiate the water balance for the root zone, the initial depletion ($D_{r,i-1}$) should be estimated using soil water content measurements. $D_{r,i-1} = 1000 * (\Theta_{FC} - \Theta_{i-1}) * Z_r$ With: Θ_{FC} = soil water content at FC, Θ_{i-1} = average soil water content for the effective root zone, in day *i-1* (initial conditions), and Z_r: rooting depth. **Usually and for simplification, the water balance initiates on a day with irrigation or just at the end of the rainy season, so $D_{r,i-1}$ is assumed to be zero.**

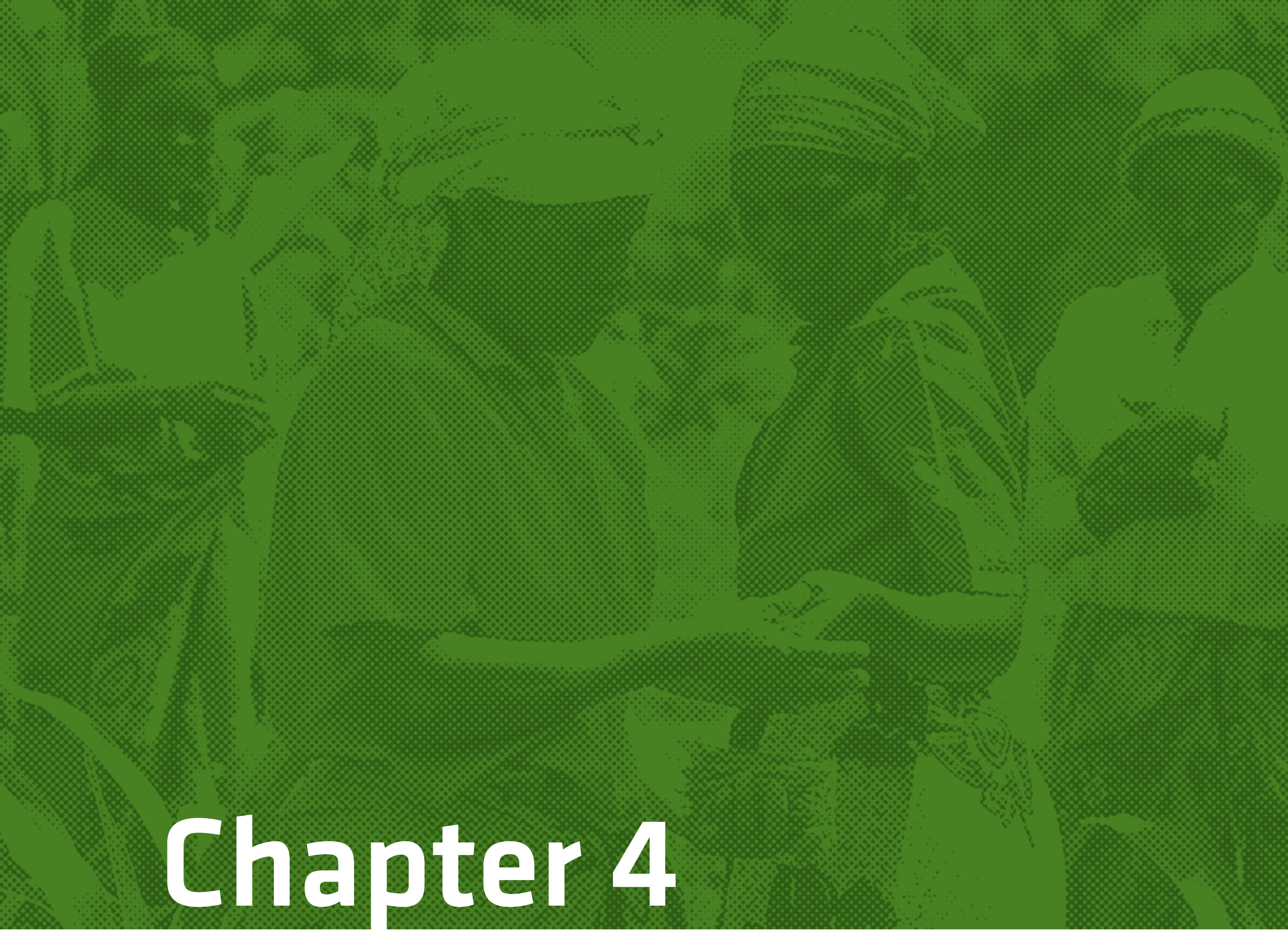
83 *Ibid.*

CR	Capillary rise. The amount of water transported upwards by capillary rise from the water table to the root zone depends on the soil type, the depth of the water table and the wetness of the root zone. CR can normally be assumed to be zero when the water table is more than about 1m below the bottom of the root zone. Some additional information on CR was presented in FAO Irrigation and drainage paper No. 24.
I	This is the parameter we want to calculate, the net irrigation depth. To avoid water stress, irrigations should be applied before or at the moment when the readily available water (RAW) is depleted ($D_{r,i} \leq RAW$). To avoid deep percolation losses that may leach relevant nutrients out of the root zone, the net irrigation depth generally should be smaller than or equal to the root zone depletion (see Chapter 6 for detailed information on irrigation scheduling). RAW is estimated as $RAW = p \times TAW$ With *TAW* being the Total Available Water and *p* being the critical depletion factor. *p* differs from one crop to another and normally varies from 0.3 for shallow rooted plants at high rates of ET_c (> 8 mm/d) to 0.7 for deep rooted plants at low rates of ET_c (< 3 mm/d). A value for p of 0.5 is commonly used for many crops. *TAW* is a function of the soil type, as it depends on the values for Field Capacity and Wilting Point. It also depends on the rooting depth.

CROPWAT solves equation 7 at a daily basis assuming I = 0 until Dr (root zone depletion) reaches the readily available water (*RAW*, see Figure 5). At this point, I will be calculated in mm/day corresponding to what is needed in order to increase the soil water content from RAW to Field Capacity (FC), and achieve a *Dr* that is equal to zero. In this way, the soil water balance equation is solved for all the days of the growing period of the crop, establishing a schedule of required net irrigation depths at a certain time interval.

The net irrigation depth, *I*, represents the water that is available to the crop in its root zone. Therefore *I* does not incorporate any inefficiency in the transport, distribution of irrigation water and application practices. If only the net irrigation depth would be applied as irrigation, the crop would be receiving too little water. Therefore we need to calculate the gross irrigation depth that includes these inefficiencies. Gross irrigation depth is calculated by dividing the net irrigation depth by the irrigation efficiency. For well-managed gravity irrigation, CROPWAT uses a default value of 70% of irrigation efficiency. This means that the net irrigation depth is 70% of the volume of the gross irrigation depth, thus 30% of the water is ´lost´ due to inefficiencies.

Note that the calculations of net and gross irrigation depths are usually done in mm. The actual water volume required for irrigation can also be calculated in meter cube (m^3). This is done by transforming the irrigation requirement in mm to m (divide by 1000) and then multiplying this with the surface area in m^2 of the field concerned.



Chapter 4

Agriculture and water quality

4.1. INTRODUCTION

Agriculture and water quality are closely connected, with agriculture being both a generator and a victim of water pollution. It causes pollution through its discharge of pollutants and sediment to surface and/or groundwater, through net loss of soil (erosion) due to poor agricultural practices, and through salinization and waterlogging of irrigated land. It suffers from pollution through wastewater, polluted surface and groundwater, and/or saline water, which contaminates crops and transmits disease to consumers and farm workers.[84] In this chapter, both scenarios are discussed.

Agriculture has **two types of pollution source: point sources and non-point sources.** In the horticulture sector, the most common point sources of pollution are effluents of water used for processing and washing products. These are discussed further in Chapter 7. This Chapter addresses non-point sources of pollution from horticulture.

4.1.1. Water quality standards and regulations

Chapter 2 introduced the definition of water quality, the concept of quality in relation to the use of the water, and the quality criteria of most interest. Water quality standards are used to provide a reference to describe levels of pollution in surface or groundwater. It is recommended that local water quality standards (the country where the agricultural activity is located) should be used where possible. When there are no local water quality standards, those from the US Environmental Protection Agency[85] or the European Union regulations[86] are used worldwide as guidelines.

Different types of water quality standards exist:

- drinking water quality standards (maximum allowable concentration of a substance in drinking water);
- irrigation quality standards (maximum allowable concentration of a substance in irrigation water);
- emission standards (maximum allowable concentration of a substance in effluents);
- ambient water quality standards (maximum allowable concentration of a substance in rivers, lakes or groundwater).

In horticulture, all of these water quality standards are of relevance. Table 1 relates these standards to specific horticultural activities. The producer needs to know the standards and regulations that apply to his/her activities and location.

84 FAO, "Control of water pollution from agriculture", FAO irrigation and drainage paper 55, Rome, FAO, 1996, www.fao.org/docrep/w2598e/w2598e00.htm#Contents.

85 EPA, "Water Quality Standards Handbook", 2015, water.epa.gov/scitech/swguidance/standards/handbook.

86 EC, Directive 2000/60/EC, Water protection and management – Water Framework Directive, eur-lex.europa.eu/legal-content/EN/TXT/?uri=URISERV:l28002b.

Water quality standards	Usage in horticulture
Drinking	Required for postharvest washing. Example: *E. Coli* or thermo-tolerant coliform bacteria shall not be detectable in any 100 ml sample (GlobalG.A.P., 2015).
Irrigation	Minimum water quality required for irrigation. Example: pH between 6.5 to 8. WHO[87] and FAO[88] provide a list of irrigation water quality parameters and guidelines on maximum allowed concentrations.
Emissions (Effluents)	Point sources of pollution, for example effluents from post-harvest activities or domestic water use. Example: 25 mg/l maximum BOD_5 concentration in urban wastewater after treatment (EC – Urban Wastewater Treatment Directive).[89]
Ambient	Crucial to understand the pollution situation of the water sources of interest, when relating these standards to actual levels of pollutants. Example: Surface and ground water shouldn't exceed a concentration of 50mg/l of NO_3.[90]

4.2. THE IMPACT OF AGRICULTURE ON WATER QUALITY

Globally, agriculture represents a major cause of degradation of surface and groundwater quality. According to FAO,[91] the main water quality problems directly associated with agriculture worldwide are salinization, nutrient loads in water sources due to leaching of fertilizers, and pesticide pollution. Sediments due to soil erosion are also a direct result of poor agricultural practices. The release of pathogens is an indirect pollution problem.

4.2.1. Salinization

Saline water is water with high concentrations of dissolved salts. 'Salt' does not only include common salt as we know it (sodium chloride NaCl, Na^+ and Cl^- in its dissolved form), but also other cations and anions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{2-}) or bicarbonate (HCO_3).

The salt concentration can be measured in parts per million (ppm) or parts per thousand (‰). Water is slightly saline between 1,000 to 3,000 ppm of salts, moderately saline between 3,000 and 10,000 ppm and highly saline between 10,000 and 35,000 (sea water has about 35,000 ppm of salts). Freshwater can naturally become saline by coming into contact with soil or geologic material that is high in salts. It can also

87 WHO, *Guidelines for the safe use of wastewater, excreta and greywater*, vol. 2. *Wastewater use in agriculture*, Rome, WHO, 2006, whqlibdoc.who.int/publications/2006/9241546832_eng.pdf?ua=1References Chapter 4.docx.

88 FAO, "Control of water pollution from agriculture", *op. cit.*

89 EC, Urban Wastewater Treatment Directive 91/271/EEC, eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271.

90 EC, Directive 2000/60/EC, Water protection and management – Water Framework Directive, *op. cit.*

91 FAO, *Agriculture and water quality interactions: a global overview*, Thematic Report 08, Rome, FAO, 2011.

become saline when evaporation concentrates naturally occurring salts, or in coastal areas, when there is saline water intrusion into freshwater sources.

When water has a relatively high proportion of sodium (Na^+) with respect to concentrations of the other cations (Ca^{2+}, Mg^{2+}), it is referred to as sodic water. The distinction is made because sodium has stronger impacts on soil and crops than other cations.

4.2.1.1. Causes of salinity

Salinity is a problem that concerns both soil and water, as one influences the other. Salinization is the process of accumulation of salts in the soil after evaporation of irrigation water containing salts. Some soils are naturally saline and/or sodic, but human activity such as application of certain fertilizers (e.g. KCl), soil amendments (gypsum or lime) and manure and wastewater applications, may contribute to soil salt problems. Because salts are water-soluble, if freshwater is applied to these soils, salts dissolve and can be washed away with drainage. However, if this drainage water is used downstream for irrigation, salts will be transported and deposited at the new location.

4.2.1.2. Impacts of salinity

Water is classified as 'saline' or 'sodic' when it becomes a risk for growth and yield of crops. As salinity in the soil increases, crop yield decreases. High salt concentrations prevent the uptake of water by plants causing crop-yield reductions. Salts accumulate in the root zone to such an extent that the crop is no longer able to extract sufficient water from the salty soil solution, resulting in water stress. If water uptake is appreciably reduced, the plant slows its rate of growth, with similar symptoms in appearance to those of drought. Soil salinization in its early stages of development reduces soil productivity, but eventually it can kill all vegetation and transform productive land to barren land[92] (Figure 1)

Figure 1 - Salt-affected field in Grand Valley, Colorado
Photo credit: Donald Suarez – Source: Salinity Forum, 2014

92 *Ibid.*

For each crop species, there is a threshold salinity below which there is no yield reduction, and then a decrease in yield with increasing salinity (Figure 2).

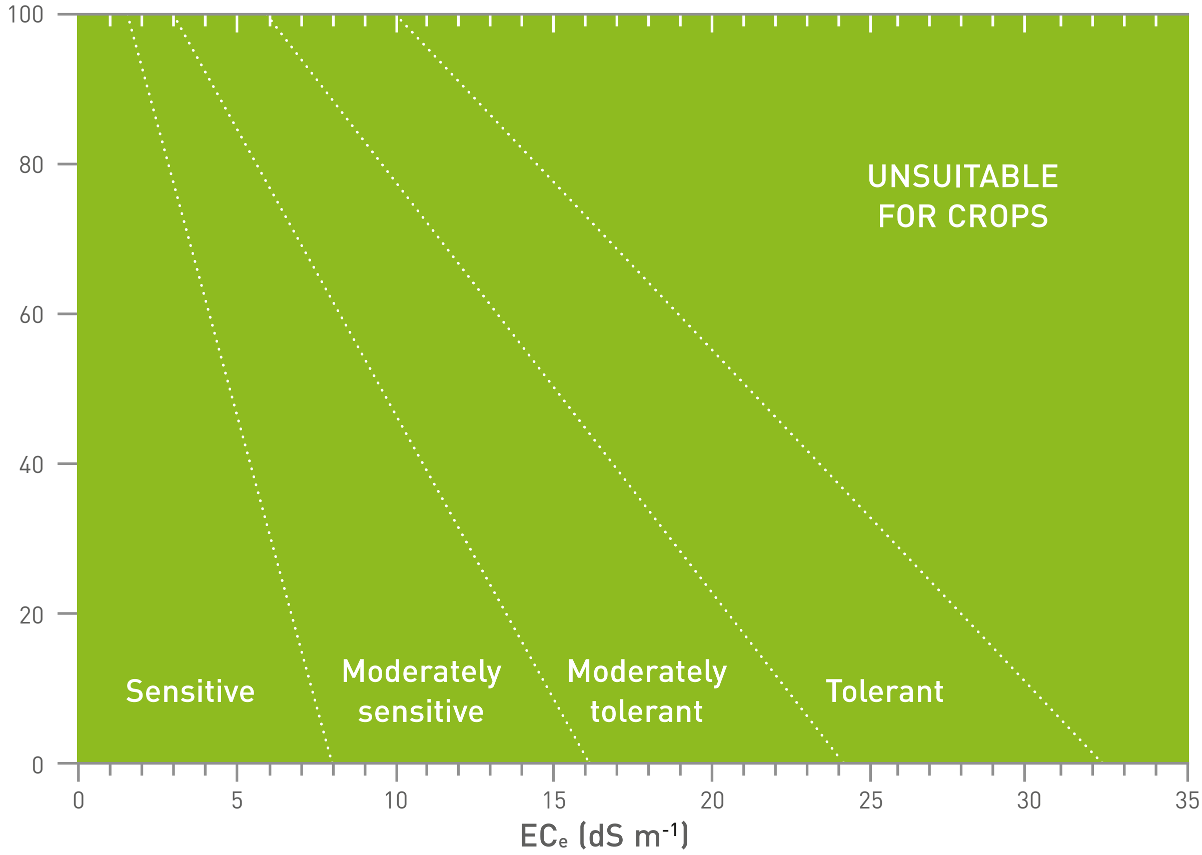


Figure 2 - Categories for classifying crop tolerance to salinity according to the USDA Salinity lab (2015)

In the case of Sodic water, depending on the type of soil (*i.e.* clay soils), sodium can change the soil physical properties leading to poor drainage and crusting. In addition, elevated sodium and chloride concentrations in water can harm plants due to direct toxicity. Sodium can also affect crop growth by causing calcium, potassium, and magnesium deficiencies.[93]

4.2.1.3. Measurement tools/methods

As explained at the beginning of this section, total dissolved solids are a good indicator of high levels of salts in water. This can be done cheaply with the help of a hydrometer (which measures the specific gravity of the water with respect to pure water and provides an indirect measure of salts) or a refractometer (which measures how much light refracts when it enters the water sample. The higher the concentration of salts, the more resistance the light will meet and the more it will bend. Refractometers are more accurate than hydrometers).

93 University of Montana, "Saline and/or sodic water and soils", 2015, waterquality.montana.edu/docs/methane/saline-sodic_faq.shtml.

Soil and water salinity can also be measured using an electrical conductivity meter. These devices send an electrical current through the material, and measure how much the material resists the flow of current. The more salts found in the water or soil, the higher the conductivity, which is expressed in deci-Siemens per meter (dS/m).

The sodicity of water is expressed as the Sodium Adsorption Ratio (SAR), which represents a mathematical ration between Na^+, Ca^2+ and Mg^2+ concentrations. Sodic water is defined as having a SAR greater than 12. If water has an EC greater than 4 ds/m (or 2 ds/m for horticulture) and a SAR greater than 12, it is considered saline-sodic (University of Montana, 2015). Both EC and SAR are therefore important parameters of water quality for irrigation.

If there are no measures available, a farmer may see a problem with saline/sodic soils, as it is often clearly visible. Excess soluble salts will often crystallize so that patchy white salt crusts will form. Also, saline soils tend to inhibit germination and emergence of plants so that growth in cropped fields will be poor and patchy. Under severe salt stress, herbaceous crops appear bluish-green; leaf tips burn, and older leaves die off. The field seems to grow in patches.

Finally, in order to manage and prevent high levels of salts in soils, the farmer needs to know levels of salt concentration in his/her irrigation water. If salts are high, the farmer needs to apply additional water to wash excess salts away. This additional water is known as the leaching requirement for salts.

4.2.2. Nutrients

Nutrients are essential for plants and are naturally present in soils. They are dissolved in water and absorbed by the plant's roots. They are divided into macronutrients, secondary nutrients and micronutrients. Nitrogen, Phosphorus and Potassium are macronutrients. Magnesium, Sulphur and Calcium correspond to secondary nutrients. Boron, Chlorine, Manganese, Iron, Nickel, Copper, Zinc and Molybdenum are micronutrients.

4.2.2.1. Causes of pollution by nutrients

Macronutrients are often lacking in soils as they are used by plants in large amounts; secondary and micronutrients are needed in smaller quantities by plants. Farmers use organic manures and synthetic fertilizers to make sure that plant nutrient requirements are met, especially in the case of macronutrients, and optimal crop yields are achieved.

The improper application of macronutrients can cause water quality problems both locally and downstream. Pollution occurs when the application of manure and fertiliser is made at times when nutrients can be easily washed away in surface runoff from rainfall, excess irrigation, or snow melt. It also occurs when the amounts applied cannot be fully taken up by the crop,[94] leading to runoff and leaching to reach surface and ground water sources. The timing and quantity of nutrient application are therefore critical.

94 EPA, 2015b. US Environmental Protection Agency. Nutrient Management. http://www.epa.gov/oecaagct/ag101/cropnutrientmgt.html

4.2.2.2. Impacts of excess nutrients in the environment

By synthetically manufacturing nutrients, humans have altered the global Nitrogen and Phosphorus Cycles on Earth. The super abundance of bio-available nitrogen and phosphorus creates enormous water quality problems. One of these problems is eutrophication, which is the enrichment of surface waters with plant nutrients (Figure 3). The presence of high levels of nutrients in water causes an increase in growth of water plants, phytoplankton, algae and macrophytes. This leads to an increase in biomass and major ecosystem changes and associated impacts. Most importantly, the increase in biomass and algal blooms can lead to deoxygenation of the water; in severe cases this results in the mortality of fish and other water life. Eutrophication can also cause a shift in habitat characteristics, with changes to composition of aquatic plant species, and the replacement of desirable fish by less desirable species (and respective economic loss). The production of toxins by certain algae increases operating expenses of public water supplies (to address taste and odour problems). Eutrophication can also lead to infilling and clogging of irrigation canals with aquatic weeds, loss of recreational use of water and impediments to navigation, etc.[95]

Figure 3 - Nutrient pollution often causes explosive algal growth which depletes waters of oxygen when the algae die. Toxic and foul smelling compounds may be produced.
Source: Weeks Bay NERRS site

95 FAO, "Control of water pollution from agriculture", *op. cit.*

Pollution by nutrients (mainly nitrate) also affects groundwater. In several areas of the world groundwater is polluted to the extent that drinking water standards for nitrate are violated. It is actually the most common chemical contaminant of the world's groundwater aquifers.

Shallow coastal marine areas also suffer the effects of excess nutrients which are eventually carried by rivers to the sea. Conditions of hypoxia (low oxygen levels in water) and anoxia (lack of oxygen in water) reported in these areas are associated with the surplus of nutrients.[96]

4.2.3. Pesticides

Pests (which include insects, mites, fungi, bacteria, viruses, nematodes, etc.) are living organisms that occur where they are not wanted or that cause damage to crops, humans or other animals. Any substance or mixture of substances intended for preventing, destroying, repelling or mitigating any pest is, therefore, a 'pesticide'. This includes insecticides, herbicides, fungicides, nematicides, rodenticides and various other substances used to control pests.[97] Synthetic pesticides were introduced from the 1940s and were seen as "miracle substances" because of the extent to which they helped to increase crop yields. According to EPA,[98] alongside plant breeding and fertilizer use, pesticides played a major role in the green revolution of the 50's, providing a massive boost to the quantity of food produced.

4.2.3.1. Causes of pollution by pesticides

About two thousand pesticide active ingredients (the chemicals in pesticide products that kill, control or repel pests) have been developed. These are available on the market as commercial products which combine the active ingredient with inert compounds and solvents.

A proportion of these active ingredients reach a destination other than their target (pests), entering air, water, soil, sediments and even our food, in particular where they are improperly applied. They can be found in rain, groundwater, streams, rivers, lakes and oceans. There are 4 major ways in which pesticides can reach water:[99]

- it can drift outside of the area where it was sprayed;
- it may leach through the soil (percolating and reaching groundwater);
- it can be carried as runoff;
- it may be spilled accidentally.

The movement of pesticides is complex and occurs not only within the area of application, but also may involve transportation over long distances due to their solubility (many active ingredients are soluble in water), volatility (potentially contaminating rainwater), adsorption to soil particles and/or persistent properties.

96 *Ibid.*
97 EPA, "About Pesticides", 2015, www.epa.gov/pesticides/about.
98 *Ibid.*
99 PAN, "Environmental Effects of Pesticides", 2015, www.pan-uk.org/environment/environmental-effects-of-pesticides.

As a result of more extensive water monitoring programmes since the 90s, especially in developed countries, an increasing number of pesticides are being detected in water bodies.[100] For example, studies by the UK government show that pesticide concentrations exceed those allowable for drinking water in some samples of river water and groundwater.[101]

Rates of increase in pesticide use are now greater in the developing economies. Global pesticide sales by region (Figure 4) show that this is the case for Asia, Latin America and to a lesser extent Europe (Eastern Europe). We can therefore expect added pressure on water resources due to these pollutants.

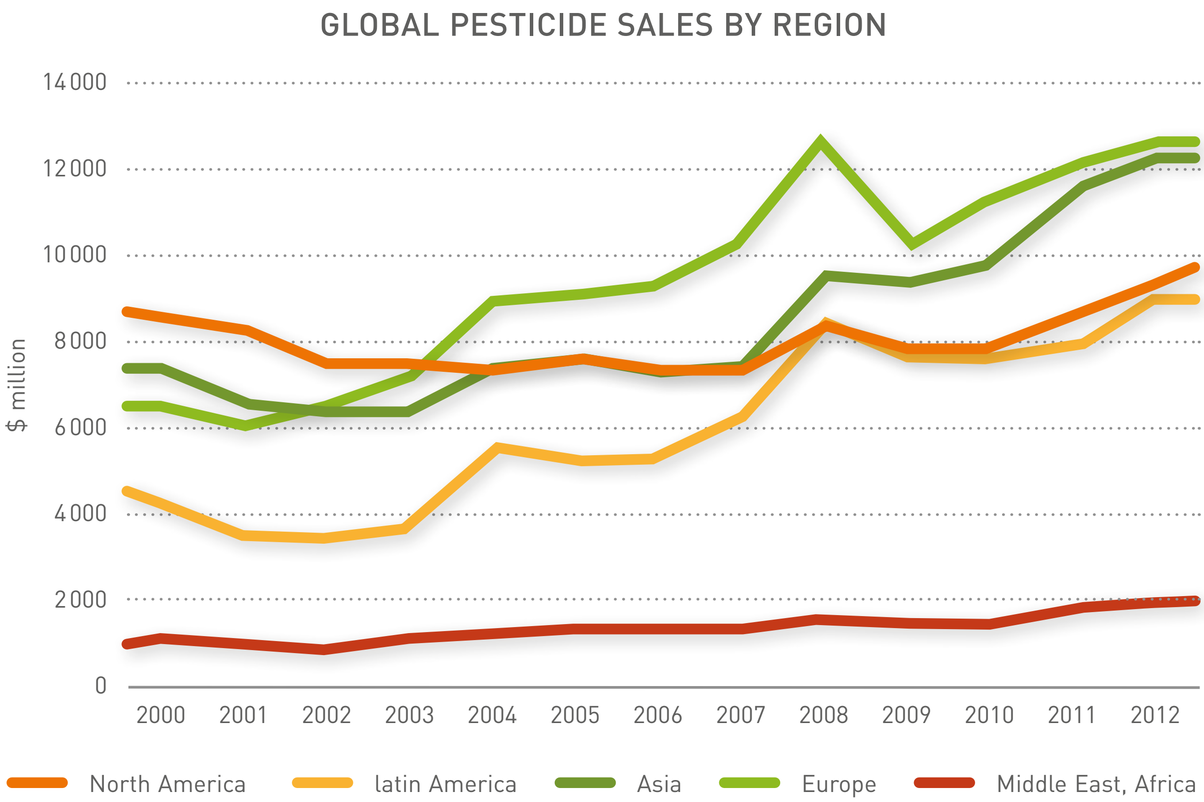


Figure 4 - Global pesticides sales by region
Source: The Washington Post, 2013

4.2.3.2. Impacts of pesticides

Chemical pesticides are synthetically manufactured; they do not exist naturally. Bio-pesticides are pest management agents based on living micro-organisms or natural products. From the 1980s and 1990s onwards bio-pesticides are available commercially and form part of integrated pest management strategies.[102]

100 FAO, *Agriculture and water quality interactions: a global overview, op. cit.*

101 PAN, "Environmental Effects of Pesticides", *op. cit.*

102 Chandler, D., Bailey, A., Tatchell, G., Davidson, G., Greaves, J. and Grant, W., "The development, regulation and use of biopesticides for integrated pest management", *Philosophical Transactions B*, vol. 366, iss. 1573, London, The Royal Society, 2011, rstb.royalsocietypublishing.org/content/366/1573/1987.

The problem with synthetic pesticides is that if they enter into the environment as pollutants, they can harm non-target organisms. Or if they enter the food chain at high levels, they could affect consumers. Pesticide pollution is in large part the result of pesticide miss-use. Recommendations for the use of each commercial product are designed to ensure that these potentially negative impacts are avoided or minimised. In addition, the more toxic early compounds have now been replaced by active ingredients that are lower risk.

4.2.3.3. Water quality standards and regulations related to pesticides

The European drinking water directive sets very stringent maximum admissible concentrations of 0.1 µg/l for any individual pesticide, and a maximum of 0.5 µg/l for the sum of all pesticides, in drinking water.

WHO[103] guidelines and US EPA maximum contaminant levels are derived from individual toxicity-based assessments of each substance. The US Pesticide National Synthesis Project[104] offers a list of types and sources of water-quality benchmarks of pesticides, providing EPA water quality standards for drinking water, ambient surface water, bed sediment and fish and shellfish tissue. It also provides human health benchmarks for pesticides, health-based screening levels as well as homologous Canadian guidelines.

A number of international initiatives have been created to address pesticide problems. With the increase of global trade of agricultural products, these multilateral agreements provide guidelines on pesticides use and are a basis for policy, since countries are legally bound. Some of these are:[105]

- The Rotterdam Convention, for information and consent, which puts chemicals in a global watch list from which governments must state whether they prohibit it or give consent to its import. This is the 'Prior Informed Consent' or PIC procedure.
- The Stockholm Convention, for eliminating persistent pesticides, has a timetable for reduction and eventual elimination of these pesticides.
- The Basel Convention, for halting hazardous waste trade, provides an international code of conduct on the distribution and use of pesticides, offering guidelines to protect health and the environment, monitor and collect data and phase out the most hazardous pesticides.

Additionally, FAO[106] issued the International Code of Conduct on pesticide management. This code of conduct is the framework for all public and private entities engaged in or associated with, production, regulation and management of pesticides.

103 WHO, "Guidelines for drinking water quality", 4th ed., 2011, www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en/

104 USGS, US Pesticide National Synthesis Project, 2014, water.usgs.gov/nawqa/pnsp/benchmarks/source.html.

105 PAN, "Environmental Effects of Pesticides", *op. cit.*

106 FAO, "Integrated Plant Nutrient Management", Rome, FAO, 2015, www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-plant-nutrient-management/ipnm-what/en/#b

4.2.4. Soil erosion and sediments

While soil erosion is a natural process, much of the more serious erosion is caused by human activity, in particular land use and practices on agricultural fields, woodlands, river banks, roads, construction, and mining sites. Soil erosion involves the loss of soil particles which are carried away by water or wind; this Chapter will focus on erosion by water.

Soil particles transported by water are referred to as sediment. Sediment in water is a complex mixture of mineral and organic matter. It is mainly comprised of small particles of clay, silt and fine sand, but it may also include medium and coarse sand and river gravels. Sediment also includes organic material, either eroded from soil or growing naturally in rivers and lakes. Transport of sediments in rivers is an important natural phenomenon for maintaining hydraulic equilibrium in river channels, for the natural development of river levees, for fertilising river flood plains and for providing sediment to coastal shorelines in order to avoid their erosion.[107]

4.2.4.1. Causes of erosion

Causes of erosion in agriculture are deforestation, overgrazing by farm animals, clearing of land for agriculture, and poor farming practices (Figure 5). Please refer to COLEACP, Training manual. *Sustainable and responsible production*, Section 2.3, for an in-depth overview of the causes of erosion.

Figure 5 - Tillage-induced soil erosion
Source: FAO.org

107 FAO, *Guidelines to control water pollution from agriculture in China – Decoupling water pollution from agricultural production*, FAO Water reports 40, Rome, FAO, 2013.

4.2.4.2. Impacts of erosion

Much of the excess sediment supply to rivers, lakes, estuaries and finally into oceans is associated with agriculture. Pollution by sediment has two major dimensions: physical and chemical. The physical dimension refers to the loss of top soil; at the source this leads to land degradation and the loss of productive potential. Downstream it leads to excessive levels of turbidity in receiving waters, and to off-site ecological and physical impacts from deposition of excess sediment in river and lake beds. The chemical dimension refers to the fractions of silt and clay in sediment that are primary carriers of adsorbed chemicals, especially phosphorus, pesticides, and heavy metals, and which are transported by sediment into the aquatic system (*ibid.*).

4.2.5. Pathogens

Livestock production and the associated organic manure is an important source of pathogens to water sources and associated health risks. So is untreated sewage from human settlements. The use of wastewater for irrigation entails potential sources of pathogens as well. Please refer to COLEACP, Training manual. *Sustainable and responsible production*, Section 4.2.3 for an overview of the main pollution risks associated with pathogens.

4.3. THE IMPORTANCE OF WATER QUALITY FOR AGRICULTURE

If farmers need water for irrigation, they need to find a suitable source, from resources that are physically and economically available. With general increasing competition for water and decreasing water quality, using marginal quality water for irrigation has become a common practice for millions of farmers worldwide. Marginal quality water is defined as: "water that possesses characteristics that have the potential to cause problems when it is used for its intended purpose". For example, brackish water or municipal wastewater are of marginal quality when used for agriculture because of high dissolved salt content and associated health hazards respectively. Marginal water quality can also affect crop yields, as shown in the example of yield reduction at different salinity levels (Figure 2).

Broadly, water for irrigation can be of marginal quality in three different ways:

- Chemical: salinity/toxicity hazards for the soil, plants and even the irrigation system through pipe corrosion or chemical clogging;
- Physical: blockage problems from suspended solid particles and other impurities;
- Biological: pathogens harmful to human and animal health as well as for the soil, plants, and the irrigation system.[108]

108 FAO, *Handbook on Pressurized Irrigation Techniques*, Rome, FAO, 2007, www.fao.org/docrep/010/a1336e/a1336e00.htm.

The following parameters should be assessed when marginal quality water is considered for irrigation.[109] Levels of each parameter should be compared to local irrigation water quality standards or, if these are not available, the standards proposed by WHO,[110] FAO[111] or Abbot and Hasnip[112] can be used instead.

- Total salinity (dS/m)
- Sodium content (meq/l)
- Calcium content (meq/l)
- Magnesium content (meq/l)
- Chloride content (meq/l)
- Boron content (meq/l)
- pH
- Trace elements concentrations (mg/l) (for example heavy metals and fluoride)
- Nutrient levels (mg/l)
- Faecal coliforms (number per 100ml)
- Intestinal nematodes (eggs per litre)
- Organic pollutants (μg/l)

According to FAO,[113] the most common types of marginal-quality water are:

- wastewater from domestic and other urban activities,
- saline or sodic agricultural drainage water and groundwater.

4.3.1. Urban wastewater use in agriculture

Urban wastewater is usually a combination of domestic effluents (water from kitchens and bathrooms), effluents from commercial or institutional establishments, including hospitals, industrial effluents when present, and storm water and other urban runoff.

In agriculture, wastewater can be used treated or untreated, in direct or indirect ways. Direct use of untreated wastewater occurs when it is directly disposed of on land used for cultivation, whereas direct use of treated wastewater occurs when water is recycled for agriculture after treatment, usually in a planned way. Indirect use of treated or untreated urban wastewater occurs when water from a river receiving the urban wastewater is abstracted by farmers downstream for irrigation.

109 Abbott, C.L. and Hasnip, N.J., *The safe use of marginal quality water in agriculture. A guide for the water resource planner*, HR Wallingford. Report OD 140, 1997, eprints.hrwallingford.co.uk/101/1/od140.pdf.

110 WHO, *Guidelines for the safe use of wastewater, excreta and greywater, op. cit.*

111 FAO, *Agriculture and water quality interactions: a global overview, op. cit.*

112 Abbott, C.L. and Hasnip, N.J., *The safe use of marginal quality water in agriculture. A guide for the water resource planner, op. cit.*

113 FAO, *Agriculture and water quality interactions: a global overview, op. cit.*

Wastewater often contains a variety of pollutants: salts, metals, pathogens, residual drugs, organic compounds, endocrine disruptors and active residues of personal care products. Many of these substances remain in the water even after treatment. They can harm human health: farmers can suffer harmful effects from direct contact with the wastewater, while consumers are at risk from eating vegetables and cereals irrigated with wastewater.[114]

Wastewater use for agriculture can also harm the environment, especially in relation to soil and groundwater pollution. Generally the use of domestic wastewater poses less risk to the environment than the use of industrial wastewater. The problem is that in many countries, industrial discharges containing toxic chemicals are mixed with domestic wastewater. Efforts should be made to reduce the mixing and the use of this mixed wastewater for agriculture (*ibid*).

The use of treated wastewater in agriculture may also have positive effects: it is a new source of fertilizers as wastewater contains macro and micro nutrients, and is available all year round. Agricultural use can even provide low-cost wastewater treatment as a result of the capacity of soil and plants to naturally remove contamination. FAO[115] recognizes that with careful planning and management, the use of treated wastewater for agriculture can be beneficial to farmers, cities and the environment.

Use of untreated wastewater is not recommended. However, in reality, surface irrigation with untreated wastewater is substantially higher than irrigation with treated wastewater, especially in developing countries.[116]

Guidelines are available to support farmers in the use of wastewater for agriculture. They provide guidance on the parameters that should be assessed to avoid or minimise health and environmental hazards, and to assure optimum crop yields. For example, the World Health Organization[117] issued guidelines for the safe use of wastewater in agriculture. FAO[118] lists important agricultural water quality parameters, which are relevant in relation to the yield and quality of crops, maintenance of soil productivity, and protection for the environment. These include: total salt concentration, electrical conductivity (EC), sodium adsorption ratio (SAR), toxic ions, trace elements and heavy metals, and pH.

Through the application of specific management strategies, farmers can maximize the benefits from the use of treated wastewater in agriculture. This requires a proper assessment of the water quality parameters relevant for agriculture. Some of them are:[119]

- An adequate selection of crops, agricultural practices and technologies: The right irrigation technology and agricultural practices should be chosen to manage suspended solids that would otherwise cause clogging. Crops

114 *Ibid.*
115 *Ibid.*
116 *Ibid.*
117 WHO, *Guidelines for the safe use of wastewater, excreta and greywater*, *op. cit.*
118 FAO, "Control of water pollution from agriculture", *op. cit.*
119 FAO, *Agriculture and water quality interactions: a global overview*, *op. cit.*

that are resistant to low water quality and high salinity should be selected. For example, salt tolerance of Artichoke is high (6.1 dS/m), of cucumber medium tolerance (2.5 dS/m) and of strawberry low (1.0 dS/m).[120]

- Management of nutrients to meet crop requirements: wastewater can be rich in nutrients, and farmers should measure or at least have an indicator of the average nutrient content of wastewater, to adjust nutrient application and avoid excess.
- Approach to market and consumers: buyers are often reluctant to buy products irrigated with wastewater. Transparency is needed, but also strengthening consumer confidence, for example through certification programmes on the production of crops in a safe environment and the safe use of wastewater.

The existing policy on how a government supports farmers for the use of wastewater in agriculture is also of fundamental importance in order to maximize benefits and minimize risks. A robust policy should be in place for this. However, in many countries where wastewater is used in agriculture, these policy frameworks are lacking or are very weak. An essential issue is to know the local current institutional framework well and to clarify the role of the different institutions (ministries, agencies) at both national and local level. In case of lack, WHO[121] provides complete guidelines for the wise use of wastewater, excreta and grey water in agriculture. As mentioned above, other good references are FAO[122] and Abbot and Hasnip.[123]

4.3.2. Saline and sodic water use in agriculture

The salinity and sodic problems were explained above. Total salt concentration (for all practical purposes, the total dissolved solids) is one of the most important agricultural water quality parameters. Plant growth, crop yield and quality of produce are affected by the total dissolved salts in the irrigation water. Equally, the rate of accumulation of salts in the soil, or soil salinization, is also directly affected by the salinity of the irrigation water. In FAO's report on Agricultural Drainage Water Management,[124] the reader can find an extensive annex with crop salt tolerance data.

4.3.3. Arsenic-laden water use in agriculture

Natural arsenic in groundwater at concentrations above the WHO drinking water standard of 10 µg/litre is not uncommon[125]. Humans contribute also with arsenic loads to water sources, through mineral extraction and waste processing, poultry and swine feed activities, pesticides and highly soluble arsenic trioxide stockpiles

120 FAO, "Agricultural drainage water management in arid and semi-arid areas", FAO irrigation and drainage paper 61, Rome, FAO, 2002, www.fao.org/docrep/005/y4263e/y4263e00.htm#Contents.

121 WHO, *Guidelines for the safe use of wastewater, excreta and greywater*, *op. cit.*

122 FAO, *Agriculture and water quality interactions: a global overview*, *op. cit.*

123 Abbott, C.L. and Hasnip, N.J., *The safe use of marginal quality water in agriculture. A guide for the water resource planner*, *op. ci*

124 FAO, "Agricultural drainage water management in arid and semi-arid areas", *op. cit.*

125 FAO, *Agriculture and water quality interactions: a global overview*, *op. cit.*

(used in many commercial applications as precursor to forestry products, in colourless glass production and in electronics). Estimates of arsenic toxicity from drinking water, causing skin lesions and various types of cancers, indicate about 130 million people are impacted (*ibid.*). There is also a concern about potential levels of arsenic entering the food chain through absorption by crops from irrigated water.

Although the chemistry of arsenic is well understood, the severity of the problem has not been quantified, for example the presence of arsenic in the food chain. Uptake and toxicity of arsenic in crops currently cannot be predicted. FAO[126] has studied some management options for prevention and mitigation of Arsenic contamination of agricultural land. In the case of rice for example, specific experiments have proven that growing rice in an aerobic environment where arsenic is adsorbed on oxidized Iron surfaces, makes this pollutant unavailable to paddy rice. Arsenic is present in the list of inorganic constituents of health significance in drinking water.

4.4. AVOIDING WATER POLLUTION FROM DIFFUSE SOURCES

Overall, water pollution from agriculture can be avoided or reduced in two ways: 1) treatment of wastewater, and 2) decreasing the release of pollutants into the environment, therefore decreasing the chances that pollutants will reach water sources.

1. Treatment is an option for point sources of pollution, because the effluent can be easily collected and treated. However, in reality, treatment of agricultural wastewater is uncommon except for special cases, for example with constructed wetlands or a buffer zones, or in high tech closed systems such as hydroponics (Figure 6). Diffuse or non-point sources of pollution, typically produced by agriculture (and addressed in this chapter), are more difficult to treat, simply because it is more difficult to collect the effluent.
2. A variety of practices exist to decrease discharges of pollutants into the environment.

126 *Ibid.*

Figure 6 - Riparian forest along a river bank in Benin
Source: en.wikipedia.org/wiki/Wildlife_of_Benin

The first step to avoiding water pollution from diffuse sources from agriculture is to be aware of the very important impacts of agriculture on the environment and on health. Second, to assume a responsible attitude in order to inform yourself and study the best possible options. Often, a significant part of water pollution can be avoided with simple changes at the farm level and of agricultural practices. Below we introduce some widespread techniques.

4.4.1. Nutrient management planning

Nutrient management refers to managing crop nutrient inputs (organic materials, livestock manure and by-products, and inorganic commercial fertilizers) both for efficient crop growth and water quality protection. Nutrient management plans are farm strategies designed to achieve these two goals. They can be described in 4 basic steps:

1. knowing what you have;
2. knowing what you need;
3. managing wisely; and
4. documenting your management.

Nutrient management plans must be site-specific, tailored to the soils, landscapes and management objectives of the farm.[127] It should be done based on in and outflows of Nitrogen and Phosphorus. Step 1 implies that the soil needs to be tested for nutrient content, in order to provide recommendations on best application rates for that specific soil and crop.

4.4.2. Integrated plant nutrient management (IPNM)

This technique comes from the recognition that plant nutrient needs can best be provided through an integrated use of diverse plant nutrient sources. It thus embraces soil, nutrient, water, crop, and vegetation management practices, tailored to a particular cropping and farming system, undertaken with the aim of improving and sustaining soil fertility and land productivity and reducing environmental degradation. IPNM aims to optimise the condition of the soil, with regard to its physical, chemical, biological and hydrological properties, for the purpose of enhancing farm productivity, whilst minimizing land degradation.[128] It does so by combinations of complementary crop, livestock and land husbandry practices which maximize additions of organic materials and recycle farm wastes, so as to maintain and enhance organic matter levels.[129]

4.4.3. Integrated pest management (IPM)

IPM is an ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimise the use of pesticides. For example, in IPM physical methods such as mechanical weeders are combined with chemical methods using herbicides. The COLEACP Training manual "*Integrated management of bioagressors*" (2017), details the IPM approach as part of an integrated crop management (ICM) strategy that aims to move towards sustainable farming.

The main principles of IPM are:[130]

- Use of synthetic chemical pesticides that have high levels of selectivity and are classed by regulators as low-risk compounds.
- cultivation practices such as crop rotation, intercropping, undersowing;
- physical methods such as mechanical weeders;
- natural products such as semio-chemicals or biocidal plant extracts;
- biological control with natural enemies;
- decision support tools to inform farmers when it is economically beneficial to apply pesticides and other controls.

127 Mississippi State University, "Nutrient Management", 2015, msucares.com/crops/soils/nutrient.html.

128 FAO, Plant nutrition for food security. A guide for integrated nutrient management. Rome, FAO, 2006, ftp.fao.org/docrep/fao/009/a0443e/a0443e.pdf.

129 FAO, "Integrated Plant Nutrient Management", *op. cit.*

130 Chandler, D., Bailey, A., Tatchell, G., Davidson, G., Greaves, J. and Grant, W., "The development, regulation and use of biopesticides for integrated pest management", *op. cit.*

4.4.4. Erosion control

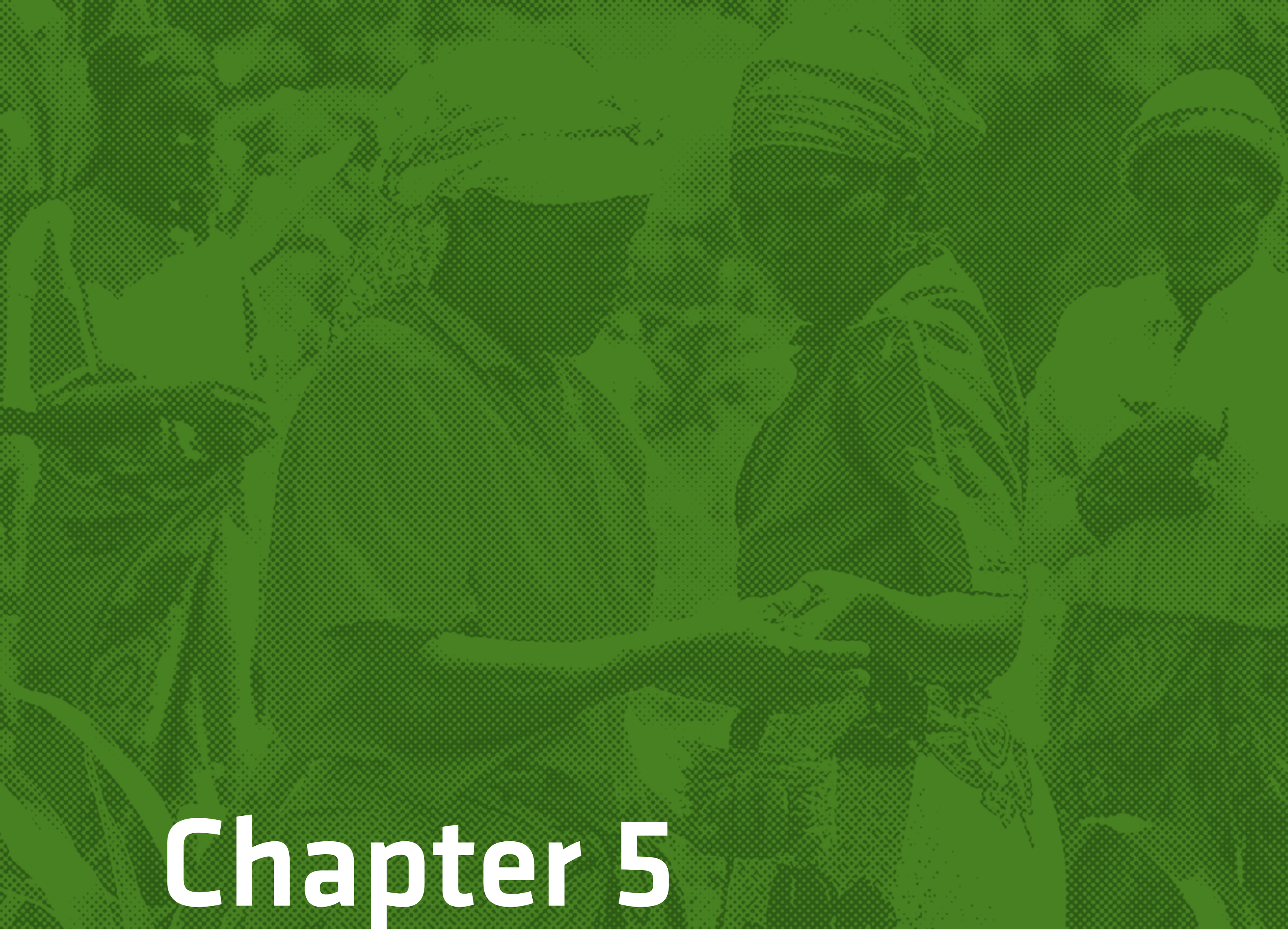
Erosion can be easily reduced by land-use practices at the farm level. Please refer to COLEACP, Training manual. *Sustainable and responsible production*, Section 2.4, for an overview of key practices to protect soils and counter erosion. Chapter 6 of this manual presents a list of good farming practices for water conservation, which include erosion reduction.

4.4.5. Capture and treatment of agricultural runoff

Agricultural runoff and drainage can be captured so that after watering the fields, the drainage water is passed through man-made structures such as gravel beds or constructed wetlands, which work as natural water cleaners. If there is space in the field to do so, this is a cheap, simple and environmentally friendly way to treat water and trap pollutants such as nutrients.

4.4.6. Recycling

Potential applications for "used" water within the same farm should be assessed. For example, if water quality is acceptable, water used for processing and washing can subsequently be used for irrigation.



Chapter 5

Irrigation

5.1. INTRODUCTION

5.1.1. 5.1.1. Context

What we know today as irrigation and the different irrigation methods is the result of thousands of years of development. Human irrigation started around the year 6000 BC, when Egyptians and Mesopotamians started to use the flooding pattern of rivers to irrigate fields. Nile floods were used to inundate depressed areas surrounded by dykes that were used as water reservoirs. Already by the year 3500 BC, Egyptians measured river levels with the so-called 'Nilometers'.[131] Archaeological evidence of canal irrigation and water storage systems in the Indus valley in north India, has been dated to stem from 2600 BC, whereas terrace irrigation and water capture and storage systems were developed in Latin America around 750 BC.[132] In Europe, the Romans already used cement pipes to carry water. They built the first aqueduct around the year 300 BC.[133]

The water and irrigation infrastructure and techniques used in agriculture today directly stem from the heritage of centuries of water engineering in all these civilizations. Still, even today, irrigation is practised in similar ways in many areas. However, in addition, very modern and highly technical systems are also being used.

Irrigation is meant to fulfil the crop water requirements when rainfall is insufficient to ensure optimal crop growth. As we have seen, factors that influence crop water requirements are: type of crop, cropping system, climate, type of soil and topography. Depending on these factors, appropriate irrigation systems and methods need to be chosen and implemented. Irrigation can also be used for non-agricultural purposes such as maintenance of landscapes, reestablishment of vegetation or to prevent soil consolidation.

This Chapter addresses the different existing irrigation methods available. Section 5.3 presents the factors that affect the selection of the most appropriate irrigation method. The layout and design of irrigation schemes are explained in Section 5.4. Finally, Section 5.5 presents water treatment and water recycling methods from the point of view of improving irrigation efficiency, which is addressed in Section 5.6.

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131 Whitcher, B., Byers, S., Guttorp, P. and Percival, D., "Testing for Homogeneity of Variance in Time Series: Long Memory, Wavelets and the Nile River", *Water Resources Research*, No. 38, 2002.

132 Bifani, P., *Medio ambiente y desarrollo sostenible*, 4th ed., Madrid, Instituto de Estudios Políticos para América Latina y África (IEPALA), 1999.

133 Hansen, R., "Water and wastewater systems in imperial Rome", Waterhistory.org, 2015, www.waterhistory.org/histories/rome/rome.pdf

5.1.2. Important considerations

While irrigation may be critical for optimum crop yield, the method used, and the general good management of irrigation systems, have important implications. Irrigation is a major user of water, particularly for intensive crops such as horticulture. This can create problems and conflict if there are other users (including households and smallholders) competing for scarce water supplies. The more basic systems can be particularly problematic; flood irrigation for example, may be more achievable and affordable in low technology production systems, but also tends to be less efficient in terms of water use.

Improving the type of irrigation system, as well as ensuring good maintenance and management practices, can relieve pressure on water supplies. For farms and businesses, it can also provide substantial cost savings in terms of abstraction costs, pumping (fuel) costs, and fertiliser purchases.

5.2. IRRIGATION METHODS

A large variety of irrigation methods exist. These can be grouped into two main types:

- surface gravity irrigation: basin, furrow and border;
- pressurized irrigation: sprinkler and drip irrigation.

5.2.1. Surface gravity irrigation methods

Surface gravity irrigation methods have been used for centuries and still are the most widely used. In the 20th century, this method has been highly improved thanks to technology. The logic of the method is that it uses soils as a conduit, and gravity as a conductor. Water is applied to the field using siphons or turnout structures, and flows across the surface until it covers an area. Water then either runs off the field or ponds on the surface. The drainage period is segregated into the depletion phase, known as the interval between cut off and the appearance of the first bare soil under the water, and the recession phase. Recession begins at that point and continues until the surface is drained.

This method is normally used under conditions of mild and regular slopes, soil type with medium to low infiltration rates and medium to fine textures. The aim is to promote lateral spread of water on the surface of the field. Under these conditions, surface gravity irrigation is the cheapest and easiest irrigation method, as no extra investments are needed for levelling or machinery. The most common surface gravity irrigation methods are basin, border and furrow irrigation.

5.2.1.1. Flood irrigation method (or basin irrigation)

Figure 1 - Ancient Inca terraces in Peru[134]

The most common land shape found for this type of irrigation is square, however, it can also be found in rectangular or other irregular shapes. The basis of basin irrigation is that the field is levelled in all directions, but very smoothly (no more than 0,1%), making water flow in all directions and preventing runoff by surrounding dykes, causing an undirected flow of water into the field. As mentioned before, this method is most recommended for flat lands, as the labour and technology investment is low. On sloping lands, basins can be created as terraces (Figure 1).

Flood irrigation is not very efficient if we compare it with other modern types of irrigation. Around half the water may be lost through evaporation, runoff or percolation. However, there are practices that can be used to improve the efficiency of the method. For example, precise land levelling using laser technology, flooding in intervals, or recycling runoff water.

Flood irrigation is suitable for many field crops. In horticulture, flood irrigation is used for example in the early growth stage of citrus. It is especially good for closely spaced and deeply rooted crops such as paddy rice, pastures and cereals. For horticultural purposes, loamy soils are preferred.[135] Flood irrigation could also be used as a control measure for pathogens and pests and their associated risks. A long flooding period could reduce them.

134 Wright, K.R., Zegarra, A.V. and Lorah, W.L., "Ancient Machu Picchu Drainage Engineering", *Journal of Irrigation and Drainage Engineering*, November/December 1999.

135 FAO, *Irrigation Water Management. Irrigation Methods*, Training Manual No. 5, Rome, FAO, 1988, www.fao.org/docrep/s8684e/s8684e00.HTM.

5.2.1.2. Border irrigation method

Figure 2 - Tree crops irrigated by a surface border system

This method is a modification of basin irrigation. It is appropriate for sloping fields, normally with long and rectangular shape (Figure 2).[136] The main feature that differentiates it from the basin method is that the intention is not to contain water, but to make it flow down the field. This method requires fields with a uniform slope in one direction, not steep (0.05%-2%), in order to avoid soil erosion problems. It is suitable for large mechanized farms. Water is released at the high end and the borders guide the water flow, which uniformly spreads across the field as a shallow sheet.[137]

The fields can have a length of more than 800 m and a width from 3 to 30 m. Heavy clay soils are not recommended for border irrigation, as they have a low infiltration rate. Medium loam soils with medium infiltration rates are preferred. Controlling the amount of water that is released is the key to this method. If the water flow stops too soon, it may not cover the entire surface. If water is released for too long, it will accumulate at the lower end of the field and will be subsequently lost through the drainage system. As rule of thumb, in sandy soils, the water flow is not stopped until it reaches the other end of the field, whereas in clay soils, water is normally stopped when it covers around 60% of the soil in the field. Wheat and other small grains are suitable for this method.

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136 UCCE, "Ground Water Protection Area. Irrigation Systems and their Performance", San Diego, UCCE, 2005, www.sswm.info/sites/default/files/reference_attachments/UCCE%202005%20Irrigation%20Systems%20and%20their%20Performance.pdf.

137 Tacker, P., "Border irrigation good alternative", Delta Farm Press, 2003, deltafarmpress.com/soybeans/border-irrigation-good-alternative.

5.2.1.3. Furrow irrigation method

The main feature of this method is trenches or furrows dug between crop rows (Figure 3). Water is released in the upper end from the field canal with siphons or spills. Subsequently, it flows down the furrows by gravity and it seeps vertically and horizontally to replenish the soil water reservoir.

Figure 3 - Furrow irrigation. Source: www.morguefile.com

In contrast to basin or border methods, furrow irrigation allows irrigation for each furrow to be controlled individually. This provides an opportunity to manage irrigation more effectively and increase irrigation efficiency. Another practice that helps to increase efficiency is to replace continuously flowing siphons with pipes that have closable gates for each furrow, so called gated pipes. The main advantages of furrow irrigation vs flood are that:

- irrigation is possible in standing crop canopy; and
- the water surface is smaller and therefore the evaporation losses smaller.

Slopes should not to be greater than 2%. Almost all soils are appropriate except for sandy soils because of their high infiltration rate. Stream size must be adapted to the conditions, but it shouldn't be higher than 3 litres per second. Furrow irrigation works well for almost all kinds of crop, including row crops such as tree crops. Crops like potatoes and tomatoes that normally do not perform well under basin or border flooding irrigation, can be effectively irrigated with furrow irrigation.

Both crops are sensitive to water covering plant leaves. In furrow irrigation, there is no direct contact between water and the crop foliage as plants are placed on the ridges and the water flows through the furrows. This method requires more labour time investment. Furrow irrigation is cheap and low-tech, making it particularly attractive in places where mechanized irrigation is difficult to apply.[138] [139]

5.2.2. Pressurised irrigation methods

Pressurized irrigation systems are appropriate for any surface, including irregular surfaces, and they usually offer a more effective and efficient application of irrigation water to the crops. As their name suggests, these irrigation systems apply water under pressure through a system of hoses and pipes. The most common pressurised irrigation methods are sprinkler, water cannon and drip irrigation systems. Generally these systems can provide a more precise water application to fields and crops. These irrigation systems can also improve land and water use efficiency and reduce labour demand.[140] Pressurised irrigation methods make better use of water resources and are especially recommended for water scarce areas. Obviously, another key difference with the traditional surface irrigation systems is that pressurized methods require external energy to build up the required water pressure (minimum 2-3 bars provided by pumps or reservoirs at higher levels).[141]

5.2.2.1. Sprinkler

This irrigation method intends to simulate rain and is also called overhead irrigation. It is used worldwide in small and large fields. This system can simply consist of long hoses with sprinklers along its length, or may have a centre-pivot system that traverses a circle in the field. The most common in small or medium size farms are hand-move systems with relatively low operating pressure (no more than 3.5 bars) with sprinklers spaced uniformly along the lateral lines, and mounted at equal spaces in the fields, so water is sprinkled uniformly in the entire area. This system is adequate for full coverage of crops like cotton or maize. However, other type of sprinklers such as mini-sprinklers can also be used for tree crops.

Sprinklers are equipped with two nozzles for the discharge of water: the range and the spreader. The range nozzle, larger in diameter, shoots a water jet and covers the area distant from the sprinkler, and it activates the rotating system at the same time. The spreader nozzle sprays the water closer to the sprinkler (Figure 4). Both of them can be managed, adaptable according to crop and other circumstance. One of the factors that highly influence the use of sprinklers is wind. The space between sprinklers must be altered according to wind conditions, and under strong wind conditions sprinklers are not recommended.

138 FAO, *Irrigation Water Management. Irrigation Methods, op. cit.*

139 Walker, W.R., "Guidelines for designing and evaluating surface irrigation systems", Irrigation and drainage paper No. 45, Rome, FAO, 1989, www.fao.org/docrep/t0231e/t0231e00.htm#Content.

140 ICID, "Irrigation and drainage journal", 2014, www.icid.org/press_irri.html.

141 Phocaides, A., *Technical handbook on pressurized irrigation techniques*, Rome, FAO, 2000, ftp.fao.org/agl/aglw/docs/pressirrig.pdf.

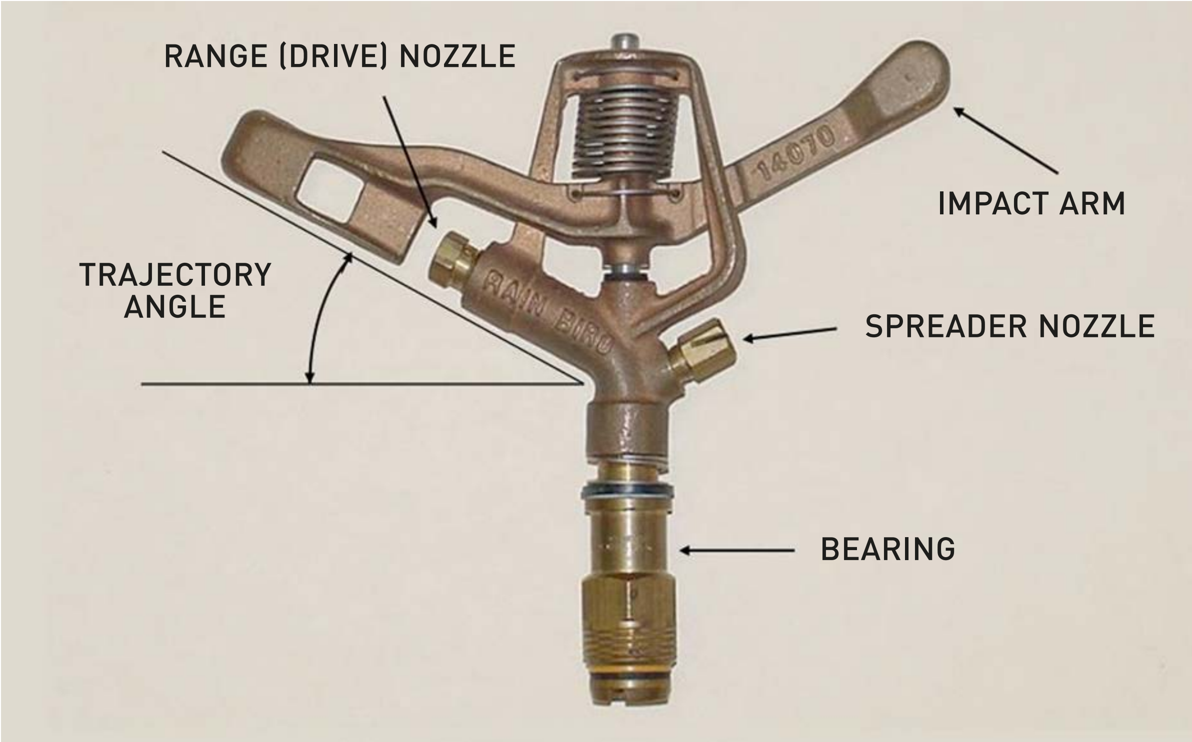

Figure 4 - Different parts of an impact sprinkler
Source: www.slideshare.net/kaushalgadariya/sprinkler-irrigation-kvg

Sprinkler irrigation systems are adaptable to all types of soils, crops and surface conditions (Figure 5). They can reach water efficiencies above 75% (see Section 5.6 for definition of water efficiency). Installation and operation are relatively cheap and easy and do not require advanced skills, although sprinkler systems require a considerable labour and time when operating without the appropriate machinery. And, importantly, the systems require careful maintenance.

Figure 5 - Sprinkler irrigation on an African farm. Source: climatetechwiki.org

Another pressurised irrigation method is water cannon irrigation that can be considered as a variation of the sprinkler system. This uses a large-capacity nozzle and high pressure in order to throw water out over the crop as the outlet is pulled along an alley in the field (Figure 6). This system is particularly adaptable to various crop heights, travel speeds, odd-shaped fields, and rough terrain. This system requires a higher (but still moderate) initial investment and more labour than other sprinkler systems.[142]

Figure 6 - Water cannon or big gun system

5.2.2.2. Drip irrigation

In this method water is applied to each plant separately in precise quantities through dripper emitters. Water is dropped continuously at the same point, moving vertically into the soil and wetting the root zone by gravity, and laterally by capillary action. **Also known as trickle irrigation, micro irrigation or localized irrigation**, this method allows water to drip slowly to the roots of plants, either from the soil surface (Figure 7) or underground, directly into the root zone. The system works through a sometimes complex mechanism of valves, pipes, tubing, and emitters, delivering water directly to the base of the plant.[143]

142 Scherer, T., "Selecting a Sprinkler Irrigation System", Fargo, NDSU, 2010, www.sswm.info/sites/default/files/reference_attachments/SCHERER%202010%20Selecting%20a%20Sprinkler%20Irrigation%20System.pdf.

143 ICID, "Irrigation and drainage journal", *op. cit.*

Figure 7 - Surface drip irrigation

The application of drip irrigation varies depending on the soil type, texture and structure. In medium-heavy soils of good structure, the lateral movement of the water beneath the surface is greater than in sandy soils. If the discharge rate of the dripper exceeds soil intake rate and hydraulic conductivity, water ponds on the surface. This results in more of the moisture spreading laterally than vertically.

Modern drip irrigation began its development in Afghanistan in the second half of the 19th century, when researchers began experimenting with irrigation using clay pipes to combine irrigation and drainage systems.

It is important to differentiate between pressurized drip irrigation systems and gravity-driven drip irrigation systems, in which pressure is given by gravity, not from an external power source. This gravity system is most applicable for small areas, and is especially cost effective if the local climate provides enough rainfall to keep a reservoir filled using rain water harvesting (see Part 2 of this manual). The basic system consists of an elevated reservoir with a pipe at the bottom, providing water into a basic drip irrigation system that can be managed either by hand or with a battery powered timer to control the rate at which the crop is watered.[144] An example of this basic system can be seen in figure 8.

144 Standish, S., "How to Irrigate On A Shoestring", Portland, Global Envision, 2009, www.globalenvision.org/2009/11/19/how-irrigate-shoestring;
Infonet-biovision (ed.), *Water for Irrigation*, Zürich, Biovision, 2010.

Figure 8 - Self-made irrigation system in Africa with a bucket as a water reservoir and simple plastic hoses for distribution

The main advantages of drip irrigation are the potential increases in yield as it can be used to keep the soil close to field capacity, and therefore provide optimum water and nutrient transport to the roots. It is also more efficient and decreases water and fertilizer use, as water can be applied according to crop needs. It also has lower labour requirements, provided that the system is managed correctly.

Using drip irrigation, it is possible to consider the use of fertigation. This involves adding water soluble products such as fertilizers, nutrients, or soil amendments to the irrigation water. The higher efficiency of drip irrigation, providing the precise volumes of water needed by plants directly into the root zone, can also be used to add precise volumes of nutrients according to plant needs. As this can reduce the overall use of water and fertilizers it can save money, as well as reducing soil erosion or runoff.

With drip irrigation it is also possible to irrigate irregularly shaped land areas that are not suitable for flood irrigation, and to use water that is higher in salt content. Low soil moisture tensions in the root zone can be maintained continuously by providing frequent water applications. Salts dissolved in the irrigation water accumulate at the periphery of the wetted soil mass, and thus plants can easily obtain the moisture needed. This enables the use of slightly more saline water, which couldn't be used in the other irrigation methods described.

On the other hand, drip irrigation is a relatively expensive method and requires careful and frequent maintenance, and precise management. Frequently drippers get clogged with sediment or salts and need replacing.

Table 1. Overview of different irrigation methods

Method		Efficiency (%)	Surface area flexibility	Soil characteristics	Economic cost (technology, energy…)	Labour intake (Operation, maintenance…)
Surface	Basin	60-65	Low	Fine texture, low/medium infiltration rate	Low	Med/high
	Furrow					
	Border					
Sprinkler		80-87.5	Medium	Medium/high infiltration rate	Med-high	Medium
Drip		95	High	Medium/high infiltration rate	High	Low

5.3. CHOOSING APPROPRIATE IRRIGATION METHODS

5.3.1. Overview

In order to find the most appropriate irrigation method for a specific crop and situation, it is important to know their particularities, advantages and disadvantages, as well as the different natural, social and economic factors involved. A general overview of these factors and the most recommended method for each case is shown in table 2. However, in many cases there is no single best solution: all methods have their pros and cons.[145] What is crucial is to have a good knowledge of the local circumstances prior to any decision.

145 FAO, *Irrigation Water Management. Irrigation Methods, op. cit.*

Table 2. Overview of circumstances (factors) and recommended irrigation methods for each case (elaboration by Good Stuff International)

Factors			Recommended method	Comments
Natural conditions	Soil type	Low infiltration rate	Surface	Surface irrigation works better in low infiltration rate soils, whereas sprinkler and drip methods are suitable for high infiltration rates
		High infiltration rate	Sprinkler/drip	
	Slopes	Irregular	Drip	Flat slopes are suitable for surface irrigation methods. Also in higher slopes by building terraces. Drip irrigation is more flexible for irregular surfaces.
		Flat	Surface/ sprinkler	
	Climate	Rainy	Surface	For dry areas, sprinklers or drip irrigation are more water efficient. In windy areas, sprinklers are not recommended.
		Dry	Sprinkler/drip	
		Windy	Surface/drip	
Natural conditions	Water availability	Constant	Surface	In areas with reliable water sources, surface irrigation is adequate. In water scarce or seasonal regions, sprinklers or drip are recommended.
		Seasonal	Surface/ sprinkler	
		Scarcity	Sprinkler/drip	
	Water quality	Salty	Surface/drip	Salty waters are easily dissolved through sprinklers, but if water is high in sediments, they are not recommended as this clogs emitters.
		High in sediments	Surface	
Type of crop	High value crops		Sprinkler/drip	As drip or sprinkler irrigation can reach higher levels of efficiency, high value crops like fruits trees or some vegetables are suitable to pay back the costs. For individual trees or vegetables, drip irrigation is recommended. Sprinkler irrigation is commonly used for seed germination and ground cover establishment for crops like lettuce or alfalfa. Surface irrigation is suitable for most types of crops, but preferably for close growing crops like rice.
	Individual plant or trees (vegetables, sugar cane…)		Drip	
	Seed germination and ground cover establishment		Sprinkler	
	Close growing crops		Surface	

Factors		Recommended method	Comments
Technology	Strong technological knowledge	Sprinkler/drip	Sprinklers or drip irrigation require higher level of complex technology, and people able to use and maintain the equipment. They also need a permanent energy supply. Surface irrigation requires less technology but more human labour inputs for construction and maintenance.
	Regular energy supply	Sprinkler/drip	
	Human labour	Surface	
	Low maintenance	Surface	
Tradition and culture in irrigation	Introducing a new and unknown methods inappropriately may cause new and unexpected problems. Sometimes farmers are reluctant to accept the new method until it really shows results. It is easier and more logical to improve traditional irrigation methods than to introduce a totally new method.		
Economy	Costs and benefits	Higher costs in Drip irrigation systems, but also high benefit possibilities	Irrigation and energy efficiency, type of sprinklers or drip irrigation systems, materials, operating costs, human resources costs and market variation of crops have a strong influence in this analysis. A costs/benefits analysis must be done in detail, studying all possible options and having the most recent data on prices and markets.
	Labour inputs	More labour required for construction and maintenance for surface irrigation methods	

5.4. IRRIGATION SYSTEM DESIGN AND LAYOUT

With a good grip of the local circumstances and factors mentioned in the previous section, it is possible to select one or more appropriate irrigation methods. An irrigation system then has to be developed for each particular situation.

Different irrigation system layouts, at different scales, can be developed to use a variety of water sources including: groundwater extracted from springs, wells or boreholes; surface water abstracted from rivers, lakes or reservoirs; or non-conventional sources such as waste-water, desalinated water, harvested rain water, or drainage water.[146]

146 ICID, "Irrigation and drainage journal", *op. cit.*

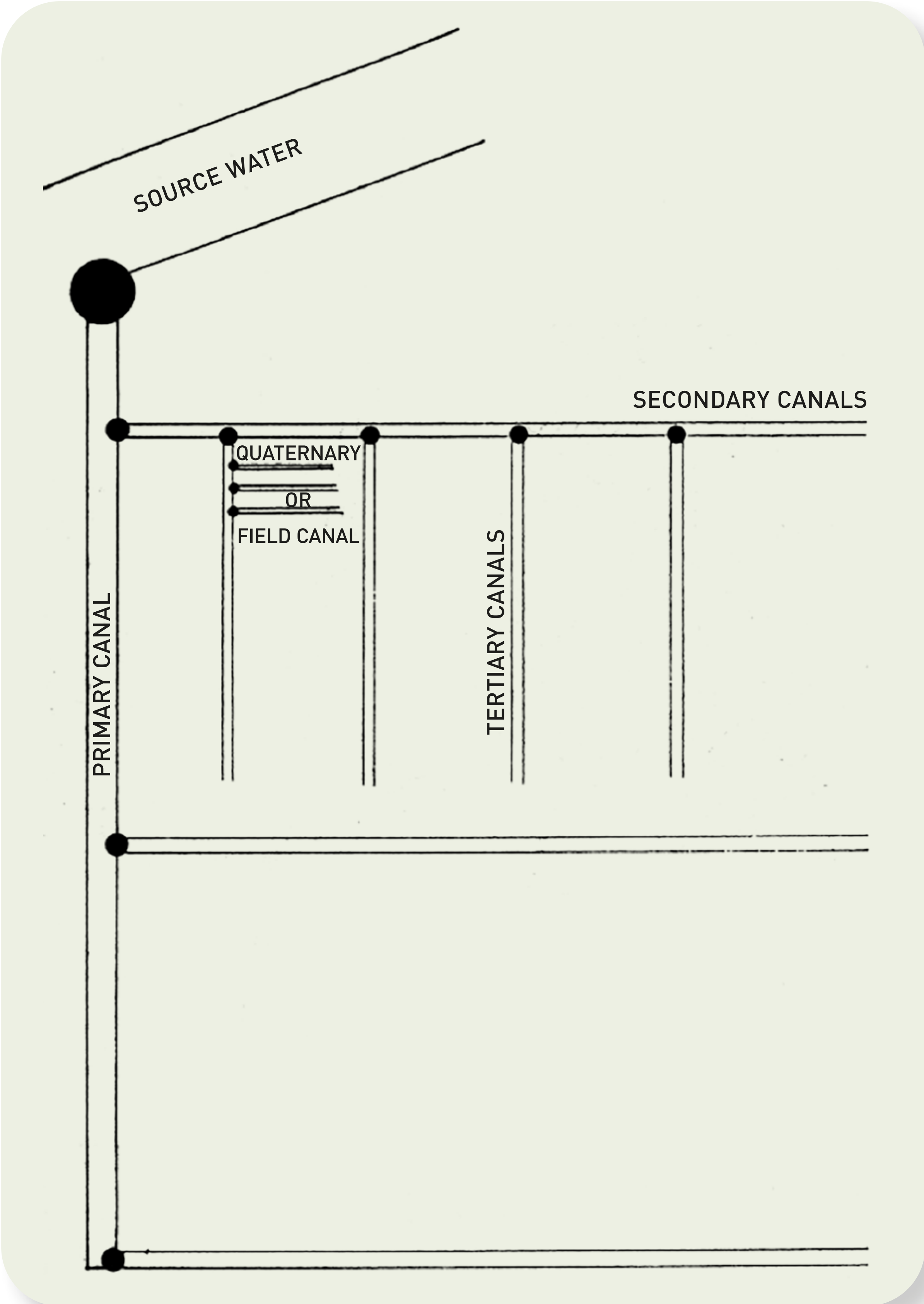

Figure 9 - Irrigation system with primary, secondary, tertiary and field canals[147]

147 FAO, *Irrigation Water Management: Irrigation Scheduling*, Training Manual No. 4, Rome, FAO, 1989, www.fao.org/docrep/t7202e/t7202e00.htm#Contents.

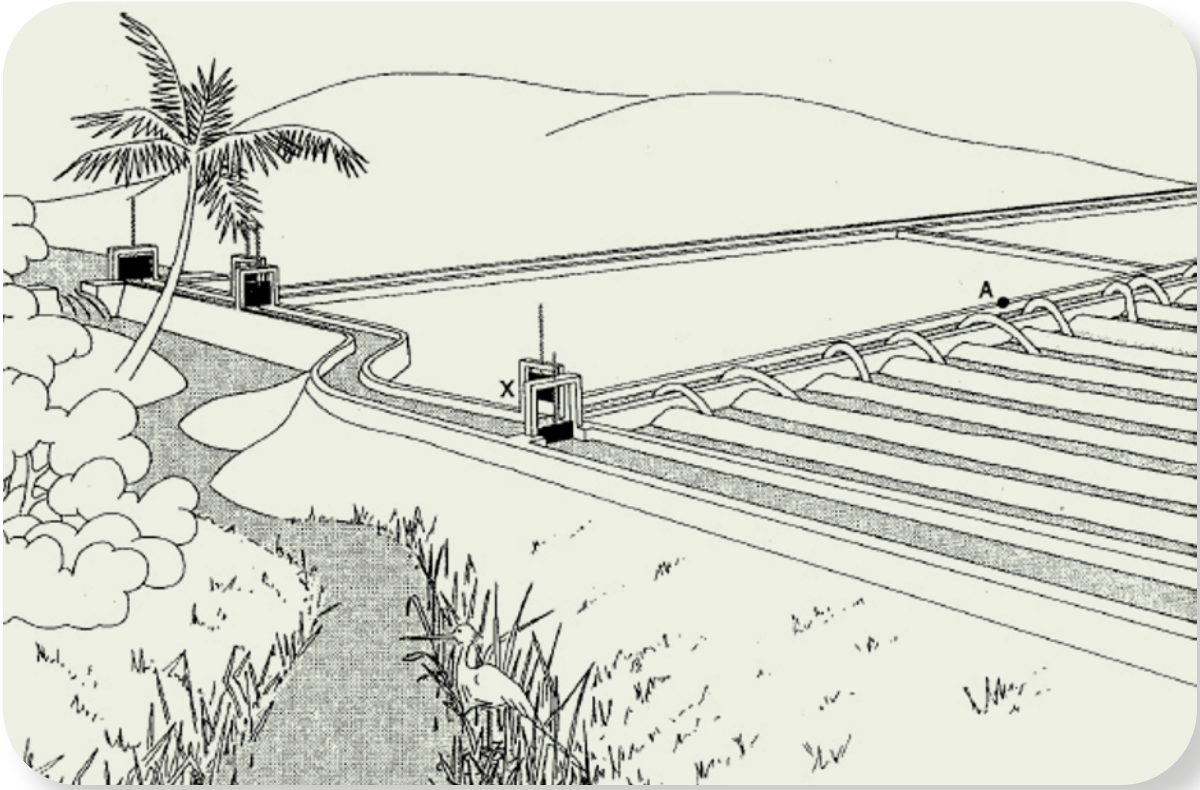

Figure 10 - Small irrigation canal system[148]

In a gravity irrigation system water flows onto the field by gravity after being diverted from a river or other source. This system consists of a network of canals that allow water to flow from the river to the field. The water flows are controlled through gates along the canals. Figure 9 shows a typical large-scale irrigation system (irrigation scheme), divided into primary, secondary and tertiary canals that distribute water from the intake at the source, to the field.

Initial design and construction costs of a gravity irrigation scheme may be high, but the maintenance costs are generally low. Usually no extra power supply is needed (and some schemes can even generate hydropower). However, in some locations, the water needs to be lifted by pumping from ground or surface water bodies, and then diverted into the canal network, fields and distribution channels. Pumping cost can be a major expense for farmers, even in gravity driven systems.

Figure 10 shows a typical basic irrigation system in a smaller scale.

148 FAO, "Irrigation Water Management", Training Manual No. 6, *Scheme Irrigation Water Needs and Supply*, Rome, FAO, 1992, www.fao.org/docrep/u5835e/u5835e00.htm#Contents.

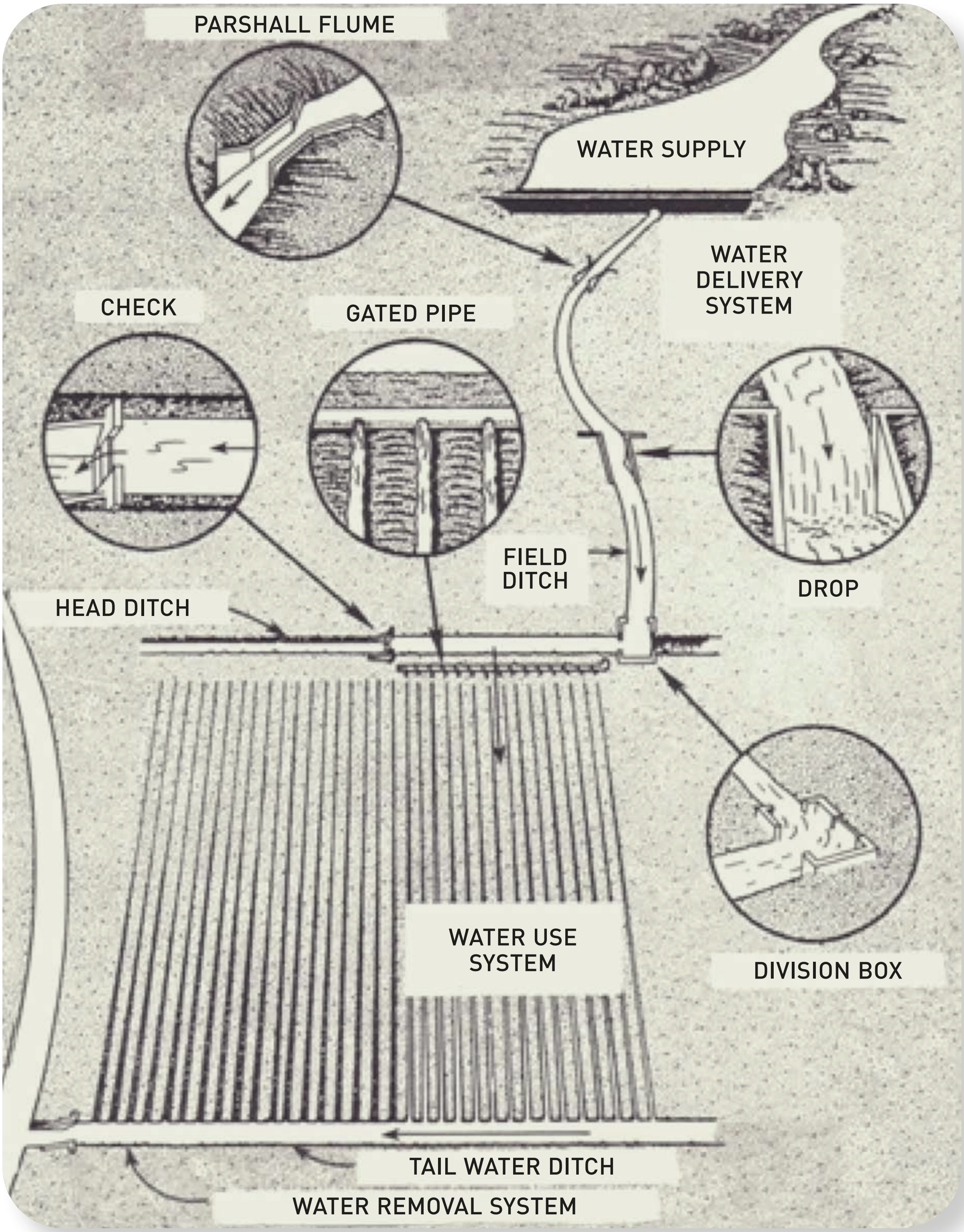

Figure 11 - Typical elements of a surface irrigation system[149]

149 Walker, W.R., "Guidelines for designing and evaluating surface irrigation systems", *op. cit.*

Figure 11 shows clearly **the different elements that normally make up a surface irrigation system**. These elements start with the water supply or source (in this case a dam). A Parshall flume can be installed (a fixed hydraulic structure with a narrowing of the sidewalls and a drop in the floor) to measure surface water and irrigation flows. The system also includes a drop to account for altitude differences. After flowing into the field ditch, a division box distributes water flow the various canals. The head ditch is the canal from which water is distributed to the field. In the field ditch there is a Check, which is built across a stream and can be used to block the head ditch temporarily to raise the upstream water level.

Water is finally applied to the field through a gated pipe. This is a pipe with small gates installed along one side for distributing irrigation water to furrows. Any water that does not soak into the soil but leaves the field as runoff is received by the tail water ditch that carries it to the water removal system or drainage.

5.4.1. Pressurised irrigation systems

Pressurised irrigation systems consists of a network of pipes, fittings, and other devices designed and installed to supply water under pressure from a water source to the irrigable area. Examples of pressurised systems are (mini-, micro-) sprinkler irrigation, drip irrigation and simple hose irrigation systems.

Some key differences between pressurised irrigation systems and gravity irrigation systems are:

- small flows can be utilised, whereas in gravity irrigation the size of flow generally needs to be much larger;
- the direction of the flow can follow the most convenient route (even against gravity);
- pressurised systems can apply water at small rates over a very large area, while in gravity systems water is applied in large volumes;
- external energy is required to build up pressure varying from low pressure systems (2-3.5 bar) to high pressure systems (5 bars).

A pressurised system generally has the following components:

- a water source (pond, borehole, river, canal, etc.);
- a pump;
- a main line, which is a rigid PVC black high density polyethylene hose. This has the largest pipe diameter in the network, ranging from 60-160mm (depending on farm size);
- submain lines, which are smaller pipelines extending from the main lines to carry and distribute the water to the various plots. Depending on the size of the system, these may connect to offtake hydrants that connect to feeder lines;
- lateral pipes with emitters ((micro)sprinkler or drippers) and end caps to close the laterals at the end;
- fittings of various types to connect mains, submains, and to laterals;

- flow control devices:
    - directional devices: shut off valves, check valves;
    - measuring devices, such as water flow meters and pressure meters;
    - auxiliary devices such as flush and safety valves and air release valves;
- filters:
    - gravel filter, a cylindrical tank that contains gravel or a sand filter bed, which is installed immediately after the water intake. All water passes through the filter to trap large particles, organic matter (algae). Water exits the filter from the bottom of the tank;
    - hydro cyclone filter to separate sand and silt, and to filter sediments from the irrigation water to prevent system clogging;
    - screen type filters/disk type filters, installed before the main pipeline, for final filtration;
- fertigation equipment to inject fertilisers into the pressurised system. This can consists of:
    - fertiliser tank installed on a bypass (not very accurate for the injection of fertiliser concentrate, but low cost); or
    - Venturi tank installed on a bypass (slightly higher costs, but more accurate injection);
    - piston pump installed directly on the supply line;
- automation equipment to automate the irrigation applications in the system.

Figure 12 gives a general layout of a pressurised irrigation system.

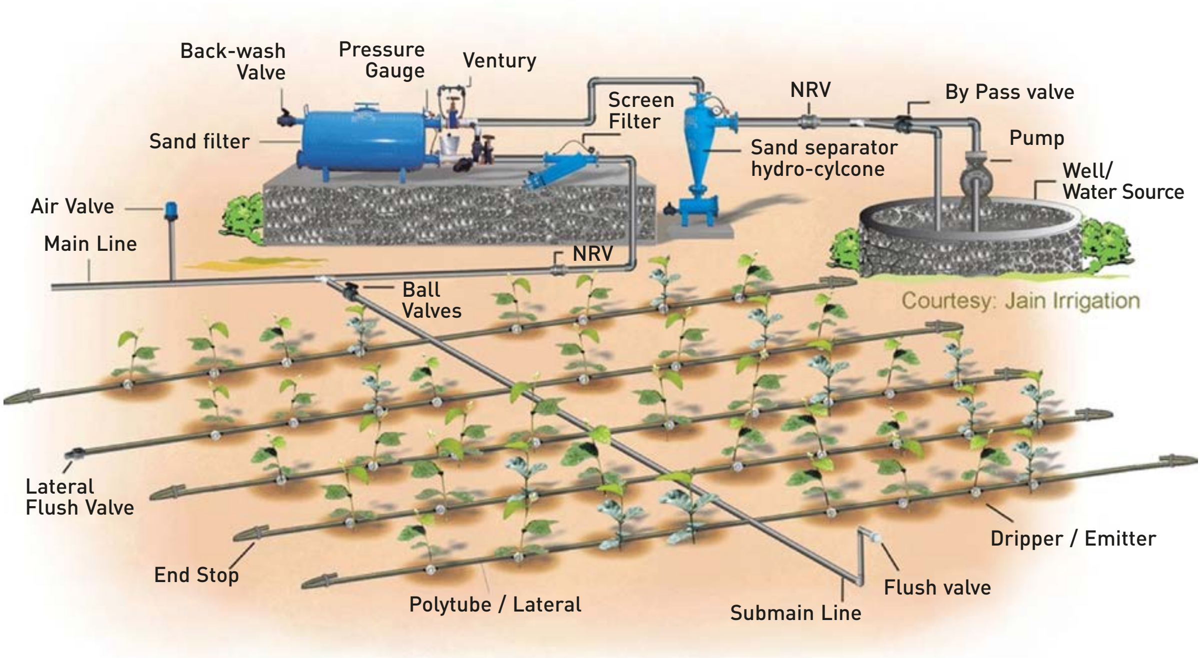

Figure 12 - General layout of a pressurised irrigation system Source: Jain Irrigation) showing the various components

Prior to installing a pressurised irrigation system, a detailed design of the layout needs to be made and, for this, specialised support from an expert is needed. The steps and general approach to designing a pressurised irrigation system are as follows:[150]

1. Determine the area of land: for example 120 m*83 m about 1 ha.
2. Determine the crop layout. For example, for water melon, rows are 2.20m apart and the plants are spaced at 0.5 m, *i.e.* 81 plants per row and 108 plant rows. The plot is divided in two parts, each with 54 rows, 40.5 m long.
3. Choose the best emission method based on soil type, crop, and water requirements (e.g. drip irrigation).
4. Calculate irrigation requirement. If crop irrigation requirement is 3.55 mm/day, system efficiency is 90%, then the irrigation requirement is 39.5 m^3, applied with a daily interval.
5. Establish the characteristics of the emitter: For example, a discharge rate of 4.0 litre/hour at 1.0 bar may be recorded for a drip irrigation system. In this case filtration of the irrigation water needs to be very good to prevent system malfunction.
6. Establish the characteristics of the laterals with drippers, pipe (16 mm LDPE, 4.0 bars) length 41 m, number of drippers 81, discharge 324 l/h (81*4 l/h). Total number of laterals 108. Total number of drippers is 8748.
7. Determine the flow rate needed for the simultaneous operation of laterals: e.g. 35 m^3/h. If this flow is not available, irrigation may have to be carried out in shifts (e.g. three shifts of 12 m^3/h).
8. Dynamic head (pressure) of the system required is 2.65 bar (see table 5.3).
9. Select the water source.
10. Determine the length and locations of the main and submain pipes, the locations of the pump, filters, fertigation equipment, the connectors, valves, meters etc.
11. Create a detailed design and bill of quantities outlining all materials that are required.

Table 3. Determining the pressure at pump in a pressurised irrigation system

Pressure required at dripper	1.0 bar
Friction losses in the lateral	0.10 bar
Friction losses in the main line	0.43 bar
Friction losses in the head control	0.90 bar
Minor local losses	0.22 bar
Total pressure required at pump	2.65 bar

More information on the engineering and design of pressurised irrigation systems can be found at ftp.fao.org/agl/aglw/docs/pressirrig.pdf.

150 FAO, *Technical Handbook on pressurised irrigation techniques*, Rome, FAO, 2000, retrieved on 8 December 2015, ftp.fao.org/agl/aglw/docs/pressirrig.pdf.

5.4.2. Fertigation in pressurised irrigation systems

Fertigation is the combined application of nutrients and water to a crop: a mix of fertilizer + irrigation. Fertilizer use efficiency for N is reported between 30-50% when applied to the soil, whereas it can go up to 95% in fertigation (TNAU, 2015).[151] For phosphorus, soil application and fertigation efficiencies are 20 and 45% respectively.

Some **advantages of fertigation are**:[152]

- Nutrients and water are supplied near the active root zone, which results in greater absorption by the crops. It allows precise control of all mineral nutrients.
- Nutrients solutions can easily be customized or modified for any plant growth stage or species.
- As water and fertilizer are supplied evenly to all the crops, higher yields can be expected (25-50% yield increase estimated).
- With the increase in fertilizer use efficiency, at least 25% of nutrients are saved – this can signify a significant cost saving, given the high price of fertiliser. When properly implemented, there is very low chance of over-fertilization and resultant salt injury.
- Time and energy use are also reduced (with associated costs savings).
- Reduces leaching of nutrients and therefore pollution.

There are also **some challenges in fertigation**, namely:[153]

- Nutrient injectors must be used for maximum effectiveness.
- Frequent mixing and applying of liquid fertilizers may increase labour costs.
- A well-designed, automated irrigation system is essential to ensure even fertilizer application.
- If not well executed, excessive fertigation can damage nursery crops and pollute the environment.

Any fertigation system requires three actions:

1. Formulating and preparing fertilizer stock solutions: either by using a commercial soluble fertilizer mix, or by creating a custom fertilizer from stock chemicals.
2. Checking irrigation water quality. Water quality has a major influence on any fertigation program. The most important considerations are the total salt level measured by the electric conductivity, and the mineral nutrient concentrations in the water that will be applied to the crop.
3. Checking the quality of the fertigation solution; pH and electric conductivity of the solution are a general check on how well the entire system is working, and should be checked weekly at least.[154]

151 TNAU, Tnau Agritech portal, 2015, agritech.tnau.ac.in/agriculture/agri_nutrientmgt_fertigation.html.

152 *Ibid.*; Landis, T., Pinto, R. and Davis, A., "Fertigation – Injecting soluble fertilizers into the irrigation system", *Great lakes Christmas tree journal*, 2010, christmastree.for.msu.edu/pdf/nutrition_manage/Fertigation.PDF.

153 *Ibid.*

154 *Ibid.*

Details of design are not presented here. For more information, we recommend the FAO manual on fertigation.[155]

5.4.3. Hydroponics

Figure 3 - Hydroponic system in a greenhouse
(Source: www.lerablog.org)

Hydroponics consists in growing plants in a soil-less medium, or an aquatic based environment. The plants are grown in an inert medium (rockwool, perlite, vermiculite, coconut fiber, gravel, sand, etc.) and a balanced, pH-adjusted nutrient solution is delivered to the roots in a highly soluble form. Hydroponic systems are efficient and productive because the plant is given exactly what it needs, when it is needed.[156]

This minimises impacts of water-related pollution on the environment, when it operates in a closed loop system. However, recycling of the inert medium can be an environmental issue.

155 FAO, "Handbook on pressurized irrigation techniques", *Fertigation manual*, Rome, FAO, 2007, ftp.fao.org/docrep/fao/010/a1336e/a1336e16.pdf.

156 Simply hydro, "What is hydroponics?", 2008, www.simplyhydro.com/whatis.htm.

5.4.4. Drainage

Drainage has some very important functions in irrigation to remove excess irrigation water from gravity-driven irrigation systems. These include: creating well drained arable lands, preventing salinization, preventing a lowering of the groundwater table, and removal of accumulated salts or toxics. A drainage system normally consists of a field level main drain (targeting both surface and sub-surface drainage) and an outlet point. At the outlet point, drainage water is discharged into another water body. As shown in figure 14, drainage water can be discharged to wells, evaporation ponds, or reused for irrigation if possible.

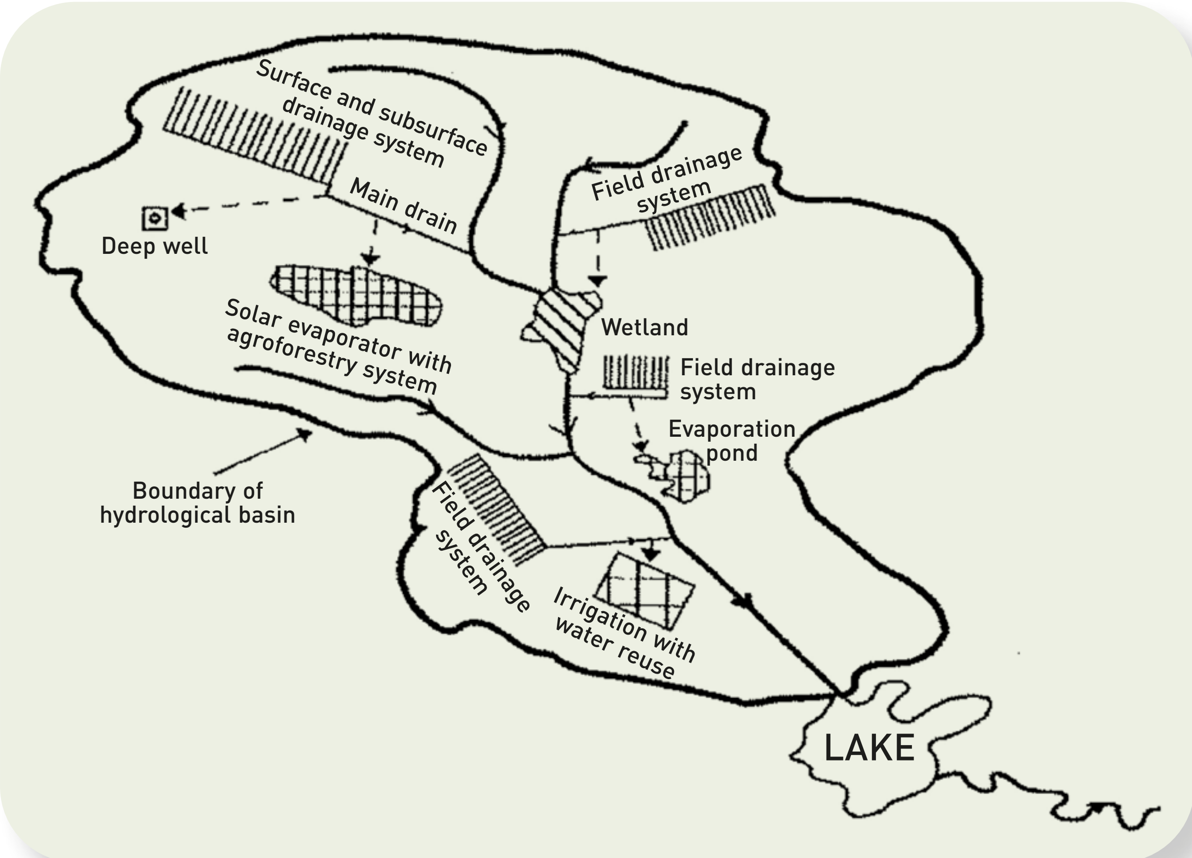

Figure 14 - Drainage water disposal options within a watershed[157]

157 FAO, *Management of agricultural drainage water quality*, Water reports 13, Rome, FAO, 1997, www.fao.org/docrep/w7224e/w7224e00.htm#Contents.

5.5. IRRIGATION WATER SOURCES, WATER CAPTURE, STORAGE AND RECYCLING

5.5.1. Water sources

Which source is used for irrigation depends primarily on the water availability in a given geographical area. The most common sources are rivers, lakes, reservoirs and ground water. As water availability decreases, other more innovative techniques are increasingly being used to obtain water including rainwater and fog harvesting, waste water re-use, and desalination.

Water availability is dependent on various factors, seasonality, pollution, other water uses in the same area, or the existence of water-holding infrastructure. In developing an irrigation system, understanding water availability across the geographic area is essential. This is especially important where water sources are shared between users, when "sharing agreements" may need to be made. Often users may have to obtain water from several different sources in order to cater for their irrigation needs.[158]

Rivers have been used for centuries for irrigation purposes. They have flowing water, which often means that the amount of water available fluctuates over time. To understand the fluctuation in river flows, it is important to view the river in the context of the watershed (the watershed or catchment is the area from which a river gets water as a result of runoff and drainage). The slopes, roughness of terrain, vegetation, sediments, and climate in the watershed all influence flow.[159] Similarly, human activity as water abstraction and storage alter flows.

5.5.2. Water capturing, storage and recycling

Along with the identification of potential water sources for irrigation, it is also necessary to understand and plan how to capture the water. Table 3 presents a summary of sources and capturing methods. Below, some of the most common capturing methods are explained in more detail:

- **Water intakes**, which can have a control gate so that the water intake and supply to irrigation canals can be controlled.
- Capturing water from rivers is sometimes a challenge when river flows fluctuate. One way of controlling changing river levels is by using **weirs**. Weirs increase the water level in a river so that water is still available during dryer periods at the river level required by the irrigation scheme (Figure 15).

158 FAO, "Irrigation water management", Training Manual No. 7, *Canals*, Rome, FAO, 1992, ftp.fao.org/docrep/fao/010/ai585e/ai585e03.pdf.

159 *Ibid.*

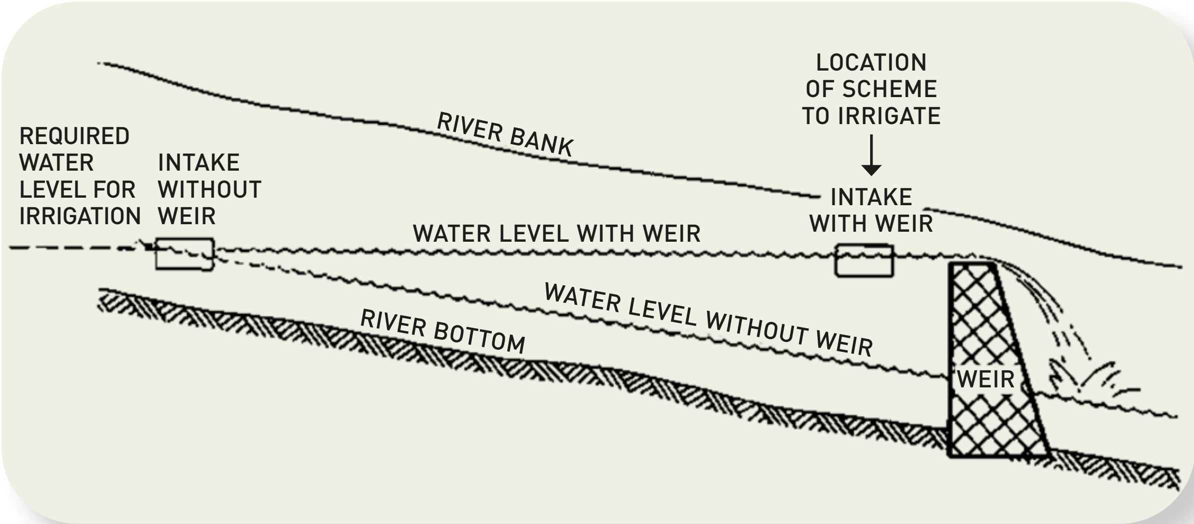

Figure 15 - River intake with and without using a weir[160]

- Water can be also **pumped** from a river when it is not possible to divert it by gravity. The cost of pumping is generally higher than building a weir or a dam to store water.
- **Reservoirs** or dams are artificial constructions aimed to store water. By building a dam across a valley, water can be accumulated. Also, water can be **diverted** to dead branches of a river to store water. A valley can be irrigated from there by gravity or through a system of **pipes**. Water stored in a reservoir can also be pumped upstream, especially in the dry season, when more irrigation is required.
- Groundwater is another important source commonly used around the world, especially for small-scale irrigation. Groundwater can be extracted naturally from **springs**, and artificially through **pumping** or lifting from **wells**. Wells can be constructed by hand for shallow aquifers, but for deep groundwater, submersible pumps are used. Water availability from underground sources is normally more stable than rivers or lakes, except for shallow aquifers that may dry up in periods of droughts. The basis for groundwater use is that extractions should never exceed recharge. This requires cooperation among water users, and precise measurements of groundwater levels.

Figure 16 provides a visual example of water captured from different water sources for irrigation.

160 *Ibid.*

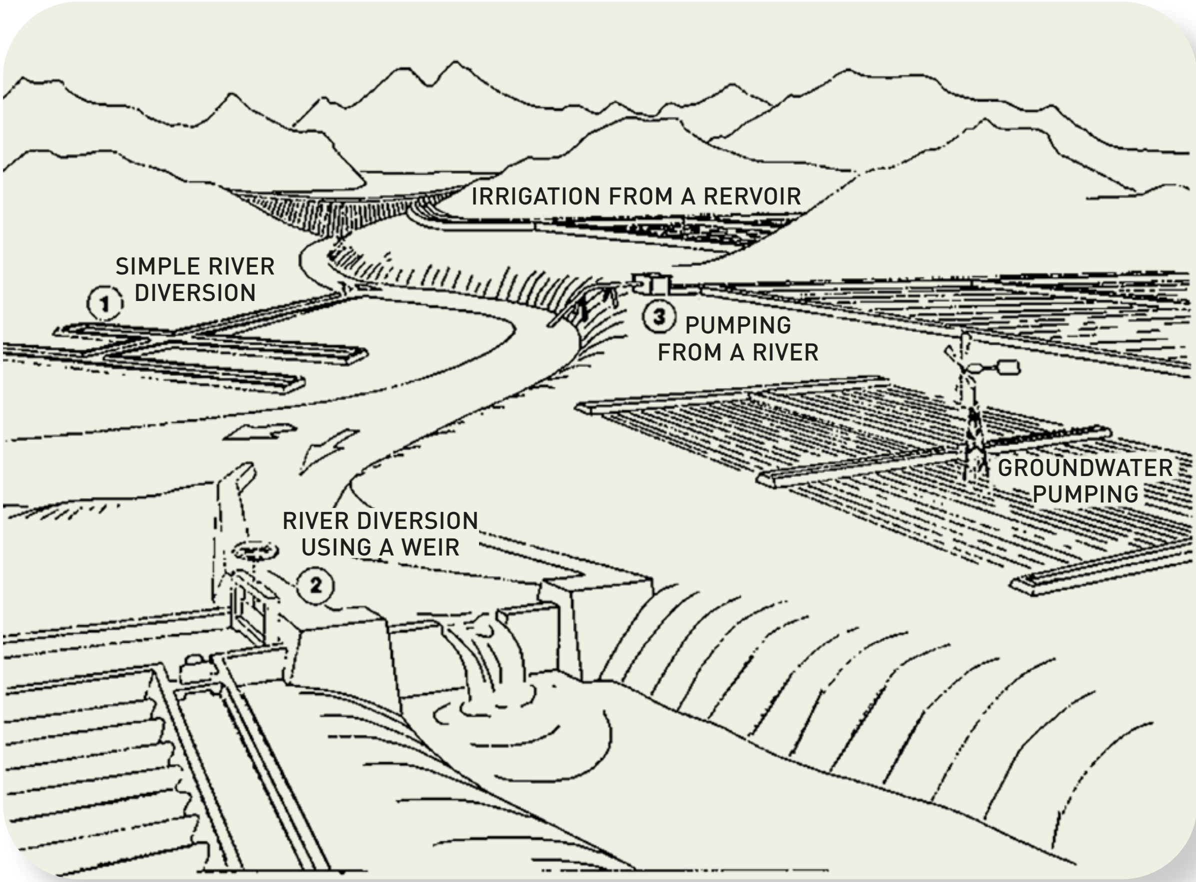

Figure 16 - Schemes irrigated from different water sources[161]

- Rain water can be harvested and stored for irrigation. This can be done for example by using rooftops. It is a cheap and simple technique especially adequate for small scale uses.[162] Rainwater is diverted to storage reservoirs, and subsequently used for irrigation, or for recharge of wells. It is generally very suitable for small farms, but can also be developed for bigger production schemes and greenhouses. Different types of water harvest systems and storage tanks have been developed. Rainwater harvest and storage can complement other water sources in periods of drought. The infrastructure needed is generally cheap and is easily adaptable and implementable in a variety of conditions. It is a good in rural areas in tropical countries with wet and dry seasons.
- Another technique particularly suitable in many ACP countries is **check dams**. These are small dams built across a stream to lower the speed of flows following storm events. As a result of lower speed, more water can infiltrate into groundwater aquifers and recharge them. The materials used can be wood logs, stones, gravels or bricks. Check dams also reduce erosion, allowing sediments and other pollutants to settle.[163]

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161 *Ibid.*

162 Hatum, T. and Worm, J., *Rainwater Harvesting for Domestic USE*, Wageningen, Agrosima/CTA, 2006, www.sswm.info/sites/default/files/reference_attachments/HATUM%20and%20WORM%202006%20Rainwater%20Harvesting%20for%20Domestic%20USE.pdf.

163 FAO, *Watershed Management Field Manual*, Gully Control, Rome, FAO, 1986, www.fao.org/docrep/006/ad082e/AD082e00.htm#cont.

Figure 17 - Stone check dam in East Africa[164]

- Other techniques can be used to adapt natural or man-made landscape elements to control streams or runoff. **Brush fill** is a continuous filling on small gullies with brush, branches of trees or stems of bushy vegetation. The main purpose of is to fill and close the gully with the soil held by the brushes. It is a cheap and effective method when brush is plentiful. **Earth plugs** are small structures constructed across gullies to hold water and let it percolate into the ground. Short diversion ditches can be constructed to lead overflow away from the ends of the plugs to prevent erosion damage and spread the water. Distribution of earth plugs depends on the gully channel gradient.[165]
- **Soil storage and infiltration systems** aim to collect rainfall runoff from the roofs of buildings or greenhouses and direct it underground, where it infiltrates into the soil. The system consists of gutters and downspouts to collect runoff; a catch basin to capture debris; underground trenches to store the water while it soaks slowly into the soil; and an observation port to aid maintenance. When the trench is filled with water during a storm, the excess water flows from the gutter onto the ground surface. The soil storage and infiltration system

164 Malesu, M.M., Oduor, A.R. and Odhiambo, O.J. (eds), *Green Water Management Handbook, Rainwater Harvesting for Agricultural Production and Ecological Sustainability*, Nairobi, The World Agroforestry Centre, 2007, www.sswm.info/sites/default/files/reference_attachments/MALESU%202007%20 Green%20Water%20Management%20Handbook.pdf.

165 FAO, *Watershed Management Field Manual*, *op. cit.*

decreases runoff, captures potential pollutants, and increases the amount of water entering the ground to recharge groundwater.[166]

- **Fog harvesting** is useful for arid and semi-arid regions. This consists of nets that catch the fog (condensed water droplets) as the wind blows. Drops are diverted through gutters into a storage tank.[167]
- Desalinated water is a potential source of water in coastal areas. **Desalination plants** extract seawater and apply thermal or membrane technologies to produce drinkable water.[168] However, the high cost of this technique make it feasible only for specific cases.
- Water can be re-used or **recycled** by constructing systems that allow drainage water and even waste water, to re-enter the system and be re-used for irrigation or other uses. Water recycling is a good option especially for small-scale farms. Domestic water can also be recycled for irrigation on a small scale. For example, in some Kenyan farms, water used in packhouses for fruit washing is afterwards used for irrigation. Care must be taken of water quality when re-using waste and drainage water, as low quality may cause contamination. Testing is recommended, and treatment of re-cycled water may be necessary for some uses.

Table 4. Summary of water capture and recycling methods for different water sources. Source of photos: www.morguefile.com

Sources		Capturing methods
Rivers, lakes reservoirs…		Canals Pumps Pipes River diversion
Groundwater		Springs Wells Pumps

166 Mechell, J., "Rainwater Harvesting: Soil Storage and Infiltration Systems", The Texas A&M University System, 2005, www.ctahr.hawaii.edu/hawaiirain/Library/papers/Mechell_Justin.pdf.

167 Schemenauer, R. and Cereceda, P., "Global warming and the third world", Fog Collection, *Tiempo*, 1997, www.sswm.info/sites/default/files/reference_attachments/SCHEMENAUER%20and%20CERECEDA%201997%20Fog%20Collection.pdf.

168 Clayton, R., "A Review of Current Knowledge Desalination for Water Supply", Bucks, Foundation for Water Research, 2011, www.fwr.org/desal.pdf.

Desalinisation		Desalinisation plants
Rainwater harvesting		Rooftops, fog drips, check dams…
Recycled water		Drainage systems, domestic water recycling

The combined use of a diversity of different water sources is the best option to achieve a sustainable and efficient water supply in the long term. If surface and groundwater are available, and other small-scale systems such as water harvesting and re-cycling are possible, higher and more secure levels of water availability can be achieved. This ensures supply for longer periods of time, and during periods of water stress.

This is becoming an important strategy to deal with climate change resilience, water table recharge, reducing environmental impacts, and increasing agricultural efficiency.[169]

5.6. IRRIGATION SYSTEM PERFORMANCE

Irrigation system performance can be assessed in two ways, through irrigation efficiency IE and distribution uniformity DU. While IE and DU are connected they point both to different perspectives relevant for irrigation system performance.

5.6.1. Irrigation efficiency

Increasing irrigation efficiency (IE) is a key element to improve irrigation system performance and water use efficiency. In this manual, when we talk about irrigation efficiency (IE) we refer to the percentage of the volume water abstracted and diverted to an irrigation system that is effectively used (evaporated) by the plants.

169 Dudley, T. and Fulton, A., *Conjunctive Water Management. What is it? Why consider it? What are the Challenges?*, Red Bluff, U. Ca., 2005.

Irrigation efficiency can be divided in 2 main factors:

- **Conveyance efficiency (ec):** this represents the efficiency of water transportation from the source to the field. The factors affecting the efficiency of conveyance are: the length of the canals, the permeability of the soil type and the condition and maintenance of the canals. In large irrigation schemes, more water is lost as canals are longer. Equally, if canals are not lined with bricks or plastic, for example, the percentage of water loss is higher. Unlined canals on sandy soils have higher losses than unlined canals in loamy or clayey soils, where efficiencies can reach 80-90%, depending on the canal length. Finally, if canals are not properly maintained, water losses will be higher year after year.
- **Field application efficiency (ea):** this is the parameter that shows the efficiency of water application in the field. The factors that influence this parameter are mainly: the irrigation method used and the discipline of the farmer in its application. The percentage of this efficiency on surface gravity irrigation methods is around 60%. In the case of sprinkler or drip irrigation systems, efficiencies can reach 75% and 90%, respectively.[170]

With the two parameters mentioned above, the System Irrigation Efficiency (IE) can be calculated with this formula:

$$IE = \frac{ec \times ea}{100}$$

If a result of 50-60% is reached, the IE can be considered as good, always depending on the irrigation method and the other factors mentioned.[171]

IE depends mainly on the water losses that occur at all stages. In the transportation stage, water can evaporate from the water surface or percolate into the ground water through holes or breaks in canal bunds. Once in the field, water losses take place as evaporation from the soil, deep percolation, and/or surface runoff. Irrigation efficiency never reaches 1.0 because some water losses inevitably occur. However, through application of effective canal maintenance, use of efficient and appropriate irrigation methods, and good agricultural practices, the efficiency can be increased. It is important to understand that a low IE does not necessarily imply a high waste of irrigation water. Some of the 'lost' water can be re-used or can be available for irrigation purposes in other parts of the farm or catchment.[172]

Water use efficiency of productivity (WUE) is defined as the ratio of dry matter produced to the rate of transpiration. The overall **water efficiency** of the system is the ratio between the amount of water abstracted and the amount of crop yield or

170 FAO, *Irrigation Water Management: Irrigation Scheduling, op. cit.*
171 *Ibid.*
172 ITF, *Irrigation Water Use and Management*, Washington, DC, US Gov't Printing Office, 1979.

profit generated. **Storage of water also plays a crucial role in irrigation efficiency**, as water availability may depend on it at critical times. Knowing the amount of water stored as well as the conditions of storage, determines the availability of water in the short and long term. Often reservoir storage efficiencies are not addressed in the design and management of irrigation water. Recent scientific studies demonstrate that evaporation can lead to a reduction of reservoir storage efficiency, with climate and design of the reservoir being the major influencing factors.[173]

Basic information required to design measures to increase irrigation efficiency includes:

- volume of water extracted and stored over time;
- methods of storage and distribution;
- application to the field;
- infiltration into the soil;
- evaporation from the soil;
- water holding capacity of the soil;
- type of crop;
- drainage requirements.

As shown in table 5, the fraction that is lost through percolation or runoff is different depending on the irrigation method used. As these fractions go down, irrigation efficiency increases.

Table 5. Expected irrigation efficiencies of selected irrigation systems in California[174]

Irrigation system	Irrigation efficiency (%)	Percolation fraction (%)	Runoff fraction (%)
Conventional furrow	60	17.5	22.5
Gated pipe	67.5	14.2	18.3
Shorter run	70	13.3	16.7
Tail water recovery	73.2	21.3	5.5
Hand move sprinkler	80	8.75	11.3
Lateral move sprinkler	87.5	5.5	7.0
Drip	95	4.0	1.0

173 Mekonnen, M.M. and Hoekstra, A.Y., *The blue water footprint of electricity from hydropower*, U. Twente, Enschede, Dept Water Engineering and Management, 2012.

174 California SWRCB 1987. Regulation of Agricultural Drainage to the San Joaquin River: Executive Summary. California State Water Resources Control Board. Doc. No. WQ-85-1.

Every system has its own approaches to reaching higher efficiencies. The experience and knowledge gathered by farmers and irrigation experts can be found in the literature, where several "rules of thumb" are accepted. One example is the 'quarter time rule'[175] applicable to surface irrigation. In furrow irrigation, the stream size should be large enough to cover the entire field in a quarter of the time needed to fill the root zone with enough water. The time that is required to infiltrate a certain amount of water is known as the contact time.

In water storage facilities, transportation, and field application, adequate maintenance is key if a high level of efficiency is to be reached. In surface irrigation, the furrows, borders and dykes must be properly constructed and maintained. In pressurized irrigation systems, sprinklers or drippers must be well looked after as they are easily damaged.

Modern techniques such as laser levelling, micro-irrigation, and improved agronomic practices for drainage or canals help to avoid problems such as erosion or water table depletion. In addition, Information Technology (IT) can help improve water use efficiency and land management using crop water needs prediction software combined with GIS (Geographic Information Systems). The better management of land, water and crops leads to higher water, crop and land productivity, and at the same improve irrigation efficiency.

5.6.2. Distribution uniformity

Distribution uniformity (DU) is a measure of how evenly water soaks into the ground across a field during irrigation. Distribution uniformity can be calculated as an irrigation performance measure and has a value between 100% and 0% (theoretically). It is calculated as the ratio of the average irrigation volume applied to the driest quarter of the field, divided by the average volume applied to the whole field. If DU is high, the amount of water that percolates below the root zone (deep percolation) is minimized.

5.6.2.1. DU of pressurised irrigation systems

To calculate the DU in a field, samples need to be taken during irrigation. For example, cans can be placed in a grid pattern under sprinkler irrigation to collect the water emitted from the drippers. After the application is completed, the amount of water can be measured (in mm) in the various cans, and the lowest quarter readings determined.

As an example, 8 cans were placed in a field and the measurements of water in the cans are shown in table 6 below.

175 FAO, "Irrigation Water Management", Training Manual No. 7, *Canals*, Rome, FAO, 1992, ftp.fao.org/agl/aglw/fwm/Manual7.pdf.

Table 6. Example field sampling of irrigation application in mm in a sprinkler system to determine the Distribution Uniformity in the field

Can 1	Can 2	Can 3	Can 4	Can 5	Can 6	Can 7	Can 8
2	5	20	6	15	12	13	15

The lowest quarter measurements are for Can 1 and Can 2, (with 2 and 5 mm respectively). The average for the lowest quarter is therefore 3.5 mm. The total average is 11 mm. This means that the DU = 3.5/11*100% = 32%. This is a very low DU if compared to the usual DU for different types of sprinkler system (*see* Table 7); and would probably result in variations in crop yield across the field. The DU may be improved by a better placement of the sprinklers in the field, and ensuring that flow volumes and the dynamic pressure in the system are high enough to reach the more distant sprinklers. Finally, DU can be improved by regularly checking the system for leaks and replacing broken parts.

Table 7. Distribution Uniformity levels for irrigation systems, achievable according to technical specification of the system, based on historical data according to www.irrigation.org *(* means derived by subtracting 20%)*

System	Achievable DU	Historical DU
Rotary sprinklers	75-85%	55-65%
Spray sprinklers	65-75%	45-55%
Gun or cannon and fixed sprinklers	85%	65%
Centre pivot sprinklers	90%	70%
Micro sprinklers and dips	95%	75%

5.6.2.2. DU of gravity irrigation systems

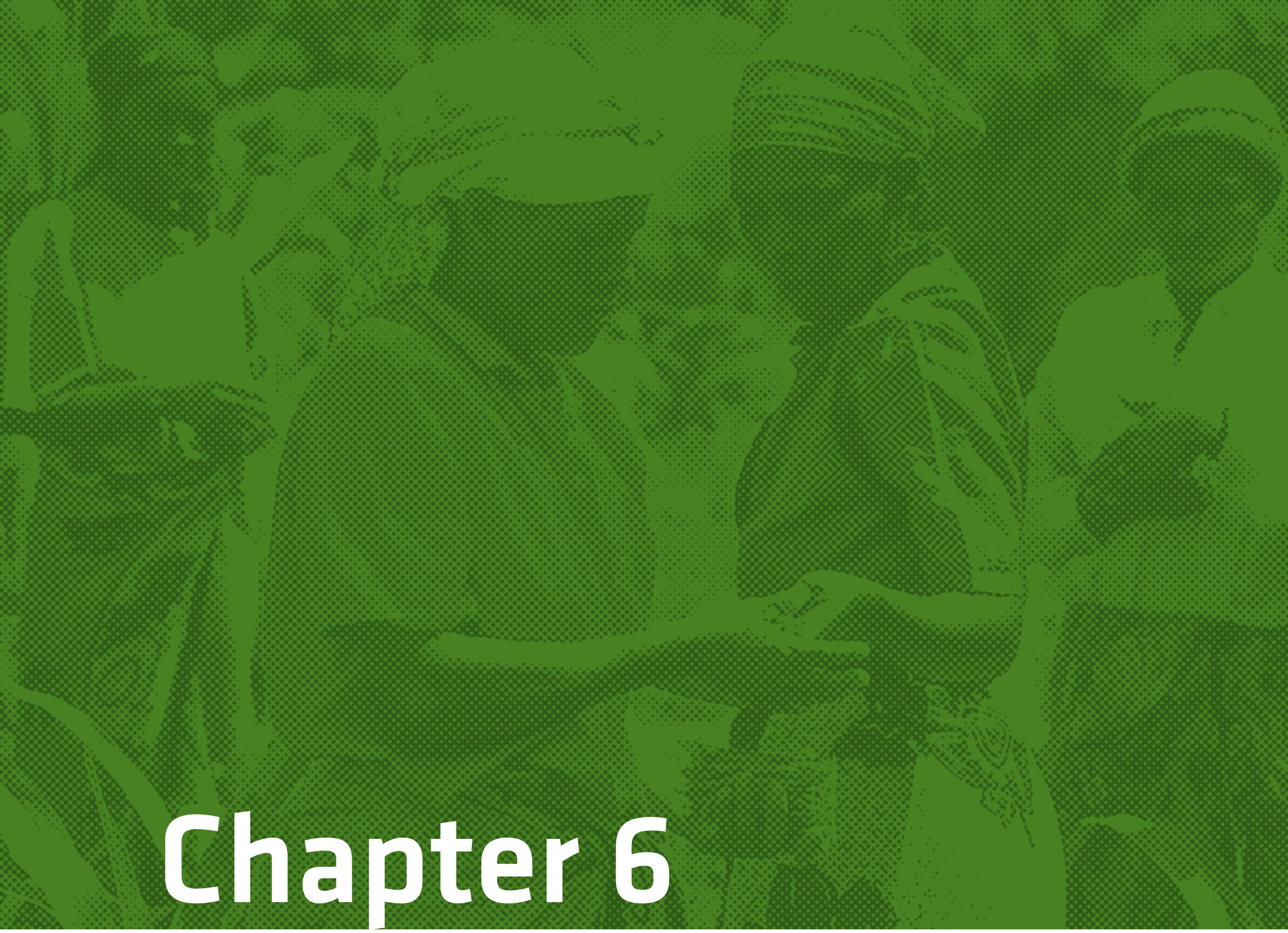
A simple way of understanding distribution uniformity in gravity irrigation systems such as flood, basin and furrow irrigation is to calculate the Advance Ratio (Hanson, 2011).[176] This is the ratio of the irrigation time and the advance time. The irrigation time is the total irrigation time for a field. The advance time is it takes from the moment when the irrigation is turned on to when the water reaches the end of the field. For example the total irrigation time is 2 hours, the advance time is 45 minutes. The advance ratio is thus 120/45 = 2.7. Assuming that the soil is sandy, table 5.8 tells us that the associated DU is expected to vary between 80 and 85%. DU's lower than 70% are considered poor, so the DU in our example is quite good. To improve DU in gravity irrigation, practices such as laser land levelling can be employed.

176 Hanson, B., "A simple way to estimate the distribution uniformity in furrow irrigation systems", U. Ca., 2011, retrieved on 8 December 2015 from cetulare.ucanr.edu/files/82038.pdf.

Table 8. Advance ratio and associated distribution uniformity (DU) in sand, loam/clay soils[177]

Advance ratio	DU sand	DU loam/clay
1-1.5	Less than 65%	Less than 70%
1.5-2.0	75-80%	80-85%
2.5-3.0	80-85%	At least 90%
4	Greater than 90%	

177 *Ibid.*



Chapter 6

Irrigation management

6.1. WHAT IS IRRIGATION MANAGEMENT?

6.1.1. Overview

In Chapter 5, we learnt about different types of irrigation systems, their layouts and designs, and criteria to select the best irrigation system and technology. Once established, the irrigation system needs to be managed. Irrigation management must aim for the most efficient use of water, while striving for energy savings, and minimizing pollution and any other negative environmental and social impacts. Good management must be applied at all stages of the system: from the intake point or pumping station, the conveyance system, and the distribution system, to the field application system and drainage.[178] A well-designed and well managed irrigation system reduces water loss through evaporation, deep percolation and runoff, as well as minimizing erosion from the irrigation water applied.

This Chapter takes a practical approach to irrigation management, providing the reader with the most important information that must be taken into account for optimal management of the irrigation system to:

- minimize losses of water;
- maximize yields with the available water;
- manage drainage water;
- minimize negative impacts on ecosystems;
- minimize negative social impacts.

Measures for the efficient use of water in irrigation and drainage are described in sections 6.2 and 6.3. Measures for minimizing environmental and social impacts are introduced in sections 6.4 and 6.5. It is recommended that the reader complements the information presented in this Chapter with the COLEACP Training Manual 9 (*Sustainable and Responsible Production*), which provides additional information on soil and water conservation.

6.2. MEASURES FOR EFFICIENT USE OF WATER IN IRRIGATION

6.2.1. The notion of water conservation

Water conservation is defined as any beneficial reduction in the use, loss or waste of water. In other words, it refers to improved water management and agricultural practices that optimize the use of water resources, and that ultimately benefit people and the environment.[179] Agricultural water conservation is both a farm and a river basin issue. The best results are achieved when water conservation efforts at both scales are aligned.

It is important to understand why water conservation is of critical importance in irrigation management. Water conservation not only aims to protect water resources from an environmental viewpoint, but also addresses the mitigation

178 FAO, "Irrigation water management", Training Manual No. 1, *Introduction to Irrigation*, Rome, FAO, 1985, www.fao.org/docrep/r4082e/r4082e00.htm.

179 Alberta Water Council, "Water conservation", 2015, www.waterforlife.alberta.ca/01549.html.

of physical, social and economic water risks In this section, we introduce the most common and achievable measures for water conservation during irrigation.

In an irrigation system, water conservation can be addressed by:

- minimizing losses during irrigation water conveyance and transport;
- optimum timing of irrigation applications (gifts) through irrigation scheduling;
- minimizing irrigation requirements through improved agricultural practices.

6.2.2. Efficient transport of irrigation water

We remind the reader that there are several types of irrigation efficiencies including conveyance efficiency (distribution of water from the source to the farm) and field application efficiency (on farm; the ratio between utilized water and the water applied). The goal is to minimize water losses and to maximize yields by making the best possible use of the water available. Losses of water refer to the fact that not all the water taken from the source (river, lake, groundwater or reservoir) reaches the root zone of the plant. Water losses are inevitable, but these can be minimized through good operation, maintenance and management of irrigation water.

Conveyance losses of irrigation water can be as high as 50% or more in long, unlined, open canals, depending on the type of soil in the canals. Losses in unlined open canals occur due to seepage, percolation, flow-through, spills and evaporation. Two problems are associated with conveyance losses:

1. the water lost is not available anymore in the river to sustain its ecosystem; nor is it being used in crop production;
2. the farmer has to pay the cost of total water abstracted and transported (energy, infrastructure), when only a part of this water is actually used.

Water lost for crop production may return to the ecosystem through percolation or seepage into the groundwater, thus recharging groundwater sources. Other parts of the water are completely lost through evaporation.

One way to minimize these types of loss is through conversion of open canals to pipelines. However, such a change must be fully assessed beforehand as it may have an impact on wildlife and livelihoods due to a loss of beneficial wet areas for wildlife, and reduced access to water by livestock and other users.[180] An environmental impact assessment may be required prior to conversion to pipeline.

In open canals, good operation and efficient maintenance are fundamental for good performance. Irrigation canals function well as long as they are kept clean and do not leak. If not enough attention is paid to maintenance, plant growth and sedimentation may occur, increasing flow-through and spills, and reducing conveyance capacity. Canals can also suffer from leakages, for example due to tree roots that open the compacted soil of the banks of the canals. It is important after each farming season to inspect canals to identify any maintenance needed. Inspection should check for

180 EPA, "National Management measures to control nonpoint source pollution from agriculture. Irrigation water management", Washington D.C, 2003, water.epa.gov/polwaste/nps/agriculture/upload/2003_09_24_NPS_agmm_chap4f.pdf.

plants, silt and debris in the canal that need removal; breaches, holes and other leaks that need to be repaired, and eroded sections that requiring rebuilding. The surroundings of canals should also be checked for waterlogging (caused by seepage losses from the canals), and leaks should be repaired, reducing permeability of the canal bank. Additionally, the original shape of the canal cross-section should be kept intact. This can be done with the help of a wooden frame or template that has dimensions of the originally designed canal cross section.[181]

If several farmers are served by the same irrigation canal, they can organize into an irrigation water user group. This can facilitate sharing of responsibilities and work to inspect and conduct the maintenance and repairs of the canals (Figure 1).

Figure 1 - Local farmers from Kunduz working to de-silt the Char Dara irrigation system in Northeast Afghanistan
Source: RAMP, Afghanistan, Susan Decamp[182]

6.2.3. Irrigation scheduling

Proper irrigation scheduling is key to improving water efficiency at the farm level. Irrigation scheduling broadly refers to: the daily accounting for the field water budget (or soil water balance); and determining and controlling the rate, amount and timing of irrigation water in a planned and efficient manner.[183] The goal is to determine and apply only and fully what the crop needs for optimal growth, with controlled and timed applications (Figure 2).

181 FAO, "Irrigation water management", Training Manual No. 7. *Canals*, Rome, FAO, 1992, ftp.fao.org/docrep/fao/010/ai585e/ai585e03.pdf.

182 USAID, "Rehabilitation of irrigation systems in Afghanistan", 2015, www.usaid.gov/results-data/success-stories/rehabilitation-irrigation-systems-afghanistan.

183 EPA, "National Management measures to control nonpoint source pollution from agriculture. Irrigation water management", *op. cit.*

To understand if a crop requires irrigation, how much, and when, we need to understand if the soil water content (SWC) is such that the readily available water (RAW) is depleted, and the crop starts experiencing water stress. Root zone depletion (Dr) is used to calculate this. Irrigation (I) is assumed to be zero until the root zone depletion Dr reaches the level of RAW. If Dr reaches RAW, irrigation takes place using just the volume of water required to raise the soil water content from RAW to Field Capacity (FC), and thus achieve a Dr that is equal to zero (see Figure 2).

Bad irrigation scheduling can result in too little water being applied to the crop, or not applied in time, leading to under-watering. Over watering occurs when too much water is applied or too soon. Under- or over-watering leads to reduced yields, lower crop quality, and inefficient use of nutrients and pesticides.

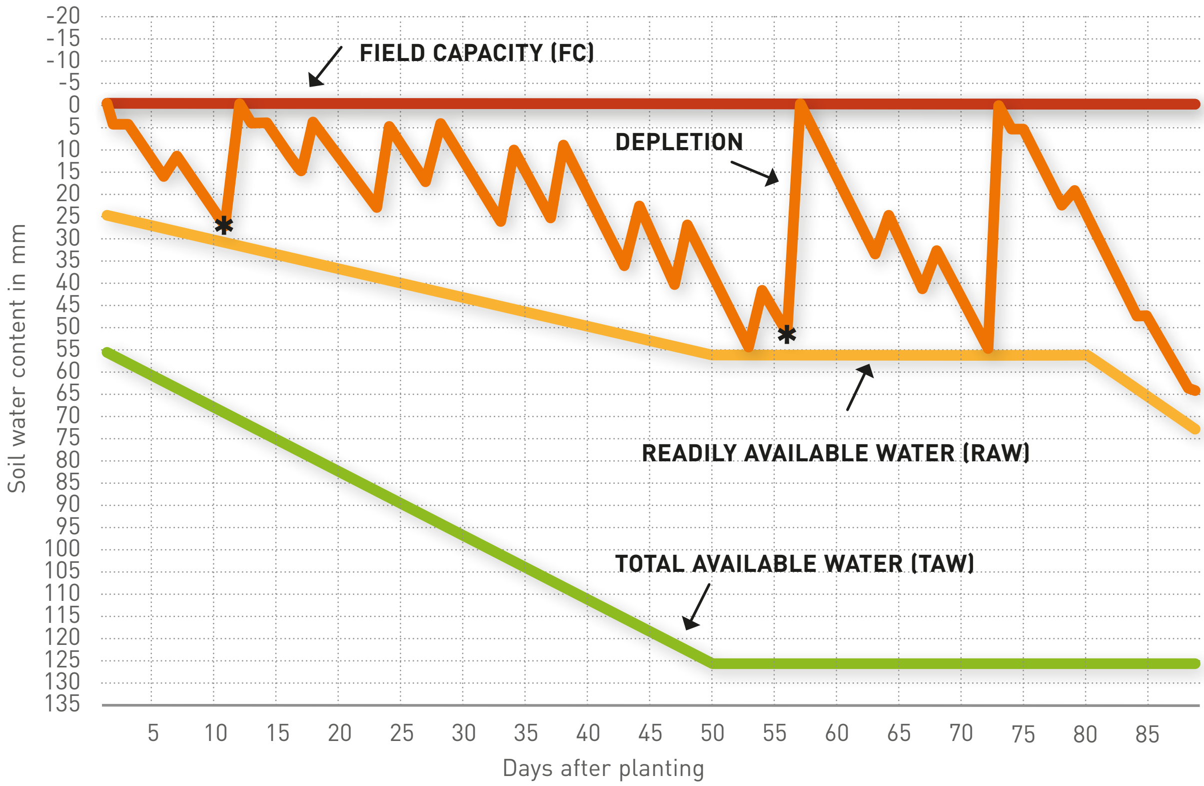


Figure 2 - Graph for irrigation scheduling showing Field capacity, the Total Available Water (TAW – green line) and Readily Available Water (RAW- brown line) as well as depletion of soil moisture content (red line) through the growing season. At the point where depletion reaches RAW, irrigation takes place (depicted by *) (Source: CROPWAT irrigation schedule for Green beans in Taita Taveta Kenya, GSI, 2015)

Figure 2 shows that for proper irrigation scheduling the minimum information needed by the farmer is:

- field capacity of the soil;
- readily available water for the different plant growth stages;
- depletion of soil moisture during the growing season.

6.2.3.1. Overview of irrigation scheduling methods

The key in irrigation scheduling is to determine when crops require water and how much they need. There are several methods and tools to determine this, which go from direct soil moisture and plant monitoring, to calculations of the soil water balance and scheduling using simulation models.[184] All these methods provide a **measurement of crop water** use and soil water content. They can be classified in three types:

- **Observational**, based on simple 'look and feel'. During visits to the field, based on personal experience, the stress condition of the plants and the soil moisture content can be assessed. This does not require equipment or technical support, and is cheap and easy. The disadvantages are that observations are generally not very accurate, and they need to be countered by using a wide margin of error. Also, by the time plants show signs of water stress, irrigation water may have already been withheld for too long, and yield losses may occur. Combining plant observation with a soil inspection using a spade or hand probe using the 'feel' method to understand soil moisture content in the root zone will help to decide when it is best to apply irrigation water, even before water stress symptoms appear in the plants.
- **Measurement of soil moisture content** with specialized equipment for this purpose. This practice is common in effective irrigation scheduling because monitoring soil moisture on a daily basis provides a basis for determining how much irrigation should be applied, and when.
- **Modeling root zone depletion** during the growing season using the soil water balance (Figure 2). This method is based on the estimation of daily evapotranspiration losses from the soil as a basis to determine the irrigation water requirement. The idea is to apply irrigation with a net equivalent to the accumulated ET losses since the last irrigation (net equivalent means taking into account on-farm irrigation efficiency). The root zone is then recharged to field capacity. These methods require accurate data management, as well as specific input information such as precipitation, crop, and soil data. They also require that the farmer identifies the yield threshold depletion level, below which the crops will suffer water stress (and yield reduction will occur). This level is used as trigger to irrigate. Table 1 presents a summary of methods for soil moisture measurement and irrigation scheduling.

184 *Ibid.*

Figure 3 - Tensiometer
Source: www.specmeters.com

Figure 4 - TDR probe
Source: www.specmeters.com

Table 1. Different methods for soil moisture measurement and irrigation scheduling. Source: Broner, 2005

Method	Measured parameter	Equipment needed	Irrigation criterion	Advantages	Disadvan-tages
Hand feel and appearance of soil	Soil moisture content by feel	Hand probe	Root zone depletion as % of field capacity (FC), irrigation is up to 100% of FC	Easy to use; simple; accuracy improves with experience	Low accuracies; field work involved to take samples
Gravimetric soil moisture sample	Soil moisture content by taking samples	Auger, caps, oven. Precision scales	Soil moisture content in weight (grams)	High accuracy.	Labour intensive including field work; time gap between sampling and results
Tensiometers	Soil moisture tension	Tensio-meters including vacuum gauge	Soil moisture tension in centibars (cbars, 1-100) Rule of thumb irrigation triggers are dependent on texture/structure and vary from 30cbar (coarse) to 40-80 cbar (moderate) to 50-150 cbar for fine soils	Good accuracy; instantaneous reading of soil moisture tension	Labour to read; needs maintenance; the water column breaks at tensions above 0.7 atm or 0.8 bar
TDR probes	Dielectric constant of the soil by monitoring the travel time of an electroma-gnetic pulse over a fixed distance	TDR probe with readout display and or data logger	Volumetric soil moisture in % of volume	Instantaneous reading, can be connected to GPS, data loggers	Affected by soil salinity; equipment rather expensive
Electrical resistance blocks. (Gypsum Blocks)	Electric resistance of soil moisture. The dryer the soil, the greater the resistance	Resistance blocks AC bridge (meter).	Soil moisture tension. See tensiometers for irrigation triggers	Instantaneous reading; works over larger range of tensions; can be used for remote reading	Affected by soil salinity; not sensitive at low tensions; needs some maintenance and field reading

Root zone depletion using the Cropwat model (FAO, 2010a)	Climatic parameters: temperature, radiation, wind, humidity and expected rainfall, depending on model used to predict ET	Weather station or available weather information	Estimation of root zone soil moisture depletion in mm, if root zone depletion approximates a critical level, irrigation should take place	No field work required; flexible; can forecast irrigation needs in the future; with same equipment can schedule many fields	Needs calibration and periodic adjustments, since it is only an estimate; calculations cumbersome without computer

6.2.3.2. The FAO CROPWAT model

The FAO Cropwat model[185] is a computer-based model that performs the soil water balance on a daily basis using climate, crop, soil and irrigation data. It has a variety of options that the user can set. The user can set criteria for when it would be best to irrigate, for example at critical depletion (related to the yield threshold level described above). This model is freely downloadable and runs on a Windows PC. It comprises a database of crop and soil information that can be used by default if no other local information is available. Additionally, climate data from the FAO **Climwat** database[186] can be loaded into the model. **Climwat** data is also freely downloadable. **Cropwat** requires a certain level of expertise in computer and spreadsheet management, but represents no big challenge for a technician.

Cropwat is a handy tool for irrigation scheduling (see also Figure 2 showing an irrigation scheduling graph output from **Cropwat**). Ideally, its results should be validated, at least through a simple visual inspection of plants and soil, The FAO website provides a full manual, the install package, as well as an example on the use of **Cropwat** 8.0. (See www.fao.org/nr/water/infores_databases_cropwat.html).

6.2.3.3. Deficit irrigation scheduling

Irrigation scheduling can be set with the aim of providing the full crop water requirement; or alternatively be designed to ensure the optimal use of water by the crop. In the latter, the water actually applied may sometimes be less than the water required to fully satisfy crop needs; this is known as deficit irrigation. In deficit irrigation, the crop is exposed to a certain level of water stress during a particular growth stage or throughout the entire season. Deficit irrigation scheduling allows the farmer to optimize the use of the water available for different crops or fields, especially when supplied are limited. The main objective of deficit irrigation is to avoid irrigation that has only a small impact on yield. Even if there are small yield reductions in one field, these can be outweighed by the benefits of diverting water to other crops or fields (FAO, 2000). In deficit irrigation scheduling, it is key for the farmer to have a good knowledge on crop yield responses to water stress. These responses are crop specific. There is extensive literature on crop yield response

185 FAO, "CROPWAT model", 2010, www.fao.org/nr/water/infores_databases_cropwat.html.
186 FAO, "CLIMWAT model", 2010, www.fao.org/nr/water/infores_databases_climwat.html.

factors, which are mathematically represented by a constant, named ky (or yield response factor). The yield response factor (ky) captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved. The relationship has shown a remarkable validity and allowed a workable procedure to quantify the effects of water deficits on yield.[187] Allen *et al.*[188] offer a good database of ky values. Deficit irrigation scheduling is also supported by the Cropwat model.

6.2.3.4. Technological innovation: Smart irrigation

Smart irrigation refers to technologies that can help farmers determine with more precision when and how much water their crops need. These technologies make use of real time climate data from local weather stations, which are then transmitted with the help of paired software to the farmer via smartphone applications or text messages. This allows farmers to easily access the data under field conditions, and to receive alerts to carry out an informed irrigation.[189] In an irrigation scheme in Uganda, this shapes the daily work of farmers; every morning they receive text messages about the weather forecast helps them decide whether to irrigate or not. Smart irrigation makes use of soil moisture, temperature and electrical conductivity devices that transmit the field information from sensors to the farmer, alongside climate information.

Farmers can make changes to their irrigation plans in real-time, saving water and alleviating time-consuming travel to the field (Conservation Gateway, 2015).[190] Examples of smart irrigation scheduling systems can be found on www.sswm.info/content/automatic-irrigation.

6.2.4. Practices that reduce irrigation requirements

Irrigation requirements will decrease when farms use practices that increase the capacity of the soil to hold moisture (soil moisture holding capacity) and/or to decrease crop evaporation. These practices include conservation tillage, cover crops, conservation crop rotations, field windbreaks, and other wind erosion control measures. A summary of such practices is presented in Table 2.

187 FAO, "Agricultural Drainage water management in Arid and Semi-arid areas", FAO Irrigation and Drainage paper 61, Rome, FAO, 2002.

188 Allen, R., Pereira, L., Raes, D. and Smith, M., "Crop Evapotranspiration (guidelines for computing crop water requirements)", FAO irrigation and drainage paper No. 56, Rome, FAO, 1998.

189 SAI, "Water conservation technical briefs", TB-6. Irrigation scheduling, SAI platform, 2010, www.saiplatform.org/uploads/Library/Technical%20Brief%206.%20Irrigation%20Scheduling.pdf.

190 Conservation Gateway, "Nature's value: water conservation through agricultural practices", 2015, www.conservationgateway.org/ConservationPractices/EcosystemServices/NaturesValues/NaturesValuesWaterConservationThroughAgriculturalPractices/Pages/nature's-values-water-con.aspx#.

Table 2. Agricultural practices for water conservation in the field to reduce irrigation requirements (Source: GSI based on MDA, 2014).

Practice	Definition	Benefits related to water
Conservation tillage	Any method of soil cultivation that leaves the previous year's crop residue on fields before and after planting the next crop; reduces soil erosion and runoff.	• Reduces evaporation at the soil surface • Reduces runoff by letting water infiltrate more easily due to the added organic matter layer. • Reduces soil erosion by 60-90% • Improves soil moisture retention
Cover crops	Grasses, legumes or forbs are planted to provide seasonal soil cover on cropland when the soil would otherwise be bare. They are best suited for places with plenty of available water in the soil for both the cover and the main crop. They are also known as "living mulches".	• Help soil retain moisture for use by primary crops • Reduces evaporation from the soil • Reduces soil erosion • Reduces runoff • Protects groundwater quality by preventing Nitrogen from leaching • Improves carbon content in the soil and, with that, soil moisture holding capacity
Conservation crop rotations	A system or growing several different crops in planned succession on the same field, including at least one soil-conserving crop such as perennial hay.	• Soil-conserving crops reduce the risk of soil erosion and runoff. • Better soil structure, higher carbon content, increased moisture holding capacity
Field windbreaks	Linear plantings/shrubs designed to reduce wind speed in open fields, preventing soil erosion and protecting adjacent crops from wind damage.	• Reduction of crop ET through reduction of wind speed and provision of micro-climates (increased humidity and reduction of temperature) • Reduction of irrigation loss by reducing wind speed and keeping sprayed water only on the targeted areas.

6.3. MANAGING DRAINED WATER

6.3.1. Overview

The purpose of drainage is to provide a root environment suitable for plant growth. This includes providing enough air in the soil, and managing salt content in the root zone. Managing drainage water is an integral part of irrigation management since good drainage management increases water use efficiency and reduces pollution. Managing drainage is as important on arid lands as on humid lands. On arid lands, drainage may be required to prevent salt accumulation in the root zone and to prevent the groundwater table from rising. In these lands, excess water is often applied to prevent salt deposition. This additional water requirement is called "leaching requirement". In humid lands, drainage systems are important to manage high water tables or floods.

Drainage water has a potentially high content of nutrients, toxic trace elements, sediments (which typically transport pesticides), salts and pathogens. From the perspective of water quality it is thus important to pay attention to it. Some good practices for managing drainage water include (EPA, 2003):

- **Water table management**: restricting water discharge from a subsurface drain, resulting in a higher (and controlled) field water table (see Figure 3). This can be done with the help of a pump that slowly and continually drains the water. There are two benefits of managing a higher water table in the field: water can go up the soil column thanks to capillary rise, helping to meet plant transpiration requirements and increasing efficiency; and enhance de-nitrification, therefore reducing Nitrate leaching (FAO, 1997).[191]

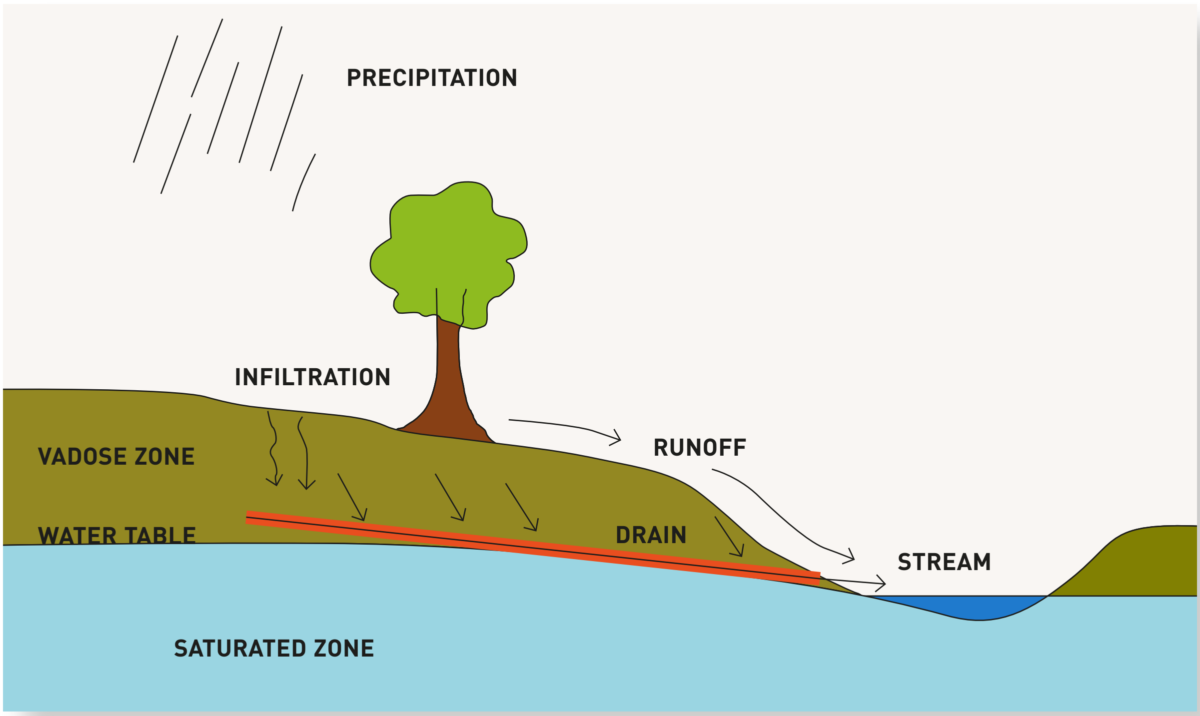


Figure 3 - A drain (in red) in the soil above the water table for water table management

191 FAO, *Management of agricultural drainage water quality*, Water reports 13, Rome, FAO, 1997, www.fao.org/docrep/w7224e/w7224e00.htm#Contents.

- **Re-use of drainage water**: this is a good option for situations where water supply is short, as well as to reduce the nutrient loads into receiving water bodies. This can be done in combination with nutrient management techniques. The practice is often not appropriate in arid regions, as the salt content of the drainage water is too high. Additionally, care must be taken when re-using drainage water more than once as concentrations of pollutants may increase to high levels. In this case, periodical monitoring of the drainage water is recommended to protect water quality and determine the number of times drainage water can be re-used.
- **Treatment of drainage water**: for example with the help of a constructed wetland. Constructed wetlands require the help of a specialist engineer to create a design for optimal removal of organic matter, sediments, nutrients, etc. Wetlands are effective in removing sediments and nutrients; if there is enough space to accommodate a wetland near fields, this is an excellent and comparatively cheap option to treat drainage water.
- **Filter strips** are strips or areas of vegetation to remove sediment, organic matter and other pollutants from drainage water leaving the fields. The principle is similar to that of the constructed wetland for wastewater treatment, but without a specific engineering design for maximal removal of pollutants.

6.4. MEASURES TO MINIMIZE THE ENVIRONMENTAL IMPACTS OF IRRIGATION

6.4.1. Managing salinity

In order to sustain yields, salts that concentrate in the soil must be managed. Practices to control salinity include minimization of salt application, choosing the right site and crop, and applying good soil/water management practices. Table 6.3 presents an overview of these practices.

Table 3. Practices to control salinity and its effects. Source: SAI, 2012

Practice	Comment
Irrigation leaching	Occasional excessive irrigation water application to dissolve, dilute and move the salts. The amounts of excess irrigation application required (referred as the 'leaching fraction') depends on the concentration of salts in the soil and in the water applied for leaching. A commonly used equation to estimate the leaching fraction requirement, expressed as a percentage of irrigation requirement is: Leaching fraction = (electrical conductivity of irrigation water)/ (permissible electrical conductivity in the soil) x 100%. For example, if a farmer wants to cultivate tomatoes and does not want the root zone of the soil to have a higher EC then 1.0 dS/m. The irrigation water that has an EC of 0.8. The Leaching fraction thus is 0.8/1*100% = 80%. The volume of irrigation water to cater for crop water requirements should be 80% higher to leach the excess amount of salts. The excess salts are drained from the soil as long as proper drainage is in place. While this sounds simple, salinity management is a complex subject. Adding a leaching fraction volume to irrigation requirements may often be an oversimplified way to deal with salinity. For a full overview of salinity management, the reader is referred to the comprehensive Salinity Management Handbook of the State of Queensland (2011): publications.qld.gov.au/en/dataset/salinity-management-handbook/resource/529b12b0-8e23-4cd3-a1cd-7659d0b9b3b4
Minimize application of salts	Through conversion to rain-fed production systems; by maximizing the efficient use of precipitation to reduce the amount of irrigation required (for example by increasing the ability of the soil to retain moisture); by reducing irrigation applications; and/or by using a higher quality water source. Minimising nutrient inputs is another option (nutrient management programs) as some salts are added in fertilizers or soil additives.
Crop selection	Some crops are more tolerant to salts than others. Vegetables are moderately sensitive to salt: upper-end examples are artichoke, asparagus and zucchini, with electric conductivity thresholds of 6.1, 4.1 and 4.9 dS/m respectively.[192] Lower-end examples are bean, carrot and onion with 1.0 dS/m (FAO, 2002). FAO (2002) Annex 1 gives a full list of crop salt tolerance
Acid injection in drip irrigation systems	Clogging of drip emitters and other components can happen when salts precipitate inside the system. Good maintenance practices include periodic or continuous acid injection (maintaining an acid pH prevents chemical precipitation). Refer to the drip system manual for specific details.

192 Root zone salinity is measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS m-1) at 25 °C.

Irrigation scheduling	Light, frequent irrigation applications can result in a small wetted zone, with limited capacity for dilution or leaching of salts, especially in arid regions. Salts accumulate at the border of the wetted zone. To leach these salts, occasional large irrigation applications may be required, even when excessive deep percolation losses of irrigation are discouraged. Managing irrigation schedules to support a large root zone helps to keep salt accumulations dispersed and away from plant roots.[193]
Seedbed placement	Seedbed placement can be adapted to avoid planting directly into areas of highest salt accumulation, since seedlings are the most sensitive to salts.
Maintaining soil organic matter (OM)	Through preservation of soil structure and permeability, OM can contribute to a higher Cation Exchange Capacity (CEC) and therefore lower the exchangeable sodium percentage, helping to mitigate negative impacts of sodium. Helling *et al.*[194] showed there is a linear relationship between acidity, pH of soils, organic matter and CEC. As rule of thumb it can be said that the higher the pH, the higher the CEC.
Trace elements monitoring	Trace elements often occur at low concentrations in irrigation water, and are often not included in routine measurements because there are no associated problems. However, in some cases, trace elements can be toxic to plants at higher concentration (e.g. Aluminum [Al] at pH lower than 5.5). Others such as iron (Fe) are not toxic to plants in higher concentrations but can lead to acid soils and orange spots on plants when using overhead irrigation. In some cases therefore, it may be important to monitor trace elements. FAO[195] gives an overview of the recommended maximum concentrations of trace elements in irrigation water.

6.5. MEASURES TO MINIMIZE SOCIAL IMPACTS

Minimizing social impacts is inherent to sustainable and responsible water management and good irrigation practices. Farmers and irrigation water managers must be aware that they are one of several water users in the river basin, and that water is a valuable and crucial resource for everyone. The person responsible for managing irrigation water should aims to optimize the water situation for the farm, as well as for other users and the environment. This basic principle is fundamental to minimize any type of social impact.

The subject of the social impacts of water consumption is complex, and is not covered exhaustively here. Instead, social impacts are defined as secondary impacts (directly affecting people) that arise from primary environmental impacts. Some examples of water-related social impacts are:

- Reduction in water availability to downstream users as a result of increased water abstractions for irrigation, or due to pollution. This results in less water for other uses, including domestic water use and sustainable livelihoods.

193 Porter, D. and Marek, T., "Irrigation management with saline water", *Texas Agricultural Experiment Extension*, 2006, www.k-state.edu/irrigate/oow/p06/Porter06.pdf.

194 Helling, C.S. Chesters, G. and Corey, R.B., "Contributions of organic matter and clay to soil cation exchange capacity as affected by the pH of the saturating solution", *Soil Sci.* Soc.Am. *Proc.*, No. 28, 1964, pp. 517-520.

195 FAO, "Water Quality for Agriculture", Irrigation and Drainage Paper 26, Rome, FAO, 1994, retrieved 3 December 2015 from www.fao.org/DOCReP/003/T0234e/T0234E06.htm.

- Negative impacts on ecosystems and their services due to reduced water availability, or increased pollution. This may affect people directly, for example through water-borne diseases, or indirectly by reducing sources of income. The latter refers to impacts on important economic activities that rely on water and the surrounding ecosystem, such as fishing, or extraction of any other water-dependent resource in the watershed.

The person responsible for managing irrigation should be aware of the potential social impacts that the irrigation may have, and should implement management actions that minimize those impacts. This is particularly important in the framework of social responsibility (see COLEACP, Training Manual, *Social responsibility*).

6.5.1. Knowledge of the local regulations

The design, implementation and management of an irrigation and drainage system should be in close coordination with local water institutions and authorities. Details and on local water policy and governance, water associations or platforms, and irrigation committees at the river basin level, should be maintained. The complete irrigation system should be designed so that it can be harmoniously integrated into the local water situation and local policy context.

6.5.2. Participatory irrigation management (PIM)

PIM refers to the participation of irrigation users (farmers) in the management of an irrigation system or scheme, at all levels of the system and in all aspects of management. This approach starts with the assumption that the irrigation users themselves are best suited to manage their own water, instead of the assumption that the public sector should have a strong role. Each particular situation and location determines to what extent PIM can be successful. It has been proven that with a strong commitment from both the private and public sectors, and with good levels of training and information, PIM is a valuable approach. The advantages of farmers' involvement through PIM are reported to be: direct knowledge of and information on the specific needs of the area; easier cost control; and greater flexibility in the different activities required to operate and maintain the irrigation infrastructure.[196] More information on Participatory Irrigation management can be found on www.inpim.org.

6.5.3. Water and irrigation management plan

The goal of a water and irrigation management plan is to manage water in the best possible way. This means making the most efficient use of water, and minimizing pollution, as well as any negative environmental and social impacts. It can be achieved through scheduling and a basic understanding of the techniques and practices that reduce the amount of irrigation water needed, to conserve water.

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196 Groenfeldt, D. and Sun, P., "The concept of participatory irrigation management", *Medit*, No. 2, 1997, www.iamb.it/share/img_new_medit_articoli/765_45groenfeldt.pdf.

In addition to responsible social practices and food safety management, private industry standards and initiatives are focusing more and more on environmental aspects. The efficient use of raw materials, better waste management, protection of water resources, soil conservation, safeguarding of ecosystems and forests, and reduced emissions of greenhouse gases, are some of the elements that farmers and suppliers are increasingly having to achieve in order to access global markets. For example, Version 5.0 of GLOBALG.A.P. Integrated Farm Assurance (IFA)[197] introduces a number of water-related compliance criteria, and requires the preparation of a 'water management plan'.

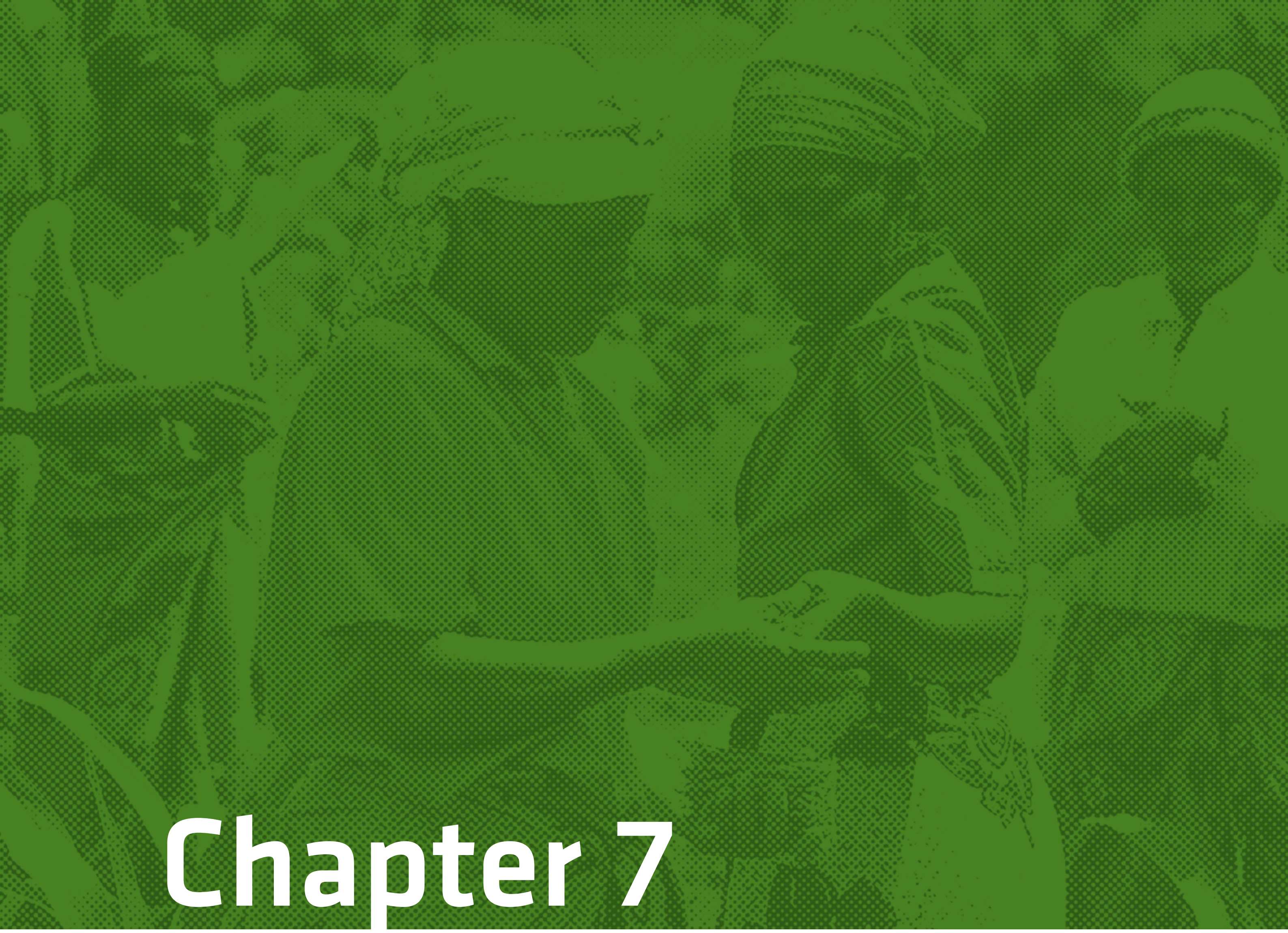
Key elements to include in such a plan from the perspective of GLOBALG.A.P. are:

- Maps, photographs, drawings, or other means to identify the location of water source(s) (name of streams and watershed), permanent features and fixtures, and the flow of the water system (including holding systems, reservoirs or any water captured for re-use).
- Permanent fixtures, including wells, gates, reservoirs, valves, returns and other above-ground features that make up a complete irrigation system, need to be documented in such a way that they can be located in the field.
- Operation and maintenance of irrigation equipment.
- Training and/or retraining of personnel responsible for the oversight of irrigation management shall be provided.
- Monitoring of water consumption and water quality.
- Action plans to improve water and irrigation management, addressing key needs such as water conservation, pollution, efficiency, nutrient and soil management, engagement in wider watershed activities.

Additionally, a water management plan should include:

- a brief historical background on the water situation on the farm and in the watershed, and an outline of current water management practices;
- a water risk analysis from the perspective of the farm (this should include information on local water regulations, policies and institutions and their implications);
- a description of the farm water permits and licenses;
- if possible, quantitative or at least qualitative knowledge of water availability during the year;
- monthly climatic information patterns;
- actions to manage water on the-farm: overall water requirements of the farm; on-farm efficient water use; and pollution reduction;
- actions to manage water at the watershed level: efficient water use, water conservation, and pollution reduction.

197 GlobalG.A.P., "Integrated Farm Assurance, All Farm Base – Crops Base – Fruit and Vegetables – IFAV5.0_July15", English Version Control Points and Compliance Criteria, Cologne, 2015.



Chapter 7

Water for post-harvest washing and processing

7.1. INTRODUCTION

7.1.1. Overview

The current world situation is demanding more food for an increasing population, and globalization is putting new challenges in the field of sustainable food production.

Globalisation is resulting in supply chains (from production to consumption) that are increasingly complex. This complexity, combined with expectations and demands for safe and high quality food, means supply chains are also increasingly subject to controls. Operators must use good practises and procedures at each stage, and evidence this to their buyers through certification.

Water is a key factor in supply chains, especially during the early stages on farm. Production (including irrigation) as well as post-harvest handling depends on having water in the right quantities, and of the right quality.

This Chapter discusses the use of water in the various post-harvest activities, and the need to carefully manage water-related issues. Special attention is given to water recycling and effluent treatment, with an emphasis on what is feasible and recommended at the farm level with respect to regulations and private standards (including food safety).

7.2. USE OF WATER POST-HARVEST

Produce quality, and therefore value, can be seriously affected if water is not managed correctly in the post-harvest stage. From the moment a crop is harvested, plants maintain biological activity but, without contact with water, they begin to dry. Transpiration or evaporation of water is the main cause of deterioration of fruit and vegetables after harvest. It affects product weight, appearance and quality.[198] Post-harvest water management is essential to maintain product quality from the point of harvest to consumption.

Post-harvest water use is also a potential source of contamination. It is therefore important to understand and manage the associated risks.[199]

Water consumption post-harvest for produce washing and processing is relatively small in comparison with consumption during the production phase. Consumption refers to water that is used and then no longer available for other uses, for example because it evaporates from washing ponds or because it is incorporated into a product (for example water used to protect flowers during transport). Most water used post-harvest returns to the system in the form of effluent, so only a small portion is actually consumed.

Depending on the crop, buyer demands, or regulations, several post-harvest activities may be involved, each using water in different ways. Table 1 summarises the most common.

198 FAO, "Water Quality for Agriculture", Irrigation and Drainage Paper 26, Rome, FAO, 1994, retrieved 3 December 2015 from www.fao.org/DOCReP/003/T0234e/T0234E06.htm.

199 Bihn, E.A., Schermann, M.A., Wszelaki, A.L., Wall, G.L. and Amundson, S.K., "On-Farm Decision Tree Project", *Postharvest Water*, vol. 7, 2014, gaps.cornell.edu/sites/gaps.cornell.edu/files/shared/documents/sanitation/Sanitation%20and%20Postharvest%20Handling-COMPLETE-FINAL.pdf.

Table 1. List of common post-harvest processes and how they use water
Source: GSI, based on V. Indira[200] and KV. Peter[201]

Activity		Comments
Reception		After harvest, reception of the product at the packhouse may use water. As the produce is offloaded, the use of water prevents abrasions, bruising or other damage. This is used in the case of several fruit crops.
Drenching		To prevent fungal infections or physiological disorders, some produce is drenched, dipped, or sprayed with fungicides or other substance. This is a common practice with some fruit crops. Water is used at this stage for the product application.
Washing		Washing is used to remove dirt, micro-organisms, pests, or other contaminants. It can be done through flotation, rising, or sometimes brushing the product. Chemicals can be added to improve the washing process. Each crop has different characteristics that may give rise to problem. For example, brushing can increase water loss in mangoes. Some products such as onion, garlic or mushrooms are not washed after harvest.[202]
Pre-cooling		Where produce is stored after washing, different cooling procedures are applied, depending on the product. Produce may be submerged in water, iced or placed in cold air rooms.
Trimming		Some produce needs to have rotten leaves or damage parts removed. Water is used at this stage for the cleaning and washing of tools, for example in the case of lettuce, cabbage or spinach.
Sorting/grading		Some products need to be graded and sorted according to markets, standards, or for packaging purposes. Products can be sorted by size, weight or appearance.
Waxing		Some fruits and vegetables lose a natural waxy layer in the washing process. In this case, extra edible waxing is applied, sometimes for appearance, and sometimes to avoid water loss, thus lengthening shelf life. This is common practice for produce such as papaya or cassava. Waxes are never mixed with water.
Post-harvest treatment	Hot water treatment	Some diseases can be controlled through submerging products in hot water for a period of time. For most horticultural products such as mango, if this is done for around 30 minutes, in 50-55 ° water (with an appropriate fungicide if needed), diseases such as anthracnose (*Collectotrichum*), can be controlled.[203]
	Vapour heat treatment (VHT)	This is based on the application of steam to heat and wet the product in a closed room. This is a good method to control insect infestations and is effective in produce such as mango, papaya or pineapple. They are kept in saturated air for 8 hours and a temperature of 43 ° for further 6 hours.[204]

200 Indira, V. and Sudheer, K.P., "Postharvest Technology of Horticultural Crops", Horticulture Science Series, vol. 7, Haryana, NIPA, 2007.

201 Peter, K.V., *Basics of Horticulture*, 2nd ed., Haryana, NIPA, 2015.

202 *Ibid.*

203 Indira, V. and Sudheer, K.P., *Postharvest Technology of Horticultural Crops, op. cit.*

204 *Ibid.*

Post-harvest treatment	Chemical treatment	Chemicals can be applied as dust or sprayed. Delayed ripening of bananas is achieved with treatments of gibberellic acid. Vegetable storage life can be prolonged if plant hormones are applied.
Post-harvest treatment	Ionization	In recent years this method has been increasingly used as it does not leave any residue and the energy demand is low. Mangoes, potatoes or onions are examples of products where storage life is extended using this method.
Labelling		To meet regulations, standards, and buyer demands, labelling with detailed information on the product and producer is required for many markets. Water is not present at this stage.
Quality control		A series of checks are needed before the produce leaves the on-farm facility. Further checks are conducted by buyers, retailers and public authorities, depending on the product and destination market.
Storage		Again depending on the destination market, produce may be packed, palletized and put into cold storage before distribution. Water is sometimes used as ice, liquid or vapour, to extend shelf-life.
Transport		Transport from the field harvest to the packinghouse, and from the packinghouse to consumers, has to be done with care. At this stage produce can suffer from water losses if it is not adequately refrigerated, ventilated and protected from direct sunlight. Water can be sprayed to control humidity and temperature.

The following sections provide more information on water use in the different post-harvest stages:

- washing;
- post-harvest treatment;
- packaging and storage.

7.2.1. Water use in washing

After a crop is harvested, it may be rinsed and washed to remove external agents that could be harmful in terms of food safety. This includes physical contaminants such as soil particles or small insects, as well as microbial agents and some chemical residues (washing can remove between 0 to 40% of some pesticides). According to European regulations, (Appendix 1, Section A of Regulation [EC] 852/2004) clean potable[205] water must be used for produce washing to prevent contamination.[206] Minimal requirements can be found in Appendix I of Directive 98/83/EC.[207]

205 Potable water refers to water meeting the drinking water quality standards (Council Directive No. 98/83/EC of 3 November 1998), whereas clean water refers to water that does not contain micro-organisms, or harmful substances.

206 The general obligation in the Regulation (EC) 852/2004 is that food business operators shall ensure that all stages of production, processes and distribution of food in Europe, including imports and exports, comply with the relevant hygiene requirements as laid down in the same regulation.

207 EPA, "Parameters of water quality. Interpretation and Standards", 2001, www.epa.ie/pubs/advice/water/quality/Water_Quality.pdf.

In addition to regulations, private standards such as GlobalG.A.P., include very specific requirements concerning post-harvest activities:[208]

- The source of water use for post-harvest treatment should be potable or declared suitable by the competent authorities. This is a major must.
- If water is re-circulated for final product washing, it must be filtered and disinfected (for example with the help of an automated sanitizer injector); pH, concentration and exposure levels to disinfectants are routinely monitored. Documented records must be maintained (Fruit & Vegetables Module).
- All equipment with a potential impact on food safety (vehicles, containers, tanks, pipes, pumps) must be kept clean and in a good state of repair.
- Water taken and used directly from untreated rainwater harvest, rivers or holding ponds should not be used for post-harvest washing.[209]

An example of a basic device for reception, washing and sorting is shown in figure 7.1.

Contaminated washing water would lead to contamination of the produce, and is a high risk to produce quality and food safety. Monitoring and controlling water quality is therefore critical. All post-harvest processes and procedures should be documented and subject to a food safety management plan (e.g. GlobalG.A.P.).[210]

Monitoring of quality can be done through measuring turbidity in water tanks. Measuring temperature is also important, as some vegetables and fruit are susceptible to water infiltration. When pulp temperature is warmer than the water into which it is submerged, water can be taken up by the fruit, and contamination of both water and product may occur.[211] Even with good quality water, it is sometimes necessary to conduct sanitation procedures in order to prevent cross contamination when many items of product are submerged in the same water. The most common practice is to add chlorine, but different sanitation practices can take place depending on the crop, growing practices, or regulations. For example, ozone has been used commercially for many commodities such as apples, cherries, kiwis, onions, etc. In 2001, ozone was approved as a safe anti-microbial agent in food processing by the US Food and Drug Administration.[212] Another common substance with GRAS (Generally Recognised As Safe) status in the USA, and effective against a range of microorganisms is Hydrogen Peroxide.[213]

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208 GLOBALG.A.P., "Integrated Farm Assurance. All farm base – Crops base – Fruits and vegetables", Cologne, 2015.

209 Suslow, T., "Ozone applications for post-harvest disinfection of edible horticultural crops", U. Ca, Division of Agriculture and Natural Resources, Publication 8133, 2004, anrcatalog.ucanr.edu/pdf/8133.pdf.

210 GLOBALG.A.P., "Integrated Farm Assurance. All farm base – Crops base – Fruits and vegetables", *op. cit.*

211 COLEACP, Training manual. Sustainable and responsible production, 2017

212 Suslow, T., "Ozone applications for post-harvest disinfection of edible horticultural crops", *op. cit.*

213 FSA, *Code of Practice for food safety in the fresh produce supply chain in Ireland*, Dublin, FSA, 2001.

7.2.2. Water use in post-harvest treatment

After washing, produce may be treated with a fungicide or insecticide, or other preservative agents to avoid disease (and potentially mycotoxins in some cases), comply with plant health rules, and extend shelf-life. At this stage, monitoring of water quality criteria is also needed, as well as temperature. The presence of pathogens in standing water is another potential risk, and this can cause serious problems during storage and consumption. It is therefore essential to drain all water every day.[214] Equipment used to submerge produce must be easy to clean and sanitize, and be made for example from stainless steel.[215]

7.2.3. 7.2.3. Water use in packaging and storage

Fruit and vegetables are perishable products, with short shelf lives varying from a few days (tomatoes), a few weeks (avocados), to a few months (garlic).[216] Water plays an important role during packaging and storage, in the following ways.

7.2.3.1. Cooling

Several methods of cooling are applied to produce after harvesting to extend shelf life and maintain a fresh-like quality. Not all of them use water; some simply use currents of cold air or refrigerators. The cooling methods using water are:[217]

- **Precooling:** Fruit is precooled when its temperature is reduced from 3 to 6 C and is cool enough for safe transport. Precooling maybe done with cold air, cold water, direct contact with ice, or by a combination of cooled air and water in the form of a mist called hydrair cooling, an innovation in cooling of vegetables.
- **Icing:** Ice is added to boxes of produce by placing a layer of crushed ice directly on the top of the crop. An ice slurry can be applied in the following proportion: 60% finely crushed ice, 40% water, and 0.1% sodium chloride to lower the melting point. The water to ice ratio may vary from 1:1 to 1:4.
- **Forced air-cooling:** Force air-cooling systems blow air at a high velocity leading to desiccation of the crop. To minimise this effect, the cooling air can be humidified with the help of cold water sprays.
- **Hydro cooling:** The crop is submerged in cold water, which is constantly circulated through a heat exchanger. When crops are transported around the packhouse in water, the transport can incorporate a hydro cooler. Hydro cooling can also help cleaning the produce. Chlorinated water can be used

214 GLOBALG.A.P., "Integrated Farm Assurance. All farm base – Crops base – Fruits and vegetables", *op. cit.*

215 Meyer, B., Newenhouse, A., Miquelon, M. *et al.*, "Work Efficiency Tip Sheets", U. Wisc. Extension Publication Series A3704, Packing shed layout, Mesh produce bags, Specialized harvest cart, Narrow pallet system, etc. Informative fact sheets, 1999, bse.wisc.edu/HFHP/tipsheets_html/postharvest.htm.

216 Kader *et al.*, *The role of post-harvest management in assuring the quality and safety of horticultural produce*, Rome, FAO, 2004.

217 FAO, *Handling and Preservation of Fruits and Vegetables by Combined Methods for Rural Areas*, Rome, FAO, 2003, www.fao.org/docrep/005/y4358e/y4358e00.htm#Contents.

to avoid spoilage of the crop. Hydro cooling is commonly used for vegetables such as asparagus, celery, sweet corn, radishes and carrots, but it is seldom used for fruit.

- **Vacuum cooling:** This method is particularly suitable for leaf crops such as lettuce. Crops like tomatoes with a relatively thick wax cuticle are not suitable for vacuum cooling. In this method, vacuum is applied so water boils at a lower temperature (at 4.6 mmHg of pressure water boils at 0 °C), and the heat of vaporization required for water to boil causes the cooling. In this process, the crop looses about 1% of its weight. This weigh loss may be minimised by spraying the produce with water.

7.2.3.2. Pest control and decay

Crops may be immersed in hot water before storage or marketing to control pests and diseases.

7.2.3.3. The case of flowers

Post-harvest water use is of high importance in the production of cut flowers. Cut flowers contain a considerable amount of water and so have high water loss, especially due to carbon catabolism processes.[218] When this loss reaches 10-15% of their fresh weight, flowers start to show wilting symptoms.[219] Depth and height of the water used to preserve the flowers is important, and affects the amount of water uptake by the flower.[220]

Flowers and foliage with a large leaf area are especially sensitive to drying out, so they need more water. Combining three factors can reduce flower water loss:

- Adequate water quality in the buckets, with an acidic pH (3.0–3.5), as this improves the flow rate up the stems
- Low temperatures and high relative humidity (95%-98%). Under these last 2 conditions, flowers can also be stored dry, wrapped and packed inside boxes.[221]
- Biocides may be added to avoid bacteria. Hypochlorite (bleach) or granulated chlorine in low concentrations is commonly used.

The most important factor for post-harvest water use in flowers is water quality. It has to be optimal and stable, therefore untreated surface water or rainwater is not recommended. A longer life, and therefore a more competitive product, can be guaranteed by using water of highest quality for flower post-harvest processes.

218 Dahal, S., *Post-harvest handling of cut-flower rose*, Department of Horticulture, IAAS, Rampur, Chitwan, 2013, www.academia.edu/3276681/POST_HARVEST_HANDLING_OF_CUT-FLOWER_ROSE.

219 Nowak, J. and Rudnicki. R.M., *Postharvest handling and storage of cut flowers, floristgreens and potted plants*, Portland, Timber press, 1990, pp. 210.

220 Sytsema, W. and Kalkman, E.C., "Post-harvest studies on Syringa vulgaris", *Acta Horticulturae*, No. 298, 1991, pp. 127-133.

221 NSW, Department of Primary Industries, "Postharvest care of cut flowers", Bettina Gollnow, Neil Wade, 2002, www.dpi.nsw.gov.au/agriculture/horticulture/floriculture/post-harvest/care.

7.2.3.4. The case of mangoes

As an example of water use post-harvest in ACP countries, mango is a useful example as it water is used at various stages. Mangoes are normally washed by being dipped in water to remove dirt or dust. They may be dipped in hot water as a post-harvest treatment to kill pathogens and the eggs and larvae of fruit flies. A summary of the postharvest water uses for mango is shown in table 4.

Figure 1 - Mango washing in packing house
Source: www.fealyfamily.com

Table 4. Water used in post-harvest operations of mango (based on FAO, 2002 and 2005)

Process	Water use
Washing	Any kind of dirt, dust or sap must be removed, and this can be done by either spraying or submerging in water.
Post-harvest treatments	In order to prevent anthacnose and stem end rot, mangoes are sometimes submerged in hot water (52 °C) for 5 minutes, adding benomyl, or sprayed with unheated water mixed with prochloraz. Hot water immersion is also recommended for pest control, to control fruit fly, and is more efficient than vapour heat as a heat transfer. The dipping time depends on the shape and weight of the fruit.
Packaging and storage	Mangoes are normally stored in conditions of 13 °C, in 85 to 90% relative humidity. Water can be vaporized or used to cool and increase humidity in the storage room, but should never be in contact with the product, as mangoes are susceptible to chilling injury.

7.3. WATER ISSUES IN POST-HARVEST WASHING AND PROCESSING

Two aspects need to be taken addressed when using water for processing:

1. Availability of clean water for processing, in terms of quantity and quality; and
2. Management of effluents.

7.3.1. Availability of clean water for processing

Consistent availability of water for post-harvest uses must be ensured. It is important therefore to have access to reliable sources of water that can provide the volumes needed.

Water used for post-harvest washing and processing be of potable quality (drinking water quality). GlobalG.A.P. certification requires water to be tested.[222] The most common sources of potable water are: water from the municipal water system, delivered through pipes, or water directly abstracted from groundwater sources (and tested). The challenge with the former is to have in place an adequate delivery infrastructure, especially outside urban districts. The challenge with the latter is to ensure adequate water quality, which will need to be tested. In regions where water is scarce in both in terms of quantity and quality, potable water may be transported by water trucks to the packhouse (see the case study in Chapter 9).

7.3.2. Management of effluents

During the cleaning, washing or packaging processes, the water used may become contaminated with pollutants. Waste water effluent may be harmful to other water users or the environment. Depending on the contaminants and the form of discharge, effluent may therefore need to be treated before it is discharged.

A risk assessment should be conducted to identify any hazards in the effluent and their level of risk. Measures should then be taken to avoid or mitigate any impacts on the environment. On-farm effluent is often discharge as surface water. In addition to treatment, and in the case of low-risk effluents (or following suitable treatment), the water may also be suitable for recycling, for example as irrigation water.

Particular care is needed when chlorine is added to washing water. In most countries, stringent regulations are in place to restrict the levels of residual chlorine permitted at the waste water effluent point. As an example, the maximum residual limit under the Safe Drinking Water Act established by the US Environmental Protection Agency (EPA) is 4 mg/L (ppm) for chlorine. The concentration of chlorine at the start of the washing/disinfection treatment is generally greater than 4 mg/L in order to control microbial contaminants.

222 GLOBALG.A.P., "Integrated Farm Assurance. All farm base – Crops base – Fruits and vegetables", *op. cit.*

7.4. WATER CONSERVATION DURING WASHING AND PROCESSING

7.4.1. Scope

Water conservation is defined as any beneficial reduction in water use, loss, or waste water. In other words, it refers to water management practices that improve and reduce the use of water resources to benefit people or the environment.[223] This definition is also applicable for the post-harvest stage. Effluent treatment and recycling is an example of a water conservation measure that can be applied post-harvest. A variety of possibilities are available, but farms/companies can be deterred by some technologies due to high cost and the need for continuous energy sources.

From a farm perspective, the various basic measures that can be used to reduce water consumption and effluent pollution are shown in table 5.

Table 5. Different types of water treatment and recycling at the post-harvest stage
Source: GSI, based in various authors.

Treatment	Common types of water treatments include flocculation, filtration and disinfection.[224] As a pre-treatment, filters are used to remove large solids. Primary treatment then removes (a) settleable organic and inorganic solids by sedimentation, and (b) floating materials by skimming. A high percentage of the biochemical oxygen demand (BOD5), suspended soils, oils and greases are removed using these simple treatments.[225]
	For on-farm effluent treatment, especially where there is abundant land but limited labour, stabilization ponds are commonly used. This is a recommended method in many ACP countries. These consist of anaerobic ponds, facultative ponds and maturation ponds.[226]
	Phytoremediation is another low-cost treatment. It involves the use of plants to remove pollutants from the environment (Figure 2). These can be either aquatic or terrestrial plants, and some species are particularly effective for particular pollutants. For example, hydrangeas absorb aluminium, and water hyssops absorb other heavy metals such as lead or cadmium. These plants take up polluted water, and retain the contaminants. This reduces potential soil and environment pollution.[227] However, this method is not recommended for recycling water for irrigation purposes if the concentration of pollutants is high, as they can be transmitted to the crop.

223 Alberta Water Council, "Water conservation", 2015, www.waterforlife.alberta.ca/01549.html.

224 Chen, L., "Development of a Continuous Water Recycling Unit for Application in Postharvest Washing of Leafy Greens", U. Guelph, 2013, atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/7618/Liang_Chen_201311_MSc.pdf?sequence=1.

225 Pescod, M.B., "Wastewater treatment and use in agriculture", FAO irrigation and drainage paper 47, 1992, www.fao.org/docrep/t0551e/t0551e00.htm#Contents.

226 IRC, "Waste stabilization ponds for wastewater treatment", May 2004, prepared by Cinara, www.bvsde.paho.org/bvsacd/cd27/ponds.pdf.

227 EPA, "A Citizen's Guide to phytoremediation", 2012, clu-in.org/download/Citizens/a_citizens_guide_to_phytoremediation.pdf.

Recycling	For reasons of product quality and food safety, the re-use of water within the washing/packaging process is not recommended without treatment. However, effluents coming from the packhouse can sometimes be used for irrigation if the concentration of pollutants are monitored and shown to be low.
	In some cases, domestic water purification devices allow the re-use of processing water for some domestic uses.
Treatment and recycling	Recent improvements to water treatments have made some advanced systems such as ultrafiltration available on-farms. These significantly reduce the use of water and energy but give high levels of water quality, allowing post-harvest water to be stored, purified and re-used for produce washing and processing.[228]
	Many manufacturers are now commercializing domestic water treatment and recycling methods. At the farm level, it is now possible to install a small purification plant for packhouse effluents, allowing re-use of the water for the packhouse, irrigation, or domestic use.

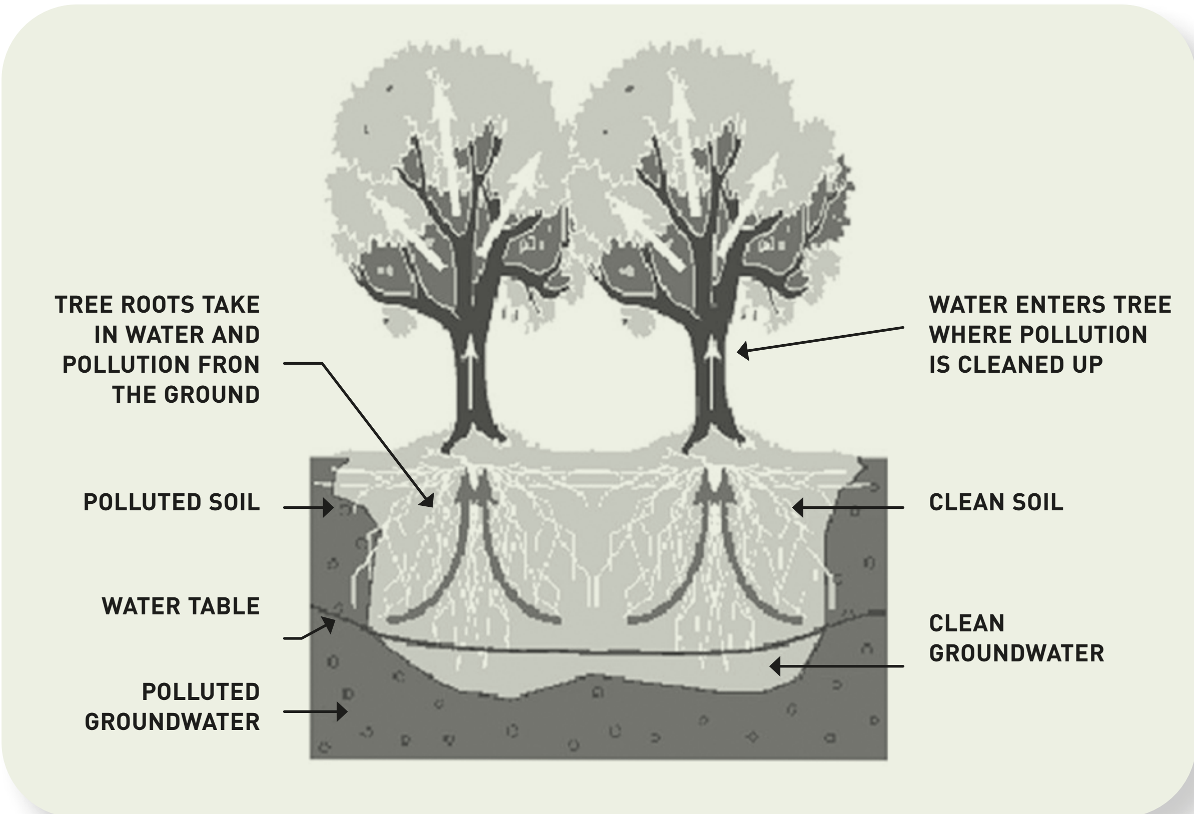


Figure 2 - Phytoremediation water treatment[229]

228 FloraCulture, "New post-harvest water recycling technology for the flower industry", *FloraCulture*, 2015, www.floraculture.eu/?p=21172.

229 EPA, "A Citizen's Guide to phytoremediation", *op. cit.*

7.5. POST-HARVEST WATER USE IN RELATION WITH FOOD LOSSES

7.5.1. Scope

As we can see, the poor management of water and moisture in the post-harvest stage can result in significant loss and waste of harvested produce. This may be because of food safety problems, deterioration of produce quality, or simply a decline in aspect that makes the produce less attractive for the retailer or consumer.

In industrialized countries, food losses take place mostly at the consumer stage, whereas in developing countries, almost all food losses take place during post-harvest and processing. Figure 3 shows the loss figures for fruit and vegetables.

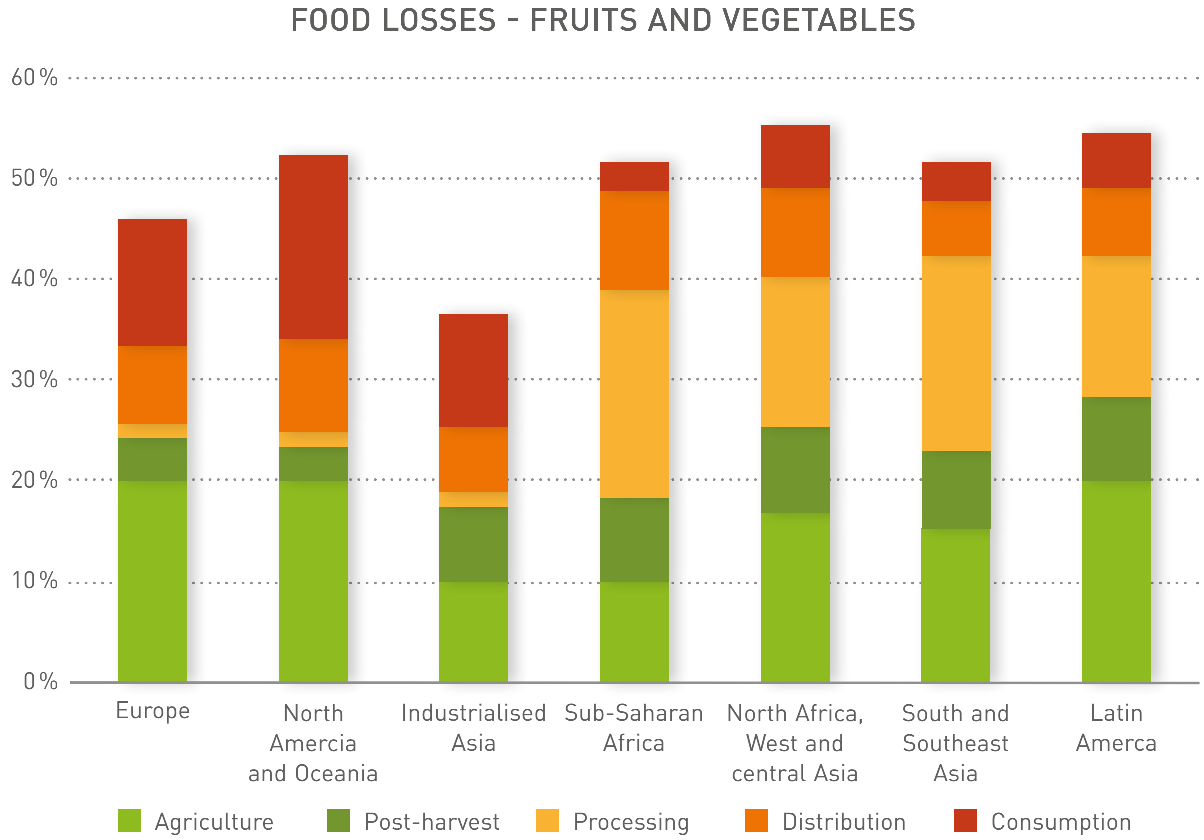


Figure 3 - Percentage of initial production of fruit and vegetables lost or wasted at different stages of the supply chain[230]

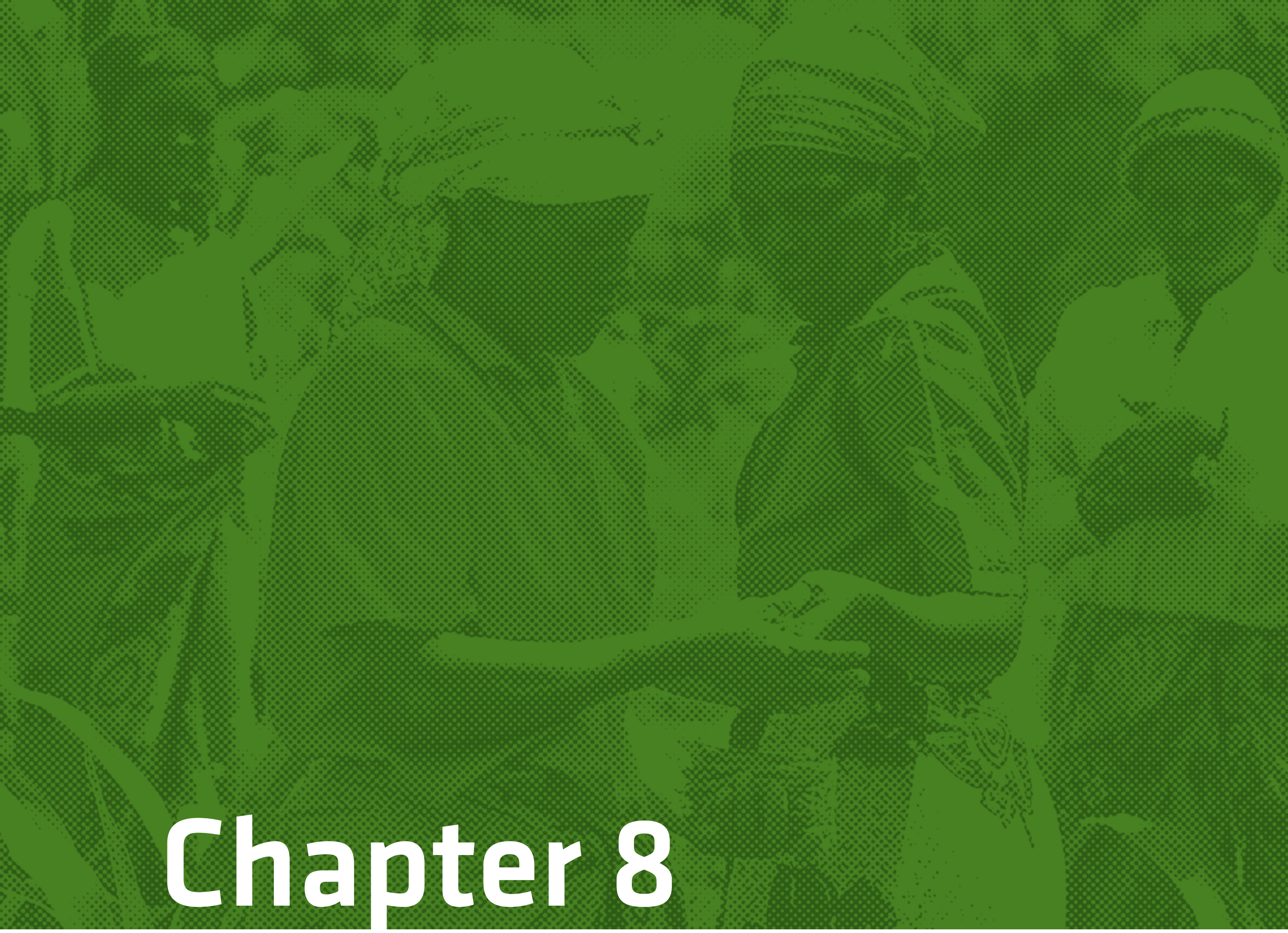
These high losses are due to factors such as climate, lack of adequate transport and storage facilities, or stringent retailer demands.[231] However, within these factors, water plays an important role.

When losses take place postharvest, in effect all the resources used to grow these crops, including the water, in are lost and wasted.[232] From a sustainable water use perspective, improving post-harvest produce handling is critically important, particularly in developing countries.

230 Gustavsson, J. *et al.*, "Global food losses and food waste. Extent, causes and prevention", Rome, FAO, 2011, www.fao.org/docrep/014/mb060e/mb060e.pdf.

231 World Bank, Natural Resources Institute and FAO, "Missing food: The case of postharvest grain losses in sub-Saharan Africa", 2011, siteresources.worldbank.org/INTARD/Resources/MissingFoods10_web.pdf.

232 WRI, "Disappearing Food: How Big are Postharvest Losses?", *EarthTrends*, 1998.



Chapter 8

Water rights, abstraction and sustainability of water use

8.1. UNDERSTANDING WATER LEGISLATION: WATER RIGHTS

8.1.1. Brief history of water rights

All societies use water. Historically, the regulatory mechanisms for water use or access to water developed differently from society to society. As a result, every society had their own specific customs and ideas about how to allocate water to different uses. Many of these are still found in customary or local law practices today, and often also interact with religious laws. Today, around the world, especially in rural areas of ACP countries, customary or local law continues to play an important role in water allocation.

Nowadays the use of water in most countries is governed by specific and specialised water legislation. In many, countries the basis of this legislation is strongly influenced by European legislation. In Europe the right to water was traditionally based on the use or ownership of land. This stems from Roman law which gave a privileged position (a water right) to owners of land adjacent to watercourses. Roman law denied the private ownership of flowing water, but considered water on owned land to be the private property of the owner. The European legislative traditions deriving from this (civic and common law, respectively the French/German and Anglo-Saxon frameworks) still contain elements of the Roman law on water. During European colonization around the world, many of these Roman elements were introduced into the water laws of many countries.

Mainly driven by the increasing pressure on water resources, a reform of the water sector is taking place in many countries, with the introduction of modern water legislation that replaces many of these traditional water laws. The main reason behind the reforming of water legislation is because the traditional land-based approach to water management has become more and more unsuited. This traditional approach:

- was not adequate to cater for hydrological and climatic conditions;
- did not take into account environmental considerations;
- did not recognize effectively the economic value of water;
- did not cater well for social aspects

8.1.2. Modern water rights

As a result, in the late 20th century the process of water sector reform began, with water legislation moving towards an approach based on water rights. There is no common definition of water rights but, according to FAO,[233] the simplest definition of a water right is: "a legal right to abstract and use a quantity of water from a natural source such as a river, stream or aquifer". Water rights also govern non-consumptive use of water, for example allocation of river flow for storage of water in a reservoir dam for later use to generate electricity. Water rights thus govern consumptive and non-consumptive uses of water. Modern water laws provide a legal framework to allocate water to users through the assignment of water rights.

233 FAO, "Modern water rights. Theory and practice", FAO legislative study 92, Rome, FAO, 2006, ftp.fao.org/docrep/fao/010/a0864e/a0864e00.pdf.

Since a water right is a legal right, it brings with it legal consequences. For example, extracting water without holding the corresponding water right can give rise to legal action from the entity that holds the water right. In an irrigation context, another form of water right exists. In an irrigation scheme, farmers hold a right to a certain amount of irrigation water from a supplier (at a certain fee rate). This 'contractual water right' concerns the right to the delivery of a volume of water through artificial structures, a service delivery right. These are not the same as abstraction water rights that concern the right to remove water from the natural environment. In irrigation schemes, the irrigation scheme manager holds the legal water right to abstract the water required by the scheme.

Water rights used in water legislation are not to be confused with the 'human right to water'. The human right to water was explicitly recognised by the United Nations General Assembly 28 July 2010, through Resolution 64/292. It acknowledged that clean drinking water and sanitation are essential to the realisation of all human rights. Although not the same as a water right, **the human right to water** is obviously an important part of the allocation of water in a country. In the context of water law it is addressed as an allocation of a quantity of water from a water resource to cater for domestic use.

7.1.2.1. Examples of modern water rights

Between countries, there are great variations in water legislation with respect to who owns and can own water resources and how water rights are allocated. In Kenya, for example, the Water Act of 2002 vests the ownership of all water resources in the state. If a person wishes to use water, a permit is required from the Water Resources Management Authority (WRMA). For minor uses of water, water abstraction from non-water stressed underground water resources, as well as abstraction of water from dams and reservoirs, permits are not required.[234]

A very different situation exists in other countries, such as Chile, where the Water Code of 1985 recognizes and protects water rights as property rights. These rights are assigned definitively and in perpetuity. While water is in the public domain, users may obtain proprietary water rights and allocate it for different purposes including agriculture. Being an asset that can be owned, water rights can be traded and a vibrant but also speculative water market has emerged. The market governs the allocation and price of water and regulation by the government has remained marginal.[235]

In water scarce situations, modern water legislation can also assign which water uses have prevalence over others. This is called a **'water use hierarchy'**. For example, the South African Water Act of 1998, gives clear prevalence to water use for basic human needs as well as for ecosystems. For this the Act established what is called "The Reserve" that needs to be set aside for any water resource in the country

234 Government of Kenya, Water Act Chapter 372 (2012 revised edition from 2002), National Council for Law Reporting within the Authority of the Attorney General, Nairobi, 2012, retrieved from faolex.fao.org/docs/pdf/ken37553.pdf on 23 September 2015.

235 Global Legal Research Centre, Legislation on Use of Water in Agriculture, The Law Library of Congress, 2013, extracted from www.loc.gov:8081/law/help/water-law/Legislation-on-Use-of-Water-in-Agriculture.pdf on 28 July 2015.

before other uses can take place. The Act states: "The reserve consists of two parts: **the basic human needs reserve and the ecological reserve.** The basic human needs reserve provides for the essential needs of individuals served by the water resource in question and includes water for drinking, for food preparation and for personal hygiene. The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource".[236]

As we can see from the examples above, water legislation not only addresses water rights but **also the governance, institutional arrangements and mechanisms to manage the water resources in the country.** Nowadays, water laws also specify how water users can engage in water management and how costs of water management will be covered. Water legislation also increasingly devolves governance of water. Examples of this are the legal provisions in many water laws of water user associations that govern water management of a lower level hydrologic unit like a sub-catchment.

7.1.2.2. Water quality and modern water rights

Modern water legislation also discusses water quality issues and other environmental issues associated with water use and water resources management. An example of this is the European Water Framework Directive (WFD). The first sentence in the directive is: "Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such" (Directive No. 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy). The WFD requires each European member state to define ´good surface water status´ for their water bodies and develop river basin plans and a programme of measures to achieve this status. The WFD aims to promote sustainable water use based on a long-term protection of water resources. Good surface water status means the status achieved by a surface water body when both its ecological status and its chemical status are at least 'good'.

While the WFD is a very strong and modern piece of legislation, full implementation up to now has been hard. For example, surface water resources in Europe suffer widely from water pollution from diffuse sources and 25% of the groundwater is of poor chemical status.[237]

8.1.3. Water rights and horticulture

From the perspective of a farmer and irrigator, it is important to understand and apply the water legislation framework in the country, namely the legal requirements for extraction of water and the permits required. It is equally important to understand how as horticulturalists, farmers can participate in the governance and allocation of water resources. The water laws of today often require high transparency and

236 Government of South Africa, National Water Act No. 36 of 1998, retrieved on 16 September 2015 from www.acts.co.za/national-water-act-1998.

237 EEA, *The European environment, state and outlook 2015*, synthesis report, Copenhagen, EEA, 2015, retrieved from www.eea.europa.eu/soer-2015/synthesis/report on 23 September 2015.

as such devolve power to local governments and citizen institutions such as Water Resource User Associations (WRUA). The legal provision of increased participation and engagement in these institutions can help farmers understand and influence the dynamics and risks associated with water based regulation. And, for farms there is a lot to win. Often horticultural products deliver higher value per volume of water consumed. In other words, they provide higher economic water productivity. In the debate on allocation of scarce water resources, horticulturalists can thus rise in the water allocation hierarchy while securing the water required for their production.

8.2. GUIDING ACTION: WHY AND WHERE TO START?

8.2.1. Overview

The drive for the sustainable use of the World´s water resources stems from the 1992 Rio Earth Summit. At the summit UN member states backed the Integrated Water Resource Management (IWRM) strategy as a way forward for efficient, equitable and sustainable development and management of the world's limited water resources, as part of an overall action plan on sustainable development. The core of IWRM is based on the Dublin principles (International Conference on Water and the Environment, Dublin, January 1992):

1. Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.
2. Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.
3. Women play a central part in the provision, management and safeguarding of water.
4. Water is a public good and has a social and economic value in all its competing uses.
5. Integrated water resources management is based on the equitable and efficient management and sustainable use of water.

Two decades after the acknowledgment of these principles, UN water presented to the 2012 Earth Summit +20 years, the status report on integrated approaches to water resource management. The short summary of this report is twofold. Progress is that 80% of the countries report to have embarked on reforms to improve the enabling environment for integrated water resources management. At the same time and in line with the context given in Chapter 1, the majority of countries perceive that water-related risks and the competition for water resources have increased over the past 20 years.

The increased attention for the sustainable use of freshwater resources led to a growing focus on water management by the private sector in the early 21st century. This has resulted in a suit of approaches and embedding of water management in business contexts. Some examples of this are:

- The application of the Water Footprint Assessment methodology has become standardised by the Water Footprint Network[238] and ISO standard 14046.[239]
- The Alliance for Water Stewardship has published the Water Stewardship Standard.[240]
- GlobalG.A.P. has introduced requirements concerning water in its Integrated Farm Assurance IFA.[241]
- Global reporting on water has been included in the water disclosure project of the CDP (Carbon Disclosure Project).[242]
- Advanced tools to understand water risks to companies have become freely available.[243]

Agricultural water management does not yet fully align with the principles of IWRM above. In order to make the best, most productive, efficient and sustainable use of water in horticulture, the five principles of IWRM described above need to become integral part of water use and agricultural practices. With the development of water-related approaches, standards and methodologies (some of them listed above), horticulturalists have the opportunity to increase their economic benefits by systematically embedding integrated water management approaches in their farm context. A general stepwise approach for doing so is outlined in Table 1 below. The table not only explains the steps but also why a certain step is taken, as well as which methodologies and tools may be used in that step. It also provides an illustration of the data and information that may be used to execute the step.

238 Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M., *The water footprint assessment manual: Setting the global standard*, London, Earthscan, 2011, waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf.

239 ISO 14046:2014, Environmental management – Water footprint – Principles, requirements and guidelines, Geneva, 2014.

240 AWS, "The AWS International Water Stewardship Standard", 2014, retrieved from www.allianceforwaterstewardship.org on 26 June 2015.

241 GLOBALG.A.P., "Integrated Farm Assurance. All farm base – Crops base – Fruits and vegetables", Cologne, 2015.

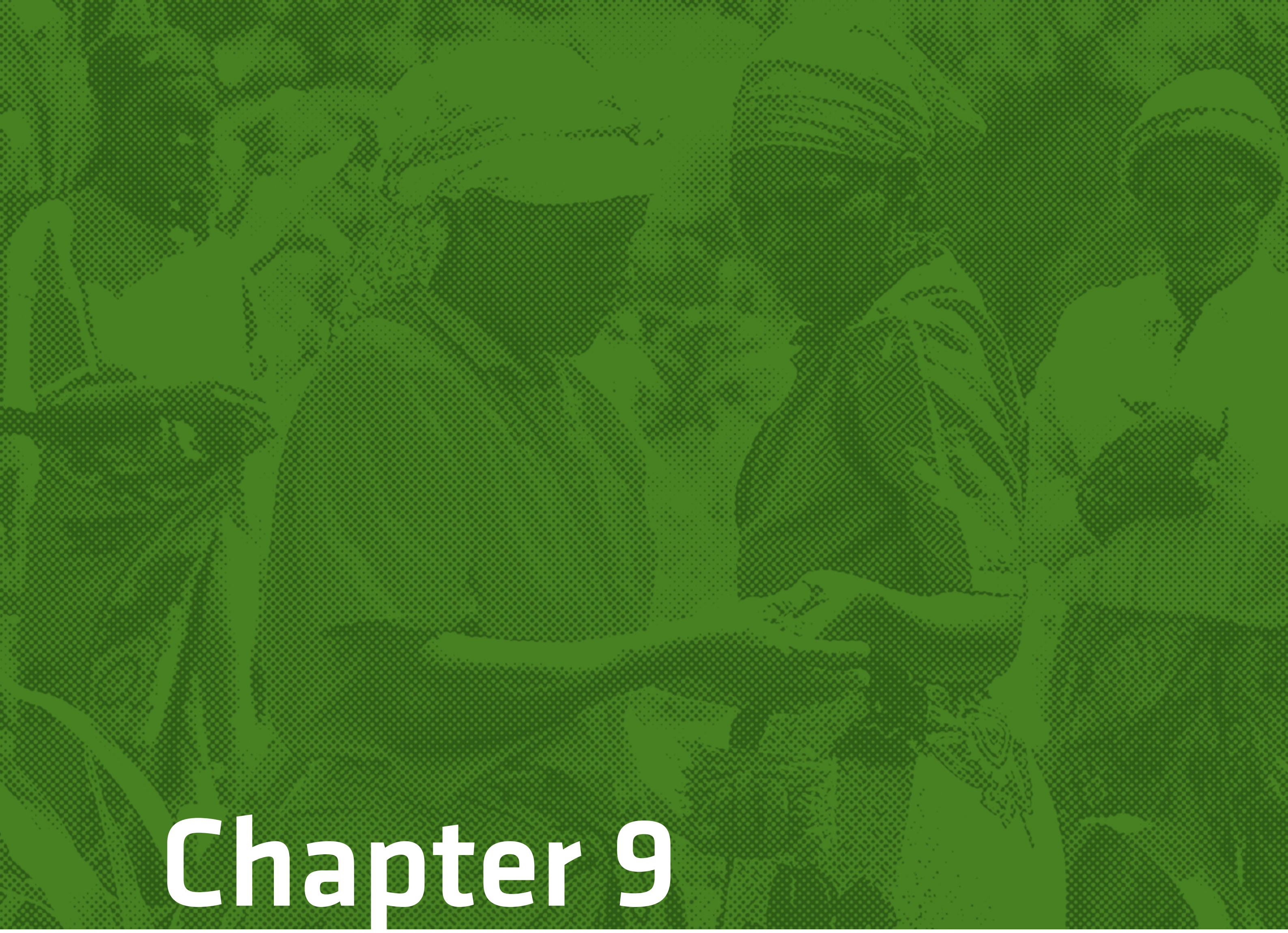
242 CDP, "Water disclosure project", 2015, www.cdp.net/water.

243 WRI, "AQUEDUCT. Measuring and mapping water risk", 2015, www.wri.org/our-work/project/aqueduct; WBCSD, "The WBCSD Global Water Tool", 2015, http://old.wbcsd.org/work-program/sector-projects/water/global-water-tool.aspx; WWF/DEG, "Water Risk Filter", 2015, waterriskfilter.panda.org.

Table 1. Overview of steps, tools, methodologies and data used for embedding IWRM in a horticulture farm context

Steps	Why	Tools/ Methodology used	Examples of data required
1. Scope and goal	To define clearly what you want to achieve with water management in your farm and beyond, and which geographic focus you take		Background data on your farm, its location, its activities (crops), general water situation in the farm and in wider region and catchment(s) of operation
Examples:	To increase the productivity, water use efficiency and decrease water pollution in the farm itself	Water footprint assessment	
	To manage water related risks originating from water use and pollution and regulatory, institutional environment around the farm	Various risk assessment tools	
	To assess if investment in irrigation is wise and effective in light of irrigation technology, farm productivity and the water situation around the farm	Irrigation planning	
	To comply with local legal requirements for water use, GLOBALG.A.P., Water stewardship or Global water reporting	GLOBALG.A.P. IFA, Water stewardship, Water disclosure	
2. Understanding the current physical water situation of your farm	In light of the goals and scope, create a baseline of the physical water situation of your farm and the catchment in which it is located	CROWPAT, Water Footprint accounting, global datasets, local data watershed delineation, hydrological modelling	Crop ET, Climate data (global local), water sources, catchment delineation, GPS location of farm, water sources and flow, abstractions of water sources, water quality measurements

3. Understanding risks and opportunities for your farm as well as the sustainability of water use	In light of the goals and scope, to interpret the physical water information in light of the social, environmental, economic and regulatory context, to understand farm water related risks and opportunities as well as scenarios for irrigation intervention and adapted agricultural practices	Risk tools, water footprint social sustainability assessment, water footprint based economic, agricultural water productivity scenarios	Regulatory information, environmental boundaries for water abstraction, environmental standards for water quality, social and economic data related to production, water supply and sanitation, catchment management plans if available
4. Developing a water management plan	In light of the goals and scope, to strategize and plan activities to improve water use efficiency, water productivity and decrease pollution at the farm and catchment level (if required) and/or to comply with GLOBALG.A.P., the water stewardship standard, regulations	IWRM principles, WS standard, GLOBALG.A.P. IFA	Data from 2 and 3 above
5. Monitoring and reporting	To continually adapt the effectiveness and impact of the activities in the water management plan, to comply with record keeping and reporting requirements	GLOBALG.A.P., Water Steward standard, Water disclosure, water footprint accounting	Farm water use and pollution, information on catchment level water management activities, information on yields and financial returns



Chapter 9

Production of fair-trade bananas in North Peru. A case study

9.1. INTRODUCTION

Banana production is an important economic activity, with economic and social benefits for a large number of small producers in the Piura department, Peru. Grouped into associations, farmers supply their bananas to the international market with the support of Agrofair, a fair trade organization and cooperative of producers.[244] Because the region is arid with very low precipitation, banana production depends strongly on irrigation. However, the current allocation of water to farm does not support sustainable water use, and this is having an impact on productivity and profitability. Farmers and farmer associations need to take action in order to improve water management at the farm and river basin levels, and therefore increase productivity and profitability. In this chapter, we describe the water situation in relation to banana production for that region and propose some of the measures that could be implemented.

9.2. SETTING THE CONTEXT

9.2.1. Targeted farms and geographic location

A sample of 120 farms was chosen for this study. These 120 producers are located in the Chira valley in North Peru, close to the border with Ecuador. They obtain water from the Chira river basin. The farm size varies from 0.3 to 6.3 hectares, with an average of 0.7 hectares. Farmers are grouped into associations but they are also sub-grouped into packhouses, with several using the same packhouse for washing, processing and packing bananas (Table 1).

The Chira river basin is a bi-national basin, also known as the Catamayo Chira basin since the river takes the name Catamayo in Ecuador. It has a surface area of 17,200 km^2, with about 33% located in Peru, in the Piura department. It has an altitudinal range that goes from sea level at the outlet of the Chira river, to 3,700 m.a.s.l. in the Ecuadorian Andes (Podocarpus National Park, Loja), where it originates (Figure 1). The main course is the Catamayo Chira River, with a length of 315 km. After crossing the national border to Peru, the river flows into the Poechos reservoir, and then to the Pacific Ocean, crossing the Chira valley.

244 www.Agrofair.nl

Table 1. Sample of farms chosen for this study in Peru, Piura department, Sullana province[245]. Source: GSI, 2013

Name of the packing plant	Name of association	No. producers	Farm size in hectares			Average yield t/ha[246]	Irrigation type
			Min	Avg	Max		
1. Yacila	APPBOSA	88	0.3	1.5	6.3	34	Sprinkle
2. Bomba II	CENBANOR	6	0.5	0.5	0.5	38	Flood
3. Carrasco	CENBANOR	4	0.3	0.4	0.5	21	Flood
4. Santos Heredia	CENBANOR	5	0.5	0.5	0.5	21	Flood
5. Grimanesa I	CENBANOR	3	0.5	1.0	1.5	35	Flood
6. Isidro III	APROBOVCHIR	14	0.3	0.6	1.3	49	Flood
Average[247]		120	0.4	0.7	1.8	34	

Figure 1 - Region of study: Chira river basin (red line), main rivers in the Chira river basin (blue lines), Chira valley (indicated with the orange arrows). The location of the San Jacinto – Piura climate station is marked with a white triangle. Both river basin delineation and river maps were taken from the global FAO database of maps[248] and exported into Google Earth.

245 GSI, "Water Footprint Assessment of bananas produced by small banana producers in Peru and Ecuador", 2013, www.goodstuffinternational.com.

246 Yield estimates based on packing plant capacities and amounts of bananas sold by producers. It is assumed that 85% of production is sold to the packing plants for export.

247 Average yield figures are based on total production and total farm area.

248 FAO, "Aquamaps", 2015, www.fao.org/nr/water/infores_databases_aquamaps.html.

9.2.2. Climate conditions

The Chira valley is a very dry region with only one rainy season in the first months of the year (Figure 2). During the rest of the year, precipitation is very low to nil. The region suffers blue water scarcity for 7 months of the year, from July to January[249] (see Figure 2). Climate change scenarios for the region predict severe water stress for the Piura region in 2050.

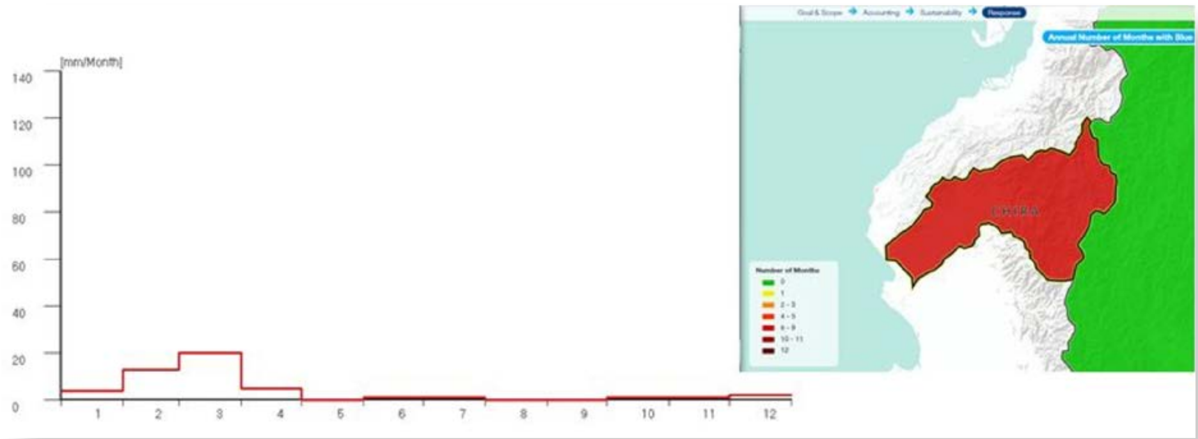


Figure 2 - Left: Average (1961 – 2000) monthly precipitation from the San Jacinto – Piura climatic station (see Figure 1 for geographic localization of the station). Source: New Loc Clim database (FAO, 2014)[250]
Right: Chira river basin undergoes blue water scarcity during 7 months of the year (data between 1996 – 2005. Source: Water Footprint Assessment Tool, WFN, 2015)[251]

9.2.3. Objective of the study

Banana farmers in the Chira valley use water in two main ways. The first is irrigation, essential for banana production due to the low levels of precipitation (the sample of farms analyzed used both sprinkle and flood irrigation – Table 1). The second is water used in the packing plant, mostly for washing.

The objective of the study, which was conducted in 2013, was to define strategies to increase the sustainable consumption of water for banana production and processing by smallholder producers in this region of Peru (and therefore the sustainability of the supply chain). Good Stuff International conducted the study[252] with the support of Agrofair and TASTE.[253] A complete report of the study in Spanish is available through the Good Stuff International website.[254]

249 WFN, "Water Footprint Assessment Tool", 2015, waterfootprint.org/en/resources/interactive-tools/#CP.

250 FAO, "New LocClim: local climate estimator", 2014, www.fao.org/nr/climpag/pub/en3_051002_en.asp.

251 WFN, "Water Footprint Assessment Tool", *op. cit.*

252 GSI, "Water Footprint Assessment of bananas produced by small banana producers in Peru and Ecuador", *op. cit.*

253 www.fairtaste.nl.

254 GSI, "Water Footprint Assessment of bananas produced by small banana producers in Peru and Ecuador", *op. cit.*

9.3. TOOLS

In order to guide the discussion on the water sustainability of banana production in the Chira river basin, GSI used the Water Footprint Assessment[255] and the Water Risk Filter,[256] combined with data collected in the field. The methodological details of both tools can be found elsewhere and are so not discussed here.[257] However, the application of these tools guided the field data collection.

A technician spent two weeks in the field for the data collection. She gathered information at the farm and packhouse, with the agreement and collaboration of the producer associations. As these are small-scale producers, little hard data was available, so much of the data was inferred by talking to farmers or by simple measurements taken at the packhouses. Ultimately, the ability of the technician to find simple and creative ways to gather information was fundamental.

Table 2. Tools used to assess water sustainability in the case study
Source: after GSI, 2013

Tool	Ultimate purpose of applying this tool
Water Footprint Assessment	• Understand actual crop water consumption in relation to crop water requirements and irrigation patterns. • Quantify availability of green water for the banana crop • Conduct a soil water balance for optimal irrigation scheduling • Compare water consumption by the crop and water consumption for processing. • Compare the water footprints of bananas at the agricultural and processing stages.
Water Risk Filter	• Score water risks at the river basin level and for the business • Understand water governance in the region • Learn about climate change scenarios for the region
Data collection in the field	• Obtain specific information about: • Yields • Sources of water used • Water quantities applied to fields • Frequency of water application • Water used for banana processing • System of water allocation to farmers • State of other issues such as salinity, canal maintenance, etc.

255 Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M.. *The water footprint assessment manual: Setting the global standard*, London, Earthscan, 2011.

256 WWF, "The Water Risk Filter", 2015, waterriskfilter.panda.org.

257 GSI, "Water Footprint Assessment of bananas produced by small banana producers in Peru and Ecuador", *op. cit.*

9.4. ACTUAL IRRIGATION PRACTICES VERSUS THEORETICAL IRRIGATION SCHEDULING

9.4.1. Actual irrigation practices

Due to the prevailing water allocation policy in the region, producers receive abundant water in a system of turns. Each turn lasts several hours. Because turns are spaced, in general producers try to apply as much water as possible to their fields during their turn, especially during the dry season, which is warmer and drier. However, producers from one of the packhouses reported the opposite. Table 3 shows a summary of the irrigation patterns.

Table 3. Irrigation patterns of the farms analysed

Irrigation pattern	Number of packing plants following this irrigation pattern
One every two weeks during the dry season, once every three weeks during the rainy season.	2
Once every three weeks all through the year.	3
Once every three weeks during the dry season, three times every four weeks during the rainy season.	1
Total	6

Because the frequency of water reception is not very high, farmers apply all the water they receive per turn to the crop, in an attempt to avoid conditions of water stress. This practice was observed for both sprinkle and flood irrigation systems. The problem with this approach is that farmers receive more water per turn than the soil can retain; this method of water application seriously impeded the water efficiency advantages of sprinkler irrigation systems. A similar pattern emerged for the flood irrigation practice where fields were over-flooded during irrigation (Figure 3). The inefficient irrigation management and application practices led to high evaporation losses, high runoff, erosion, leaching of nutrients, salinization (Figure 4) and bad drainage.[258]

258 Agrofair Sur, TASTE, ApecoInca, Master SRL, "Factores que predisponen el crecimiento y desarrollo del cultivo de banano orgánico en 'Savanna grown'", 2011; *id.*, ApecoInca, Master SRL, "Introducción de bananos 'Savanna grown' y 'Mountain grown': hacia nuevos conceptos para una fruta tropical más sostenible. Estudio territorial ambiental y estudios de caso socioeconómicos y ambientales de fincas bananeras en Perú", 2011.

Figure 3 - Flood irrigation to banana crops in Peru

Figure 4 - Salinization problems in the Chira region
Source: Agrofair Sur[259]

259 Agrofair Sur, "Factores que predisponen el crecimiento y desarrollo del cultivo de banano orgánico en 'Savanna grown'", *op. cit.*

In addition, no irrigation water is available between turns, leading to water stress for the banana crop. Crop yield reductions associated with water stress were estimated at 27% (using the CROPWAT model).[260] Reduction in the quality of the fruit was also reported. This in turn affects profitability.

Irrigation water comes either directly from the Poechos reservoir, or from the Miguel Checa irrigation canal (Figure 5). This canal also serves rice producers and, according to banana farmers, rice producers are prioritized; there is therefore competition for water, especially during the dry season, with serious consequences for banana production.

Figure 5 - Miguel Checa irrigation canal

9.4.2. Irrigation scheduling

The Cropwat model[261] helps to plan an optimal irrigation schedule for the crop; it also allows for the input of real data (see Chapters 5 and 6 for more details on Cropwat), which means that it is possible to compare the planned schedule with the actual irrigation schedule (and thus estimate potential irrigation water losses). The study results show that for most of the sample packhouses (CENBANOR and APROBOVCHIRA, see Table 1), irrigation water losses are very high. The model shows that the producers here apply more water than the soil can retain per application, with the excess water being lost to evaporation or runoff.

260 FAO, "The Cropwat model", 2010, www.fao.org/nr/water/infores_databases_cropwat.html.
261 *Ibid.*

An example is given here from another of the packhouses. Geographical coordinates are used to determine the closest climate station and most suitable climate data. According to Cropwat, the banana crop specific to this location has a water requirement of 2236 mm/yr in order to grow fully, without any water stress. Precipitation is 45 mm/yr, so Cropwat determines that 2191 mm/yr (the difference) would be needed as net irrigation. However, through the incorporation of real irrigation data, the model estimates that in reality this crop evapotranspires only a total of 1730 mm/yr under the current irrigation pattern. From this 1730 mm/yr, 45 mm/yr is from precipitation, so the crop actually evapotranspires 1685 mm/yr from irrigation water. Thus the crop does not evapotranspire all the water that it needs for full optimal growth. The result is that the crop is suffering from water stress, with respective yield reductions.

Looking at data on irrigation applications to this crop, the total net irrigation for the crop was 4656 mm/yr (the model requires a default irrigation efficiency, of 70% in this case). This means that the difference, 4656 – 1685 = 2971 mm/yr (63%) was applied without any benefit to the crop. This water can be considered 'lost'. So while the crop suffers water stress, at the same time irrigation water is lost. A yield reduction of 27% due to water stress was estimated by Cropwat. It is worth noting that the application of irrigation water was not systematically measured, so results and conclusions should be handled with care. The information on water applied was inferred from the design information of the distributing pumps and conversations with farmers on how they use the pumps. Still, a visual verification of this situation was conducted. Cropwat provides a quantitative support for this analysis.

Because of the water allocation system in place, having flood or sprinkle irrigation does not make any significant difference for the amount of water used and the crop yield.

9.5. WATER FOR WASHING AND PROCESSING

Clean freshwater is very important for washing and preparing the final product. Farmers bring their bananas to the packing plants, where they are washed and packed in ready-for-export boxes (Figure 6). In this region, clean water is scarce and comes from two sources (Table 3): groundwater (Figure 7) or water obtained from lorries transporting potable water to the processing plants.

Figure 6 - Washing of fair-trade bananas for export in Valle del Chira, Peru.
The technician collecting data is having a visual inspection (with orange bag).

Figure 7 - Extraction of groundwater for washing and processing bananas for export in Valle del Chira, Peru

Due to operational reasons, it was not possible to address water pollution from washing and processing in a quantitative way. However, qualitative data was collected on chemical additives to the water for processing and the fate of wastewater (Table 4).

Table 4. Use of water for washing and processing in the banana packaging plants

Banana association	Source of water used in the packaging plant	Fate of wastewater	Possible pollutants in wastewater*
APPBOSA	Groundwater	Canals take waste water directly into the Chira River	Chloride, Potassium Alum[262], BC-1000[263]
CENBANOR	Groundwater	Canals take waste water to the banana crops	Chloride, alum, Lemon, BC-1000
APROBOVCHIRA	Lorry delivering potable water	Waste water discharged directly to the land beside the packaging plant	Potassium Alum

* All substances added to freshwater for washing and treatment of bananas

The amount of water used for washing and processing per kilogram of banana produced is significantly smaller than the amount of water required for irrigation, as the water footprint results presented in the following Section indicate.

9.6. RESULTS AND MAIN MESSAGES

- The average water footprint of bananas in the sample analyzed was 599 m^3/t, which corresponds to 11.4 m^3/box of fruit for export. 94% of this corresponds to blue water, indicating the strong reliance on water for irrigation, and the very small contribution from rain (6% corresponds to green water). Less than 1% of the total blue water footprint is from the packhouse phase, showing that the biggest proportion of water consumption is for irrigation.
- The water risk filter[264] provides information on two types of water risks: company-related and basin-related risks. Scores are measured from 1 to 5, with 5 indicating the highest possible risk. In this case, results obtained are 3.7 and 3.5 respectively, showing a high level of water risk for the bananas cultivated in this region. According to the water risk filter, the company could significantly increase water efficiency, while the physical water scarcity and competition for water among users in the Chira valley are critical.

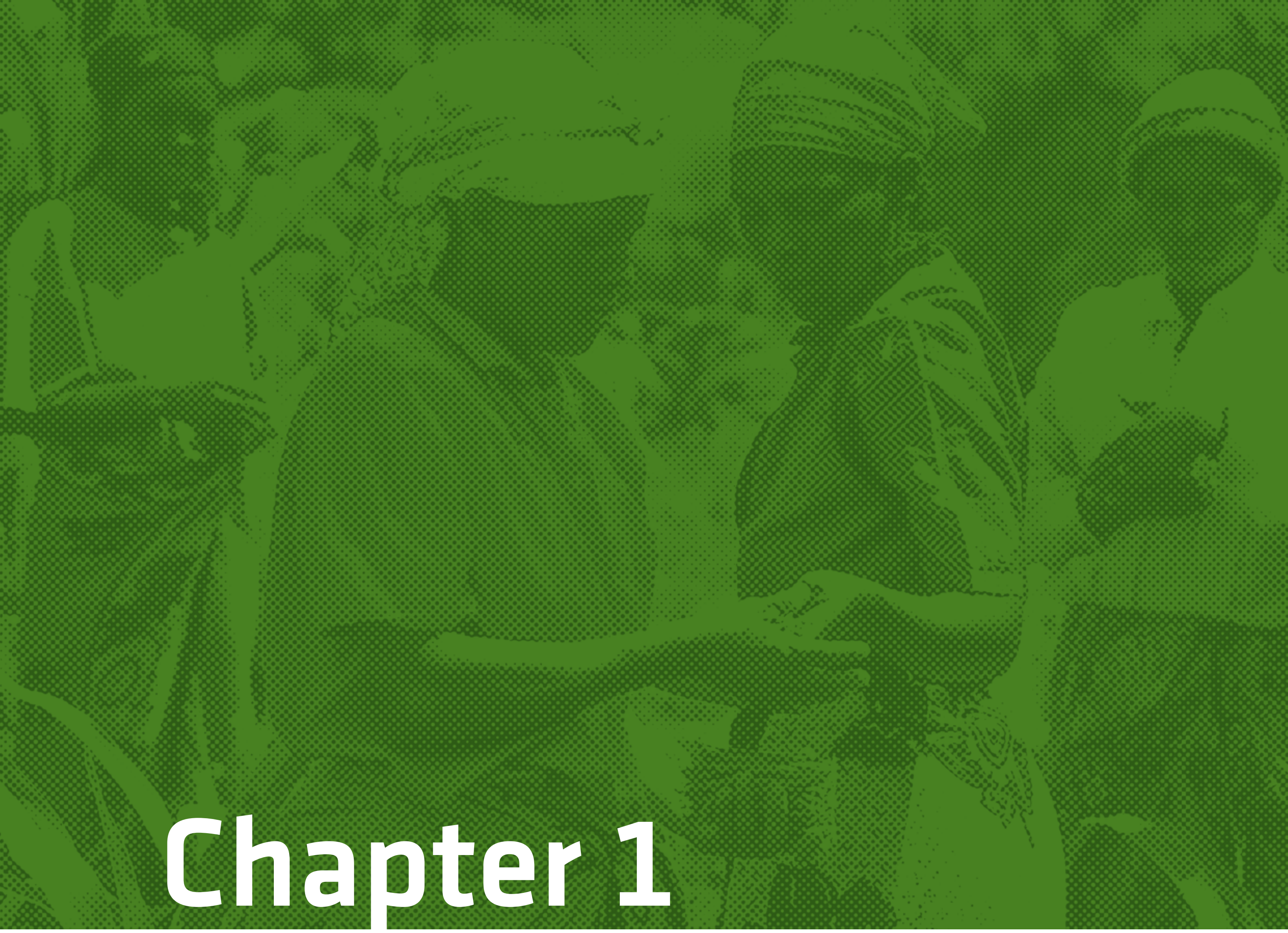
262 Hydrated Potassium Aluminum Sulphate, a healing-bleach substance, antioxidant.
263 BC-1000 is an organic bactericide and fungicide.
264 WWF, "The Water Risk Filter", *op. cit.*

- The specific tools of the water footprint assessment and water risk filter provide a solid and globally recognized framework for data collection and for understanding and communicating the water situation in the farms and the river basin. They guide the preparation of a company water management plan.
- Often the technical or financial resources to apply these tools are not available. Through visual inspection, collection of a minimal amount of data, and the application of irrigation scheduling, it would be possible to get at least a qualitative idea of how efficient the water resources for irrigation are being used. It is also recommended that farmers engage in water discussions at the catchment or river basin level to start managing basin-related risks, and to increase opportunities to influence water allocation policies.
- Water for irrigation is used in a very inefficient way. There are two main reasons for this: the first is related to the way water for irrigation is managed at the river basin level. The frequency and amounts of water allocated to farmers should be revised. The second relates to a lack of knowledge about the advantages of scheduling irrigation and managing it in an integrated way, together with salt and nutrient management practices.
- In view of the water scarcity situation and the climate change prognosis, it is recommended that stakeholders work towards two main strategies:
    1. At the farm level, storing the water received from the irrigation districts so that during the turns, only the water required by the crop is applied, and the rest is kept for the following days and weeks when the crop will need water again (Figure 8). Farmers or associations could become organized to better find the location and financial resources for storage facilities.
    2. The second, at the river basin level, refers to engaging in river basin discussions, water platforms and groups, in order to promote better water distribution to farmers, more in line with the current climatic conditions and soil and crop requirements. The latter is a long-term and perhaps more challenging strategy as it involves other stakeholders as well as changes in policy.
- Engaging in dialogue at the river basin level is crucial, not only for the water allocation and distribution discussion, but also to motivate actions related to other severe water problems in the basin, for example the bad maintenance of the Poechos reservoir and irrigation canals, pollution problems, competition for water and climate change scenarios.

Figure 8 - One farmer in the sample stores the water received during his turn for his banana crop. For this, the farmer needed enough space (which is not always possible) and to invest in simple infrastructure. Although there are evaporation losses in these reservoirs, the crop receives water with a better timing, and therefore is less stressed.

SUSTAINABLE WATER MANAGEMENT

PART II



Chapter 1

Water in horticulture

1.1. MAIN USES OF WATER IN HORTICULTURE

To manage water on the farm for production and post-harvest activities, there are four basic water-related principles:

1. Ensuring sufficient quantity of water to cover needs
2. Ensuring adequate water quality
3. Avoiding pollution.
4. Managing water as a shared resource.

Access to water in the right quantities, at the right time, and of the right quality, is fundamental for horticulture. It is a prerequisite during production, but also for many post-harvest activities such as washing, processing and packaging.

1.1.1. Water for production

Good yields rely on adequate levels of water for the crop to germinate, establish and grow. Water is used by the plant for transpiration (95%), photosynthesis (5%), nutrient uptake, and to maintain cell pressure (turgor) and prevent wilting.

Water availability to the plant is determined by the amount of water in the root zone. This in turn is affected by water levels in the soil, and soil type and characteristics. In water-abundant regions, horticulture can be rain-fed, while in drier regions or dry seasons, irrigation is an advantage (or even essential) for crop production. Irrigation water can be obtained from a variety of sources including rivers, boreholes, reservoirs, springs or piped mains. The quality as well as quantity of irrigation water is important to achieve good yields, high quality and safe produce, and to prevent soil degradation.

Soil type and soil characteristics affect the way in which water penetrates the soil (rather than being lost as runoff), and the way in which is it retained, keeping the soil moist.

Managing water for optimum crop growth therefore requires an understanding of water availability, water quality, soil type, and soil management. These points will be covered in more detail in later chapters.

1.1.2. Water use post-harvest

Water is used in produce washing, post-harvest treatments, packaging and storage. Using water of the right quality and in the right way is essential for maintaining product quality and preventing food safety risks.

Figure 1 - Post-harvest management of fruits
Source: Pennwalt Ltd

1.2. THE BUSINESS CASE

Water is a fundamental resource for the sustainability of any horticultural business. To ensure profitability, it is essential to take a pro-active approach to water management at the farm level. Farmers should understand how much water is used in all farm activities, how much water is actually needed by the crops, what sources of water are available, and how to be more water-efficient. By being more water-efficient, the productivity of the farm will increase, and with that the profitability. The relationship between water, soil and crops means that adopting better and more efficient water use will also increase the nutrient-efficiency of the farm, and improve the soil.

1.2.1. The business case for managing water

1.2.1.1. Increasing farm productivity and profitability

To optimize crop yield, sufficient water must be available at the time the crop needs it. By knowing exactly when and how much water the crop needs, irrigation can be tailored to avoid unnecessary or excessive applications, and cost savings can be made on water extraction. Efficient irrigation management can also lead to savings by reducing indirect costs such as pumps, fuel, maintenance and fertilizer. Water extraction costs can also be reduced by water capture and recycling, as well as by managing the soil to improve water retention. Measures to improve water management, many of them simple and inexpensive, can increase yield, reduce costs, and increase overall profitability.

1.2.1.2. Increasing overall sustainability

The only way a business can remain productive and profitable over time is by ensuring that the use of key resources and inputs, including water, is sustainable.

Managing water well at the farm level:

- ***Increases overall resilience to climate change.*** By monitoring crop water needs versus water availability over several crop cycles (or years), it is possible to understand how climate change is affecting the business. This allows for forward planning to anticipate and take the actions needed to ensure the sustainability of the business.
- ***Ensures long-term water security.*** By protecting local water resources, farms can help to maintain a water-secure business in terms of both water quality and quantity.
- ***Improves soil quality, decreases erosion, and increases the efficient use of fertiliser.*** This drives down costs and decreases negative environmental impact.
- ***Reduces negative social and environmental impacts of water use.*** For example, in areas that are water scarce, efficient water use and the avoidance of waste will mean that there is more water available for other people and the environment. Preventing pollution means fewer impacts on the health of people living downstream, and more fish in the river.

Figure 2 - Farmer-led water management
Source: DW

1.2.1.3. Meeting buyer demands

A water secure farm business will be more productive and resilient, and better able to provide a consistent, reliable and high quality supply of horticultural produce to its buyers. In many areas, managing water is becoming a key factor of competitiveness.

In many export and high-end local markets, water management is a requirement to access markets, and buyers demand evidence from their suppliers that they are using water responsibly. The main farm-level good agricultural practice standard (GLOBALG.A.P.) includes several water-related compliance criteria. For example, maintaining records of water use, and implementing a water management plan, are obligatory to obtain GLOBALG.A.P. certification.

1.3. WATER AS A SHARED RESOURCE

1.3.1. Impact

Around the world people are becoming more aware of water as a critical resource that needs to be preserved and protected. Water, especially clean water, is becoming scarce in many areas, while at the same time pollution of surface and ground water is a growing concern.

The way in which individual farms or businesses use water also has an impact beyond the enterprise itself; responsible water use is essential to protect the environment and other users.

In recognition of these issues, many local and national governments are strengthening policies, laws and controls for better water management. The private sector is also targeting responsible water management through private standards and certification, now obligatory in many global supply chains.

The result is that farmers are increasingly facing demands from society to comply with water regulations and standards. These include:

- ***Laws governing abstraction.*** These cover aspects such as: water rights, water permits, water associations, the cost of water, and water hierarchy (who gets priority to receive water when water is becoming scarce).
- ***Laws on water pollution*** covering water discharge and water quality standards for effluents.
- ***Irrigation schemes.*** Members are required to follow certain rules or agreements. Being a scheme member implies interaction with other farmers, associations and institutions.
- ***Supply chain controls.*** Many buyers demand that their suppliers are certified under one or more private standards before they will enter into a contact. Increasingly water is specifically addressed in international supply chain standards, for example the GLOBALG.A.P. IFA and ISO Water Footprint 14046.

Introductory exercises for horticultural farms and businesses

- List the different uses of water on your farm for production and post-harvest purposes.
- List the sources of water used on the farm.
- Draw a rough map of your farm showing water sources on and around it.
- Do you know how much water you use? Do you know how much water you need? If not, do you have any ideas how you may measure or estimate these?
- List any water-related problems you have encountered in the farm/business.
- Do these issues have a significant impact (or potential impact) on your operations?
- Do you think water management on your farm affects productivity, profitability and competitiveness?
- Do you know the main water regulations in force in your locality? Do these regulations affect the water availability to your farm? In what way?
- What are the main water institutions in your location (e.g. Water Authority, irrigation schemes, user associations)? Are you involved with any of these? If yes, why and how? If not, should you be?

1.4. EXAMPLE

1.4.1. Suzan and Kioko

Susan runs a 10-hectare farm in Taita Taveta County in South East Kenya. Her farm is called Taita Veg and Fruits. She specialized years ago in growing vegetables and fruits. Next to farming on her own farm, she buys farm produce from small-scale farmers nearby. Taita Veg&fruits sells this produce in Mombasa. She is very lucky that her sister lives there and maintains the contacts with supermarkets, hotels and restaurants, where she sells her vegetables and fruits.

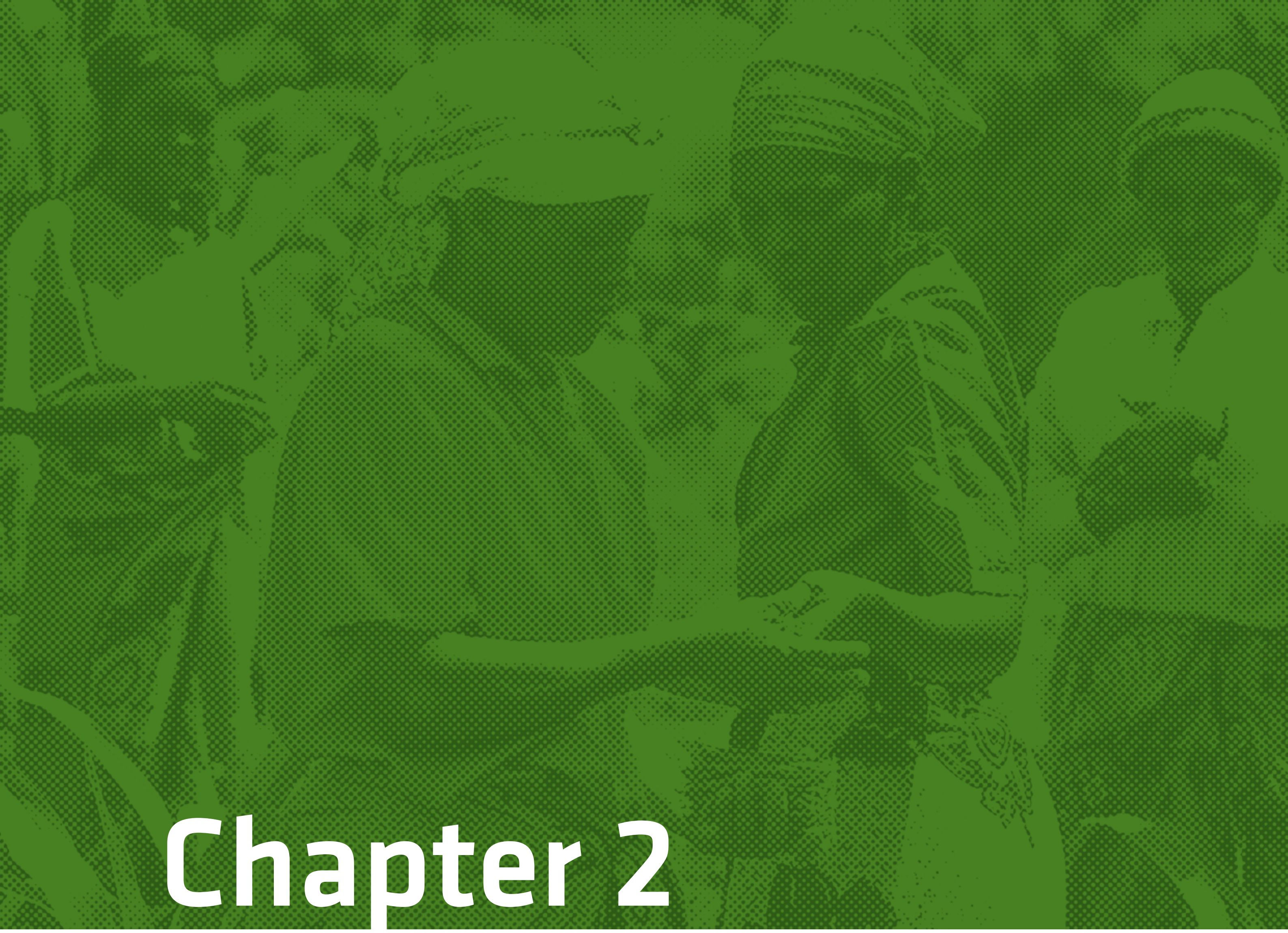
Her most important crops are tomato, onion, kales and mango. She also grows banana in the low-lying wet parts of her land. She is now in the middle of the tomato-growing season and irrigates her crop regularly. She gets the water from an irrigation canal, as she is a member of the local irrigation water user association. However, the volume of water from the canal is often not sufficient for her crops. So, as many farmers do, she supplements the canal water with water pumped from the nearby river. Often in this period of the season, many farmers pump water out of the river and it seems that the river level goes down because of that. Susan sees the water level is dropping further every year and sometimes wonders if in the future there will be enough water for her crops.

Figure 3 - Growing tomatoes in Taita Taveta

Kioko has a 0.5 hectare farm. Apart from maize, he grows tomatoes that he supplies to Susan after harvest. This season, he grows maize on half of his land. He has sown at the start of the long rains. His maize is not irrigated and sometimes Kioko suffers yield losses. His tomatoes are on the other half of his land that is located near a spring. He takes water from the spring when he feels that the tomato crop needs it. Then he hires a pump and buys fuel to flood his field. When the field is fully flooded and he sees the water flow from the lower end of his field, he stops the pump. At that time he does not really know how much water he has applied on the field. He feels the tomatoes have enough water now for a week, until it may rain again. If not, he needs to water his crop again, but he is not fully sure. He does not realize that the water flowing from his field removes fertile topsoil and washes away some of the fertilizer that he applied a couple of days earlier. Kioko knows that he is not allowed to take water from the spring just like that, but he does it, as it is normal practice among all farmers. Water is free for everybody.

What if:

- Susan and Kioko understood a bit more about how much water their crops really need for optimal growth and when it is needed. They could save money on fuel and pumping costs and her crop could have a higher yield.
- Kioko understood that the fertilizer flowing from his field does not only cost him money but also ultimately pollutes the river below that his family uses for washing.
- Both Kioko and Susan would realize that the total amount of water in their location is limited and that water is a key and valuable input for their farms to be productive. As water is considered to be free by farmers, most likely a lot of it is wasted. As it is clear, water has become less available, the canal water is not available at certain times and river levels are dropping. Susan perceives an increased risk to her farm productivity.



Chapter 2

Water use and abstraction

2.1. SOURCES OF WATER

2.1.1. Definitions

In order to implement an effective water management plan, it is essential to have a clear understanding of the water available to the enterprise in terms of quantity and quality. There are three main categories of water according to source.[265]

Green Water. In many places, the primary source of water for crops is precipitation (rainfall). Water from rainfall that does not run off or recharge groundwater, but is present on or in the soil root zone, is known as 'Green Water'.

Blue Water. Fresh surface and groundwater is known as 'Blue water'. This includes water from freshwater lakes, reservoirs, rivers, boreholes and springs.

Grey Water. Domestic or farm water that is recycled and re-used is known as 'grey water'. This could be sourced from household activities such as washing/laundry, or from the washing of farm produce. This waste water is likely to be mildly polluted but may be suitable for some purposes, or may need to be treated (grey water does not include waste water contaminated with sewage and human faecal matter, which cannot be re-used on farm).

The advantage of blue water over green water is that it can be accessed whenever and wherever the crop needs it, provided the necessary infrastructure is in place and sufficient water is available.

Green water availability ultimately depends on rainfall, which may not be reliable or dependable. However, the retention of green water in the soil depends on soil type and soil characteristics, and this can be influenced by management. Increasing soil organic matter content, for example, can increase the capacity of the soil to absorb water and to hold it for longer.

The use of blue and green water can be enhanced and made more efficient by capturing and recycling grey water.

2.2. MAPPING SOURCES OF BLUE WATER

Availability of blue water can make a big difference to the productivity and profitability of a farm business

Having a solid understanding of what water is available on a farm throughout the year, and at different locations, helps to better plan cropping and associated activities, including irrigation, so that water availability meets water needs. It is therefore highly recommended that farms identify and map all the potential sources of blue water on and around the farmland. It is also important to note if there is any seasonal variation in the availability of blue water from these sources.

Making a map of blue water sources is a starting point to the establishment of a water management plan. Once farms have mapped blue water sources:

- They are aware of the different blue water sources, and their geographical location with respect to a farm in terms of distance and accessibility. They will know,

265 www.waterfootprint.org/en/water-footprint/glossary

for example, if there are other farms, protected lands, or physical barriers such as hills, between the source and the farm, that will affect if and how the water can be accessed.

- They have an understanding of the topography of the land, and how water flows over and around it. Among other benefits, this can help to identify ways of capturing water.
- They are aware of other farms, houses or communities that may use and depend on the same water sources
- They have an understanding of the seasonality of the water source, and how this may affect cropping patterns or location.

The mapping process will enable the farmer to assess the different options available to access blue water. This is particularly important in circumstances where a farm or business is affected by limited water availability in certain locations and points in time, or if the use of some sources is limited by poor water quality.

Water mapping can be done in number of ways (Table 1).

Table 1. Mapping water sources around a farm

Technique	Description	Comment
Draw by hand	Draw an outline and orientation (North, East, South, West) of the farm on paper. Mark the sources of water including rivers, irrigation channels, reservoirs, boreholes and springs on the farm and close by. Add other important landmarks (e.g. forests, hills, valleys, farm house and buildings, etc.).	Simple and inexpensive, but generally less accurate in terms of scale and detail.
Using GPS combined with Google Earth or Google Maps (if available)	Walk the farm and surrounding area with a GPS device or Smartphone application, and record GPS coordinates for the farm, water sources, and other important features. With a computer or Smartphone, mark the coordinates directly into Google Maps or Google Earth. If not available, they can simply be written onto a hand drawn map.	Requires access to a computer and Internet, or Smartphone. This provides more accurate information, and, when combined with Google Earth, adds additional geographical information about the farm and surrounding area.
Using a Geographic Information System and a GPS	This uses the same method as described above of recording GPS coordinates. The readings are then placed into a GIS. In many areas, it is possible to download an open source GIS onto a computer (e.g. QuantumGIS).	This is more complex, and requires knowledge of GIS. The advantage is that it is possible to create a digital map of the farm and water sources, onto which other geographic information (e.g. land use, roads, towns) can be overlaid.

2.3. IMPORTANT FACTORS AFFECTING BLUE WATER SOURCES

In addition to knowing the geographical location of blue water sources, it is important to record key additional information about each source, some of which can be included in the map. This is needed for the development of a water management plan, but will also help to identify and manage any potential risks that could affect the farm and business, or other water users.

The list below itemizes the most relevant characteristics that should be analyzed and recorded for each individual water source.

2.3.1.1. Blue Water availability

- How much water is currently abstracted by the farm/user from that source? Is this enough to meet water needs?
- Is the source shared with neighbors (and, if so, how is water allocated to each user)?
- Is water available throughout the year, or only at certain times?
- Is the amount of water available from the source decreasing over time, or becoming short during certain periods (e.g. rivers or springs running dry; more pumping needed to extract from wells and boreholes; disputes occurring between users)? If so, where and when?

2.3.1.2. Legal controls

- Are there any authorities (legal institutions) locally that are responsible for issuing abstraction permits and/or setting local rules and bylaws about water?
- Is it usual for local farms/businesses to be in contact with these authorities?

2.3.1.3. Other water users

- Does anyone else use this water source?
- Do other users have permits or legal rights of access or abstraction?
- If so, who (including other farms or businesses, other households, communities)?
- What kind of access do other users have (animal watering, fishing, washing of non-agricultural products)?
- Is there a water association, an irrigation scheme, a water platform or any other organisation that manages the use of water?
- Is there any dialogue and engagement with other water users, either informally or through an organised scheme/association/platform?

2.3.1.4. Water quality

- Has a water quality analysis been conducted on the different water sources?
- Is a report available on the general water quality of the region?
- Are there any known water quality issues that limit/affect what the water can be used for?

- Do farmers measure the quality of irrigation water regularly? If yes, is the water of the right quality required for irrigation?
- Is there a risk that any of the water sources on the farm could be polluted? If yes, by what (e.g. by human or animal effluent; chemicals)?
- Are there other users or habitations such as a city/town/village discharging untreated effluents upstream? How far upstream? How big is the city/town/village in relation to the water source (river/lake)?

2.4. MEASURING WATER USE

There is a strong business case for measuring water use. It helps to identify where farms and businesses can save water by extracting only what is necessary, and by using extracted water more efficiently.

More efficient water use can increase productivity and profitability as well as creating a more water-resilient business over the long-term. But, to achieve this, and to manage water risks better, it is essential to know how much water is used, and when. Having this information enables farms and businesses to plan water use so that it is more efficient, productive, and profitable.

2.4.1. Reducing water use

There are several drivers for reducing the amount of water used.

- Farmers may want to reduce the amount of water they rely on because they have water availability problems, suffer from water scarcity, or have disputes with neighboring water users
- There may be competition between users, and pressure from neighbors or local communities to reduce water use, especially in situations of scarcity. This can particularly affect producers and suppliers of cash crops if their activities are reducing the water available for subsistence agriculture or household water.
- Farmers may want to reduce the risk of crop losses during dry periods by becoming less dependent on blue water
- They may want to save money by reducing pumping or abstraction costs
- Farmers may simply want to understand how water-efficient their crop production currently is in order to see if they could increase yield with the same water usage.
- In some cases it has been shown that effective water management increases final harvest quality and reduces post-harvest losses.
- Reducing the amount of water stored or transported can reduce capital costs of infrastructure and the maintenance of the equipment and facilities
- There may be pressure from buyers, particularly in the case of export or high-end local markets, to record water use and to provide evidence that measures are being taken to improve water use efficiency.

Below are some basic techniques to estimate or measure irrigation water use.

2.4.2. Measuring or estimating water use

2.4.2.1. Estimating flood irrigation when distributed by gravity (on a small scale)

- Using a container such as a bucket with a known volume (e.g. 20 liters), catch the water flowing into the irrigation channel and measure how long it takes to fill the bucket.
- Record the number of hours of irrigation (start and end times).
- Calculate the total volume of water applied. Using a very simple example, if it takes 5 minutes to fill a 20-liter bucket, and the irrigation continues for 1 hour, the total volume applied = 20 x 12 = 240 liters.
- Repeat this at different times during the day and the growing season to see if there are flow fluctuations (you may need to estimate an average).
- Depending on the size of the irrigation system, it may be necessary to repeat this in several places where the water is applied to the field, and then add up each location to estimate the total for the whole field.
- Record the number of hours of irrigation each day to calculate an estimated total for the season.

2.4.2.2. Estimating flood irrigation, when distributed by gravity (on a larger scale)

- Estimate the water flow in by calculating the speed of the flow (in meters/second), and then multiplying by the area of the cross section of the channel (in m^2).
- Velocity can be calculated by dividing the distance a floating object travels in a given time (meters per second).
- The cross section of the channel can be estimated by multiplying average depth with the width of the channel.
- Do this at different times during the day and the growing season to evaluate if there are flow fluctuations (you may need to estimate an average).
- Depending on the size of the irrigation system, it may be necessary to repeat this in several places where the water is applied to the field, and then add up each location to estimate the total for the whole field.
- Record the number of hours of irrigation each day to calculate an estimated total for the season.

2.4.2.3. Measuring irrigation water applied using a pump

- Check the design characteristics of the pump.
- The provider usually refers to a maximum amount of water that can be pumped, when the pump is operating at full capacity. Also, the pump instructions should indicate the pump curve, which shows the flow (for example in litres/second) according to the pressure used and size of the pipes.
- Note how many hours the pump is working.
- With these two variables, calculate the amount of water applied to a field.

This needs to be done every time the field is irrigated to record total water use throughout the growing season.

2.4.2.4. Measuring water used for purposes other than irrigation

- Make an inventory of all water uses in addition to irrigation, such as post-harvest washing or household activities.
- For post-harvest washing, collect the water used for washing a given amount of product in a tank. The washing container should be impermeable with gutters to guide the water to the tank. Measure the volume of water in the tank used for washing a given amount of product. The total amount of water used can be estimated by multiplying the volume used for one wash, with the number of washes made.
- For toilet facilities, measure the volume of water used for flushing, and note how many times a day the toilet is used.
- For showers or taps, let water flow into a small bucket with a known volume and measure how long it takes to fill the bucket. Estimate the length of time and number of times each tap or shower is used in a day.

2.4.2.5. Using a flow meter

- There are several flow meters available on the market.
- This is the more precise option to measure water use in a variety of activities, but it is also the most sophisticated and costly.
- Operating a flow meter depends on the model and farmers should refer to the user's guide.
- In open irrigation channels, a common method for measuring flow is to measure the height of the liquid as it passes over an obstruction as a flume or weir in the channel. Alternatively propeller meters can be installed to measure larger volumes of water.
- For closed systems such as pipes, more advanced magnetic or ultrasonic flow meters can be used.
- It is worth considering whether a group of farmers or a community using the same source could join together to purchase and share a flow meter.

Mapping and quantifying water use with farmers

- Describe the type and sources of water available (for irrigation and other uses).
- Describe the precipitation pattern on the farm. Do they need to use irrigation? For how many months of the year?
- From memory, encourage farmers to draw a simple map of their farm. Indicate on the map the sources from which they take water, and any other water sources nearby. Note the seasonality of water, if this varies. Include any other important landmarks on the map that help to provide orientation, and to identify any factors that affect the flow or transport of water around the farm.
- Describe the difference between a dry year and a wet year, and how that changes abstraction and irrigation patterns.
- Can farmers describe any changes they have noticed over the past decade, and encourage them to consider how they may adapt to these changes?
- Do farmers know of any water quantity or quality issues related to the water sources indicated on the map?
- Ask the farmers to answer the questions in Section 2.3. above, as far as they are able for the known water sources.
- Do the farmers know how much water they use on their farm?
- Do they measure water use? Do they know how to measure water use?

2.5. EXAMPLE

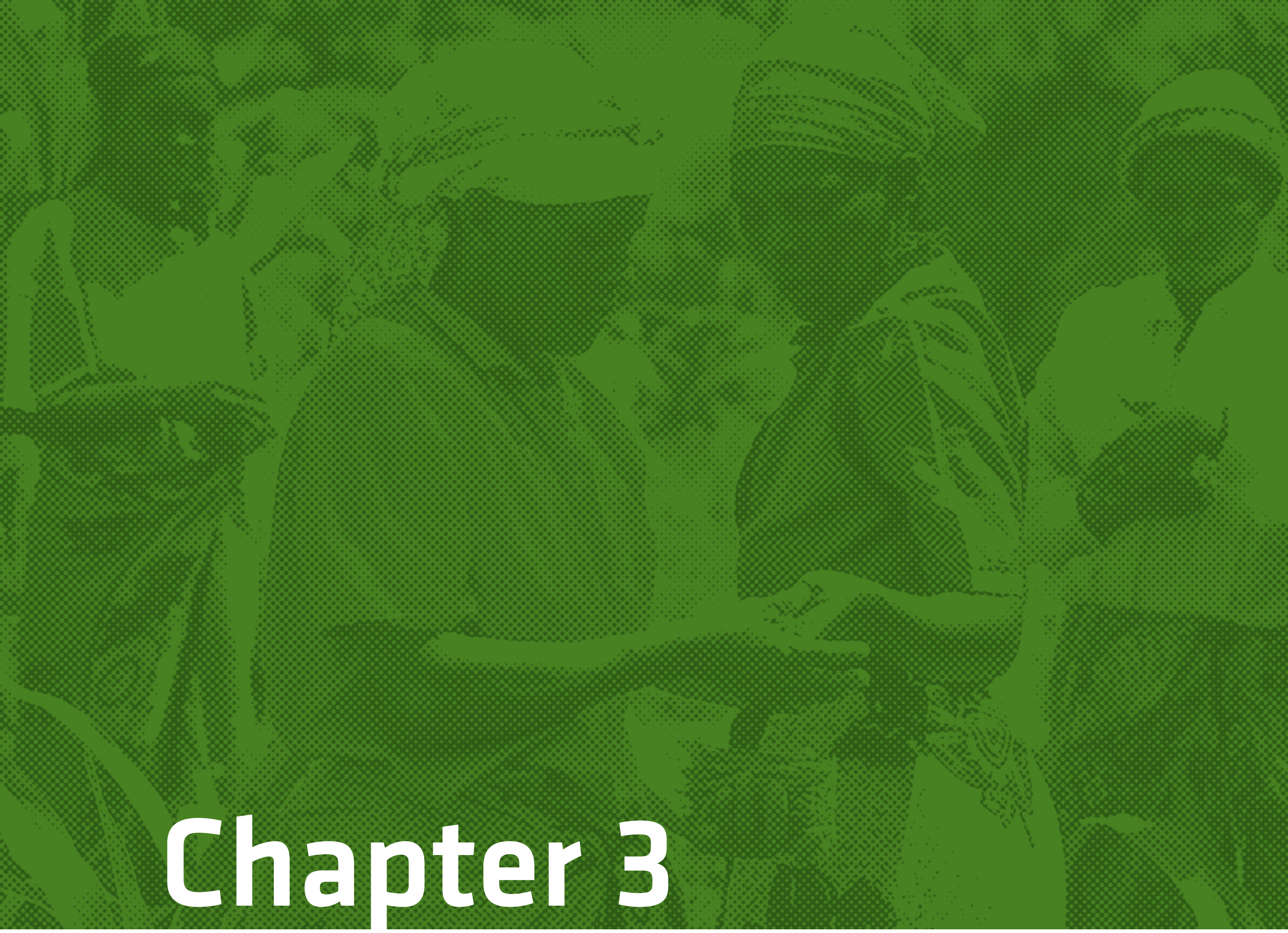
2.5.1. Suzan and Kioko

Last week, there was a training course on water and horticulture in Taveta town. Susan and Kioko both attended and listened to the woman from AgriWaterProfs. The trainer explained that it is possible to increase productivity and decrease costs by knowing more about water. She also explained that it is important to know where the water that you use comes from and how reliable the sources of water are. Susan thinks about this and feels that she has a good picture of her water sources. She knows that the water for the cultivation of her vegetables comes from the canal. And, if the canal does not have enough water, she extracts additional water from the river using a portable pump. She understands that the canal is not wholly reliable in its supply. This is the main reason why she has to switch to taking water from the river. The river itself may also not be a fully reliable source. She observed many times that the water level drops rapidly when there is no rain. Like herself, she knows many farmers use water from the river without a water use permit; it is normal practice. In a way she does realize that the uncontrolled abstraction of water from the river lets the water level drop. She also remembers that she also uses water for washing the produce after harvest. As she needs clean water for this, she buys it from a water truck that fills a couple of tanks on her farm.

During the training, Kioko was reminded of last season when part of his tomato crop failed because there was not enough water in the spring at the time he needed it. After that he had to work as a farm laborer on one of the larger farms to make some little money. His neighbor said that the rains failed because of climate change and the spring dried up because many farmers were using the water. He is not sure about all this, but he sure lost part of his crop. This year he has borrowed some money to buy seeds and has sown his fields anew. He decides to take a bit of time to have a closer look at the water sources he has in and around his farm. He draws a map of his farm, puts in the road to the village, the river and the spring. The AgriWaterProfs lady explained to him that it is also important to know when the sources have water. He decides to write on the map when water is available. He writes that the river runs all year but has little water between the short and the long rains. The spring, he has recently found, can also go dry, but he cannot recall that this had ever happened before. He does not use water from the river as the distance is quite far and he has to cross the fields of neighboring farmers. For his tomatoes last year, he took water 12 times. Every time 4 hours of pumping. He calculates how much water this is, the pump's capacity is 30 m^3 per hour, so 4 hours is 120 m^3. The last time he wanted water he could not take it, the supply of water from the spring is a bit risky. Maybe he can try to take water from the river? He did not dare to think about that last year but if he wants his tomatoes to survive he may need to find a way.

Susan thinks about another question that the trainer brought up. Does she know now much water she uses in a season? And, if this volume is too much or too little for her tomatoes? She thinks about her tomato crop now and realizes that she does not really know how much water she applied to her fields. But also she does not exactly know how much her tomatoes need. The trainer said that applying too much water is not only a waste of water but also a waste of money. Too much water affects the tomato yields and washes out valuable nutrients from the soil. It can even degrade the soil through waterlogging and erosion. Susan did know that these things are not good and threaten the business. Susan decides to try and understand a bit more about how much water her crop needs and to estimate the amount of water that she takes from the canal and river.

PERSONAL NOTES



Chapter 3

Water harvesting and storage

3.1. WATER HARVESTING: COLLECTING RAIN AND RUNOFF

3.1.1. Overview

Rainwater harvesting refers to the collection and storage of rain for use in production or other purposes on a horticultural farm or business. Rain water is collected from impermeable surfaces (where water cannot infiltrate/soak in) such as rooftops and cemented areas of land or roads. Harvested water can be stored in tanks or reservoirs so that it is available for use when needed, for example in irrigation.

For the collection, storage and distribution of rainfall, four elements are involved:

1. gutters that collect water from a rooftop or impermeable surface;
2. filters to take out debris and smaller sediments;
3. a storage tank or reservoir, which will receive the water from the gutters;
4. a pump and pipes to distribute the harvested water to where it will be used.

The volume of rainwater harvested depends on the size of the impermeable surface, on how much it rains, and on the storage capacity of the tanks or reservoirs.

As shown in the example later in this chapter, a small surface such as a shed roof may only collect a few cubic meters of water which, though insignificant in terms of total water requirements for crop production, can still be useful for some household or post-harvest activities, or general site maintenance and washing.

Runoff harvesting refers to the collection of water flowing on the ground during rainfall into a tank (below the surface of the ground) or a reservoir. Capturing this water requires an understanding of the direction of runoff flow, and a storage space that is dug into the ground. The volume of runoff that can be harvested depends on the size of the tank/reservoir, its placement with respect to the flow of runoff (*i.e.* slopes in the terrain), and any additional necessary infrastructure such as ditches and canals to collect and carry the water.

3.2. HOW TO HARVEST AND STORE WATER

Water harvesting and storage can vary from inexpensive and simple systems, to those that are more elaborate.

3.2.1. Harvesting and storing rain from rooftops

A low cost, low input system using gutters can be installed to harvest water from the roofs of houses, sheds or barns. Clay tile roofs work well as they are impermeable; straw roofs are not suitable. Large clean plastic tanks are placed at the end of the gutters to collect the water.

When the storm has ceased, tanks should be covered to keep out insects, leaves and other contamination. Water harvested from rooftops is generally clean, as rainwater itself contains very little chemical or bacterial contamination. However, the water may pick up dust, leaves, small insects and bacteria from the roof. Leaves, twigs and other debris can be removed using leaf traps. Smaller particles can be removed with a simple filter made from meshes covered by gravel or sand, or by using more sophisticated ready-made filters purchased from specialist shops or suppliers. Gutters need to be periodically checked for leaks, and kept clean and free of leaves and other debris.

Figure 1 - Simple rooftop rainwater harvesting[266]

The potential volume that can be harvested is estimated as follows:

1. The roof surface area in m^2 is calculated by multiplying the width by the length (in meters).
2. The volume of water that can be harvested is estimated by measuring total rainfall in a given time in meters (10 mm = 0.010 m), and multiplying by the surface area in m^2.
3. The result is the estimated volume in meters cubed (1 m^3 = 1,000 liters).[267]

More sophisticated integrated rain harvesting system are used in higher input systems. These incorporate meshes and traps to prevent gutters blocking, screens to keep mosquitoes and pests out of the tank, rainwater filters, and a water level indicator. Other equipment can be added to enhance water quality, water harvesting efficiency, and to protect the pump. This option is particularly suitable if the harvested water is to be used for post-harvest purposes such as produce washing.[268]

266 www.water4everyone.org/category/rainwater-harvesting.

267 answers.practicalaction.org/our-resources/item/rainwater-2.

268 www.clemson.edu/public/sustainableag/pdfs/rainwater%20harvesting.pdf.

3.2.1.1. Water quality

Water that is stored for a long time can deteriorate in quality, though the length of time that water can be stored depends on a range of factors. Stagnant water (that does not flow and is not regularly refreshed) will deteriorate more quickly. To avoid this it is advisable to use water from the storage tank on a frequent basis, and to check regularly for any signs of a bad smell, murkiness, sedimentation or biofilm (slimy bacterial layers on the surfaces). If these are present, the storage tank must be cleaned.

To assess if the harvested water is fit for use, especially for post-harvest washing, it is essential to conduct a water quality test. A simple and cheap water quality test is the H_2S striptest bottle that will check for bacterial contamination. If necessary, water can be treated by chlorination[269] [270].

If no testing is done and there is doubt about the quality of the water, it should not be used for human consumption or produce processing and packaging, though may still be suitable for irrigation.

3.2.2. Harvesting and storing runoff from ground-level surfaces

3.2.2.1. Harvesting and storage

For a low cost/low input option, storage tanks or simple reservoirs can be constructed to catch water that runs off impermeable surfaces such as paved roads or courtyards. This will depend on the terrain (slopes), and whether or not there is a suitable place and space for a reservoir.

Figure 2 - Low cost water storage tank
Source: Indian Council of Agricultural Research (www.icar.org.in/en/node/1417)

269 www.rainwaterclub.org/docs/MANUAL%20ON%20ROOFTOP%20RAINWATER%20HARVESTING%20SYSTEM%20FOR%20SCHOOLS.pdf.

270 www.youtube.com/watch?v=4gFbCdHle0w.

At the most basic level, these structures can be simple earthen dams to collect and hold water. More sophisticated and larger structures can be installed including water pans, lined dammed reservoirs, or subsurface concrete tanks. These more complex systems generally need engineering expertise to construct.

Even when using simple systems, the reservoir can be made less permeable using, for example, a layer of clay or bricks and cement, or plastic sheeting. It can also be covered to exclude pests, and some fish species may be introduced to manage mosquitoes. Additional infrastructure such as sediment traps and mud filters can be added so that the water can be used for purposes that require higher quality, such as drip irrigation.

If an open tank or reservoir is used to store water (with no roof or cover), it is essential to install appropriate fencing to safeguard livestock, wildlife and children, and prevent them from accessing the water or falling in.

The storage capacity of a reservoir can be estimated by calculating the surface area of the tank in meters (average width x average length) and multiplying this by the average depth in meters. This will give an indication of the volume of water stored in meters cubed (1 m^3 = 1,000 litres). Once captured, some water may be lost due to infiltration and evaporation.

Figure 3 - Runoff harvesting structure (left) with thatched cover and fence (right) in Sri Lanka, Source: Technical brief runoff rainwater harvesting[271]

3.2.2.2. Excess runoff

If the tank is relatively small compared to expected rainfall, or severe storm events may occur, a water overflow from the tank or reservoir is needed to avoid localized flooding. This can be as simple as inserting a pipe just below the level of the bank to lead excess water to a nearby spillway, drain, ditch or river course. The pipe must wide enough to cope with the volume of excess water. If an overflow is not installed, damage may occur to houses, roads and nearby land and buildings.

271 practicalaction.org/rainwater-harvesting.

3.2.2.3. Water quality.

Note that the quality of water from surface runoff can be poor as it may contain pollutants and sediments that have been washed off fields, yards and dirt roads (among others). In order to assess if the water has the necessary quality for its intended use, water testing is recommended.

3.2.2.4. Transport

In order to take water from the tanks or reservoirs to the point of use, either a gravity flow canal system can be constructed, or pumps and pipes can be installed to carry the water to the fields. A variety of pumps are available from specialist outlets suppliers ranging from diesel, wind and solar powered or gravity ram pumps (for use with a reservoir or spring[272]) and water turbine pumps (using river flow energy for water transport[273]).

3.2.3. Harvesting and storing extracted blue water

Excess water abstracted from a river, an irrigation channel or a reservoir can also be stored for later use. Storage of extracted blue water is possible and recommended when more water is received than is needed. This can occur, for example, when a farm is allowed to pump water from the river for a certain number of hours, but the total amount of water obtained exceeds that which the soil can hold. If all the water received is applied to a field, excess water that cannot be retained by the soil will simply runoff, which is a waste (except for the occasional over-watering needed to wash out accumulated salts).

The characteristics of the soil determine the maximum amount of water that it can hold before there is runoff. This is known as the field capacity. Field capacity can be raised with improved soil management, particularly by increasing organic matter content.

In order to harvest and store extracted water, it is important to know how much water is needed to reach the field capacity of the soil, how much water is required to wash away salts, and how much water is available for each application. Any excess water can be stored and used during periods when water is scarce.

3.3. THE BUSINESS CASE FOR WATER HARVESTING AND STORAGE

3.3.1. Costs

The systems and equipment available for water capture and storage vary from the very basic, to the very sophisticated. For lower input systems, the main initial capital costs include: guttering (in the case of capture from a roof), filtering equipment, pumps, storage tanks, or reservoir construction. Ongoing costs include running, repairing and replacing equipment, and general maintenance such as periodic cleaning and the removal of excess sediment from tanks or reservoirs.

272 www.youtube.com/watch?v=Zk9zs0EQIQ8.
273 www.youtube.com/watch?v=seNswRYkZdE&feature=youtu.be.

If there is a need and the potential to capture large quantities of water locally, it can be worth exploring the possibility of creating a farmer or community association to share the building and management of a common reservoir and associated infrastructure.

3.3.2. Benefits

Water harvesting can have many direct benefits for a horticultural business:

- Reduced costs of water abstraction and pumping (fuel) (to be offset against possible costs of water storage).
- Increased crop yield, by having water available during periods of water scarcity.
- Increased water availability when abstraction rights are limited.
- Less competition with other users for blue water resources.
- Better water quality (harvested rainwater is usually of higher quality than, for example, river water).
- Water risks are better managed, and the farm is less sensitive to dry periods.
- Public relations and corporate image: water harvesting and storage are seen by the community and by buyers as good practice (CSR), appropriate for a responsible business.
- In areas and at times of water scarcity, water abstraction for farm activities may be causing water shortages and hardship for other users nearby, and the environment.
- Market access: particularly in areas of water scarcity, buyers may insist on evidence of water harvesting and storage before they will issue a contract.

3.3.3. Assessing the business case

Prior to installing any water harvest and storage infrastructure, it is essential to make an assessment of whether or not it will be a cost-effective strategy for the farm and business. The following aspects should be taken into account:

- water needs (in terms of volume, timing, and quality);
- availability of water (in terms of volume, timing, and quality);
- the risk of water scarcity;
- municipal water price and pumping price;
- costs of constructing and maintaining water capture and storage infrastructure.

To assess the business case, it is essential to know the volume of water currently used, the current and future water needs for crop production and associated activities, and the risk of water scarcity (and potential impact this can have on the production, profit and resilience of the business).

The potential benefits of increased water availability (and reduced risk of water scarcity) should then be weighed against the cost of installing and maintaining a system to harvest, pump, distribute and store additional water.

If there is unlimited access to water, if water prices are very low and/or if pumping costs are negligible, then there may be no significant economic return from installing the infrastructure needed for water capture and storage. In this case there would be little justification for making the investment. However, even in this situation, factors such as climate change, or the expansion of villages, towns or industries upstream, may affect the status of the water supply in the future.

Exercise with farmers: Is water harvesting and storage an option? (Note that the farm water map can be used to add information on slopes, runoff, and potential water capture and storage areas).

- From which areas on and around your farm could you capture water (e.g.: rooftops, clean impermeable surfaces, roads, slopes in the landscape where there is runoff)?
- Would it be possible to construct a system to capture this water and divert it to a tank or reservoir? What would you need to construct this system? Where could it be located? Is there a suitable place on or around the farm where a reservoir could be constructed?
- Can you estimate the cost of the infrastructure needed to capture and store water, and to transport it to where it is used (consider: dams, gutters, piping, sediment and debris traps, storage tanks/reservoirs, pumps pipes and hoses)?
- Do you suffer from constant or periodic problems of water scarcity? If so, what water uses are affected (e.g. irrigation)? When/how often?
- Is the cost of water very high (for abstraction or pumping costs), and a significant part of your total farm costs?
- At times of water scarcity, does water abstraction on your farm mean that other users (e.g. households or small-scale farmers nearby) suffer from water shortages?
- If you could store water, would this help to secure sufficient water for post-harvest crop washing or processing, or to meet irrigation requirements, or do you have enough water already?
- Do you have quality issues with your current water sources? How would you assess and ensure the quality of harvested and stored water?
- Taking into account the cost of the infrastructure, your water needs, and the current availability and cost of the water you use, could there be a business case for harvesting and storing water on your farm? Is this a possibility that you would consider investigating further?

3.4. EXAMPLE

3.4.1. Suzan and Kioko

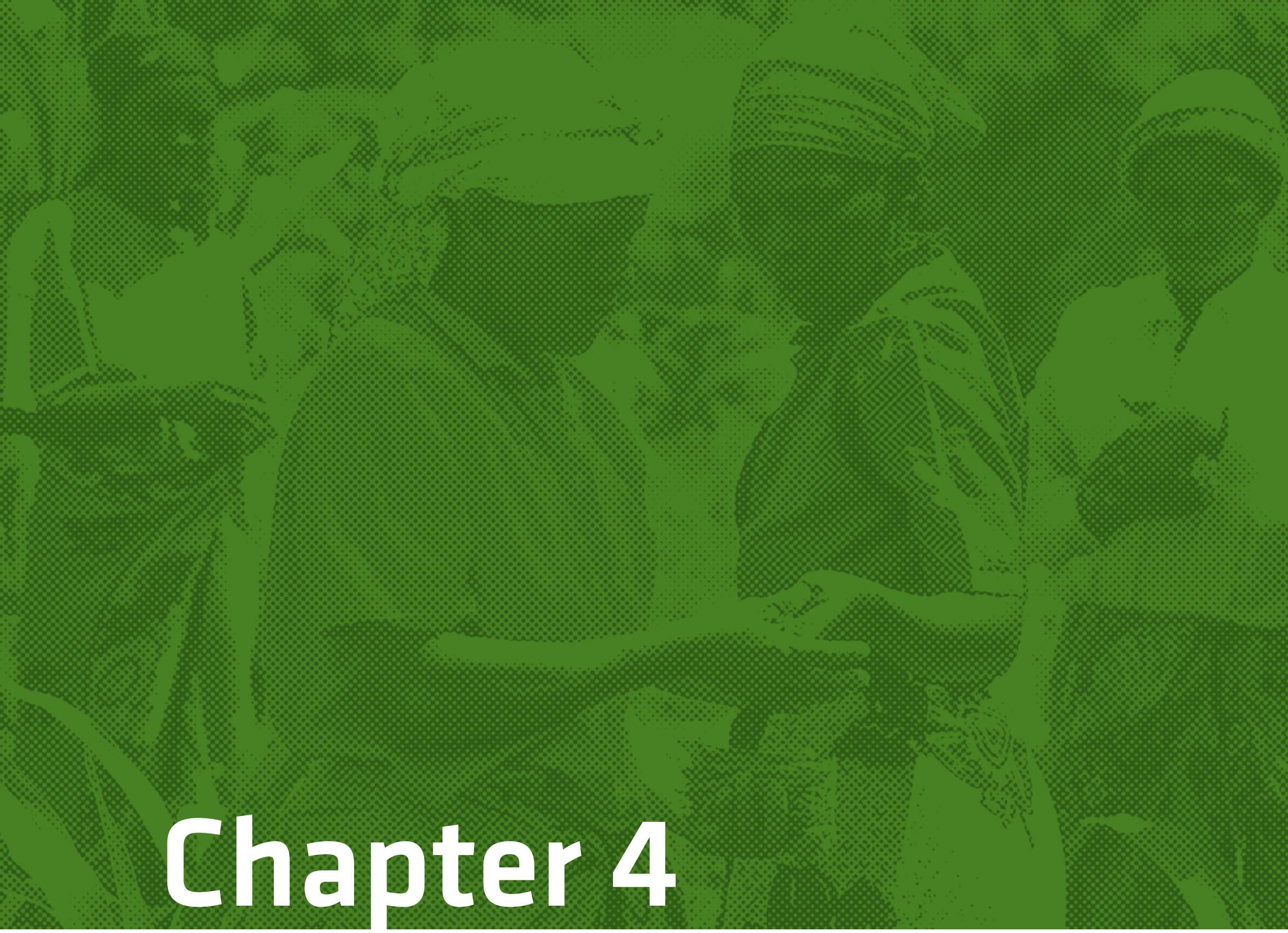
Kioko understands that he needs to have more sources of water available. It was possible for him to irrigate once a week last season, but he did not have enough for the last turn. His field is a quarter hectare and he floods it with 120 m^3 of water every time he irrigates. He got to know the farmers that take water from the river, and found they would be willing to allow a hose to pass by their land for any extra water if he needs it. It is costly as the distance is quite far and the pumping time would need to increase.

He is also thinking of something else. In his village there is a lady that takes water from the roof of her house to water her plants in the home garden. Last year, on the edge of his land, he built a small shed with a tin roof to stay in when he guards his tomatoes close to harvest. The lady has only a small plot of land that she waters. Kioko has 0.25 ha with his tomato plants. He has no idea how much water would come from his roof but feels that it may be too little. But he also thinks that every litre of water may help improve his crop. He will go to the lady in the village to understand a bit more about what she did and how she did it.

On her farm, Susan walks is thinking about when she needs water most for her crops, for washing and packaging. Of course this is during the dry season; a dry season vegetable crop always fetches a good price because the supply to the market is less than during the rains. She has been able to grow her tomatoes and onions in the dry season but increasingly she finds that water is less available.

However, in the rainy season there is ample rain, canal and river water. What if she could capture water in the rainy season, store it and use it for her vegetables in the dry season? That would be an excellent way to have water for her crops. This might be also a way to deal with the erratic supply of water in the canal and the lowering water availability in the river during the dry season. She will definitely need to do some calculations: how much rain can we capture on roofs of sheds and houses as well as on the harder surfaces in the farm, and how big should a storage tank be? She just realises that in the rainy season she does not use all the water from the canal, maybe she can also store that. But not now; this would all take too much time and she is too busy with harvesting, packaging and selling her tomato crop.

Thinking about the harvest, the water she uses for washing the tomatoes comes to her mind. She could use her roofs to collect clean rain water for washing. The tanks are already installed, she just needs to buy some extra piping to take the water from the roof to the tanks. She feels that this could be cheaper than buying water from the truck.



Chapter 4

Recycled water

4.1. INTRODUCTION

4.1.1. Definitions

Grey Water: "Re-used domestic or farm water that has been mildly polluted, or is waste water, which can be effectively recycled and purified. This does not include water contaminated with human fecal matter".

If a farm experiences periods when water is scarce and crop yields and farm production are threatened by water shortages, it is worth considering if recycling water could be an option. 'Recycling water' means capturing and reusing water that has been used previously on the farm. An example is using treated wastewater to irrigate crops. Even when water is not scarce, recycling can reduce the amount of water that needs to be abstracted. This increases efficiency (and profitability if the price of water is high) and can have a positive impact on the environment.

Water use takes place in almost all activities in the farm from irrigation to post-harvest and processing, as well as for household/domestic use. Many of these activities generate wastewater that can be recycled. These include:

- **Irrigation water.** If more water is applied to a field than can be retained by the soil, it will leave the field as runoff. With a drainage system to capture the runoff, this excess water can be collected, stored and pumped back to the field for irrigation.
- **Post-harvest washing and processing.** Water collected after post-harvest washing can be used for small-scale irrigation if it is close to the production areas.
- **Household water.** Water from some household activities can also be recycled and used for small-scale irrigation where risks of contamination are low.
- **Hydroponic water.** Hydroponic wastewater can be used for crop irrigation but great care must be taken in farm nutrient management, as hydroponic wastewater is loaded with nutrients and leaching of nutrients near to water courses should be avoided or minimized.

The purpose is to identify what will have an impact on the company, by distinguishing the requirements of European and international regulations from the requirements of the market, in particular the requirements of large supermarket chains.

WHAT IS GRAYWATER?

CLEAN WATER	GRAY WATER	BLACK WATER
Springs, wells, purified water, city water, rain water	Used water without toxic chemicals and/or excrement	Contaminated water with toxic chemicals and/or droppings

4.2. WHY RECYCLE WATER?

4.2.1. Benefits

Water recycling can have numerous benefits for a horticulture business:

- Reduced overall water abstractions.
- Increased water availability in times and areas of water scarcity, or when abstraction rights are limited.
- Reduced energy and transportation costs.
- Increased water use efficiency (higher productivity with the same amount of abstracted water).
- Corporate image: well-planned water recycling is an important element of appropriate and responsible water use. For larger companies this can form part of their corporate social responsibility (CSR) strategy. Communicating about responsible water use improves the image of a farm or company within the wider community. It can also make them more attractive to buyers, especially when selling into global supply chains.
- Potential to reduce the discharge of certain pollutants into water bodies. An example is when pollutants or sediments in water following washing are retained in the soil when the water is reused for irrigation; the process can be seen as natural filtration.
- Increasing overall farm efficiency. An example is where recycled water is used for subsistence crop cultivation on smallholdings. Wastewater can (for example) be channelled into soil around fruit trees, increasing productivity with minimal investment.

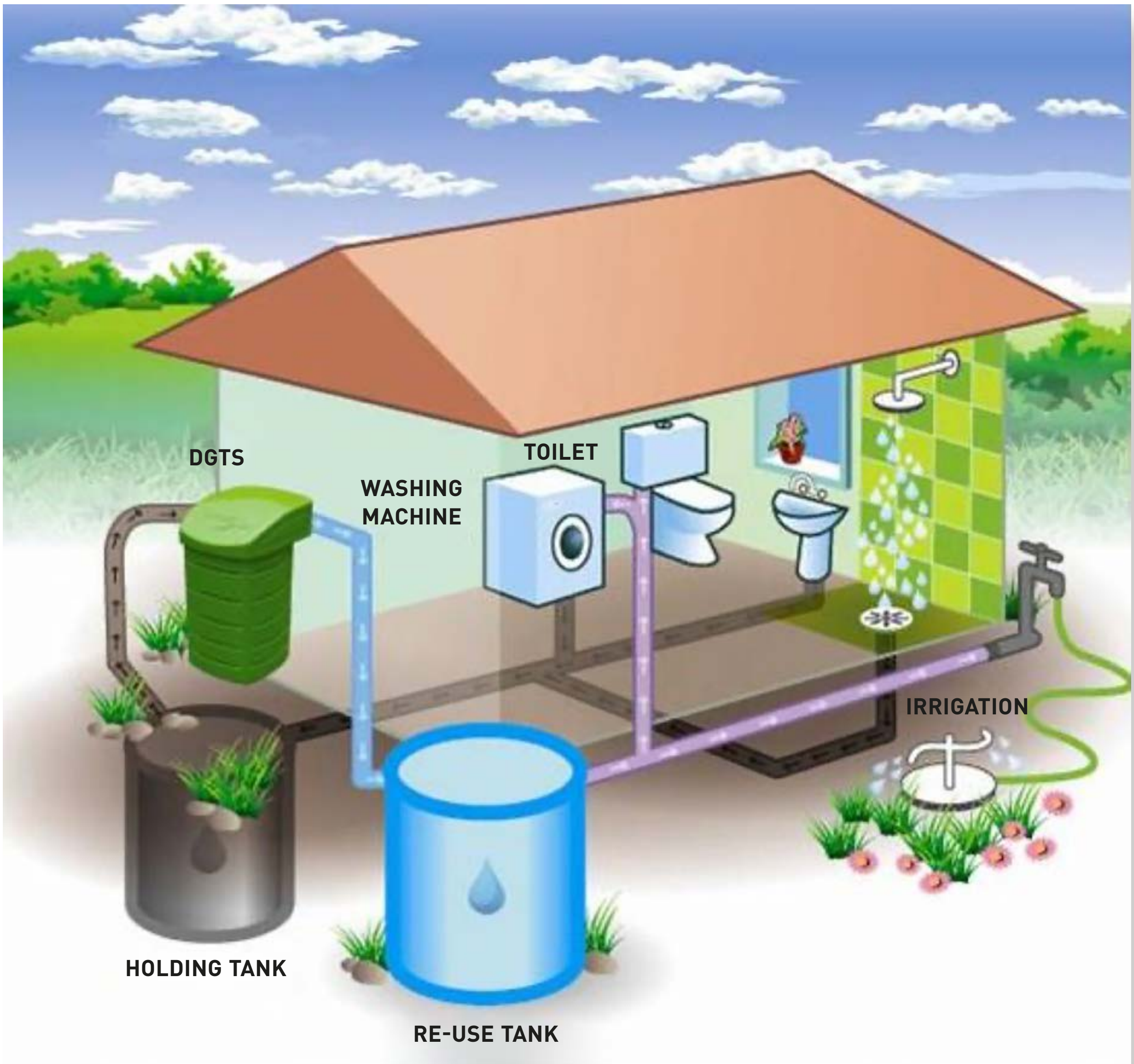
Often the water available for recycling is limited compared to the total crop water needs on the farm. In the case of irrigation, for example, recycling may provide only a small proportion of the total water requirement. Nevertheless, it can make a valuable contribution in areas where water is scarce.

4.3. SOME BASIC RULES AND GUIDELINES FOR USE OF GREY WATER

4.3.1. In brief

Untreated grey water is different from fresh water and requires a different approach for it to be used safely. As a guideline:

- Don't store grey water (for more than 24 hours). If you store grey water the nutrients in it will start to break down, creating bad odors.
- Minimize contact with untreated grey water, as it could contain pathogens. This type of grey water is best restricted to uses where it soaks into the ground (e.g. irrigation), and not for people or animals to drink.
- Infiltrate grey water into the ground, don't allow it to pool up or run off. Pooling grey water may contribute to insect breeding (such as mosquitoes), as well as creating a place for unsafe human contact with grey water.
- Keep your system as simple as possible; avoid pumps, and avoid filters that need upkeep. Simple systems last longer, require less maintenance, require less energy, and cost less money.



4.4. WATER QUALITY

4.4.1. Some precautions

Water quality is among the most important considerations to be addressed when considering recycling. Depending on the previous use, recycled water can be of poorer quality. Water collected and re-used following domestic or packhouse use (e.g. washing fruit), or from runoff after irrigation, may carry sediments or pollutants. If this is the case, recycled water may require treatment before re-use.

It is therefore important to monitor contaminant levels (see Chapter 6 for details on water quality parameters) to know when treatment is needed.

In cases where treatment is not possible, the water can still be recycled, but with restricted use to avoid contamination of crops and soil. Of critical importance is the avoidance of microbial contamination of irrigation water when using domestic effluents.

Some general rules to ensure the safe use of recycled water:

- Use only clean water (of potable quality) and not recycled water, for domestic and post-harvest uses. Here alternative sources of water such as rain water harvesting may be considered, together with a sanitizing agent to ensure water quality criteria are met (see Chapter 6).
- Untreated sewage should never be used for irrigation. Treated sewage water can be used, but must comply with WHO water quality criteria (see Chapter 6).
- Post-harvest water (e.g. from washing fruit and vegetables) can be used for irrigation, but again care must be taken to meet irrigation water quality standards (see Chapter 6).
- Drainage water from irrigation can be collected and reused for irrigation if the quality is adequate. However, of particular concern here are the potential salt and nutrient loads, which must be monitored and controlled.
- Periodic analysis of irrigation water quality is recommended, especially for harmful human pathogens such as *E. Coli*, and for harmful plant pathogens such as *Phytophthora*, *Pythium* etc.

4.5. WATER TREATMENT

Depending on the previous use, wastewater may contain sediments, agrochemicals, cleaning materials, or microbial contaminants, among others. A variety of water treatment methods are available to remove them, depending on the contaminant and the intended future use. In deciding on a treatment option, other factors such as cost and the technical capacity (human resources) for ongoing maintenance, are also important. These options include the following.

4.5.1. Sediment filters

These act as sieves to remove particulate matter. Sediment filters reduce sediment but do not remove chemicals or heavy metals. They are most commonly used to improve the quality of the municipal water supply, to take dirt and sediment out of water from wells, or to remove particulate matter from storm water runoff. These filters require periodical replacement of the filtering bed. They can be made simply using minerals or synthetic materials. The choice of filter depends on the quality of the inflow, volume, and price range. For details on design, the US Environment Protection Agency is a good source of information: water.epa.gov/polwaste/npdes/swbmp/Sediment-Filters-and-Sediment-Chambers.cfm.

4.5.2. Fat traps

These are used to remove oils and greases, which mostly come from domestic wastewater (kitchens and restaurants). They are based on the principle that fat naturally deposits in layer on top of the water, since it is lighter than water and does not dissolve, if the water remains stagnant in a container for some time. Fat traps require periodical cleaning. Good design guidance can be found at: www.ocsd.com/home/showdocument?id=536.

4.5.3. Septic tanks

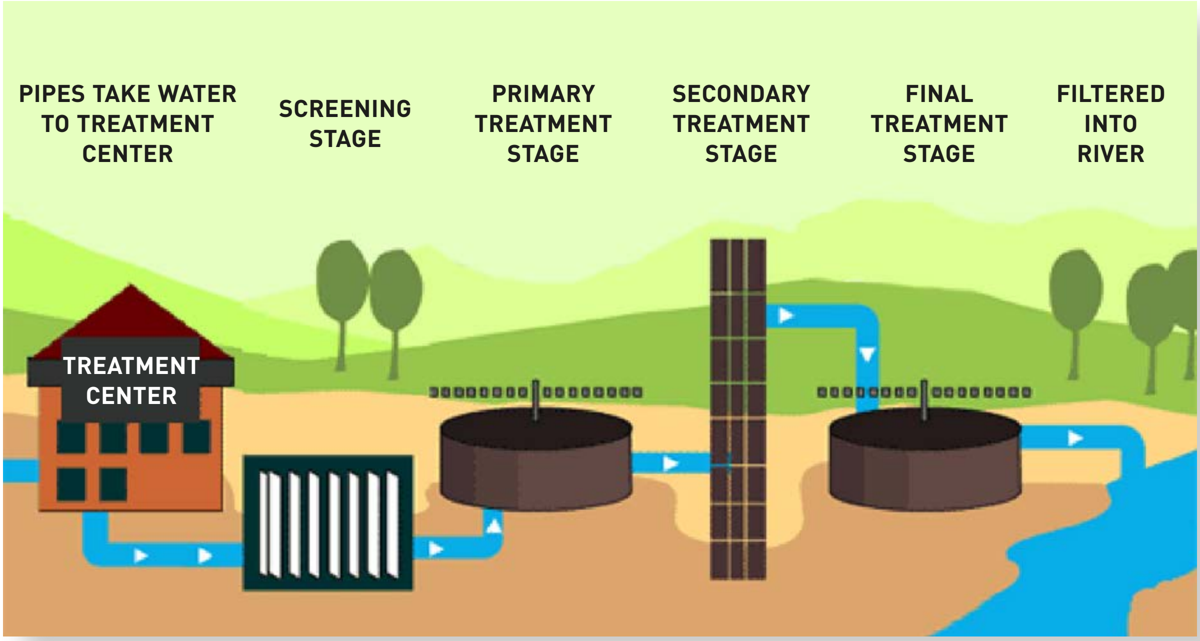
Septic tanks are key components in small-scale sewage water treatment (when sewage cannot be treated by a municipal facility). They are the most common form of primary wastewater treatment. Their main goal is to remove organic matter (measured in the parameter Biological Oxygen Demand BOD5); this relies on the presence of anaerobic bacteria, which decompose the waste. They are usually installed together with a trap for solids, so the effluent being treated goes through the solid trap before entering the septic tank. Septic tanks remove between 30 and 50% of BOD5. FAO provides good references for the design of septic tanks: www.fao.org/docrep/t0521e/T0521E0k.htm.

4.5.4. Helophyte filter

This is a simple and low-cost method to improve the quality of recycled water before it is reused or discharged into water courses, or recharges groundwater. A helophyte filter works by letting used water flow into a pond with marshland vegetation, such as reeds and rushes. If done well the purification rate (BOD and nutrient removal) is over 50%. More information can be found at: emis.vito.be/node/22504.

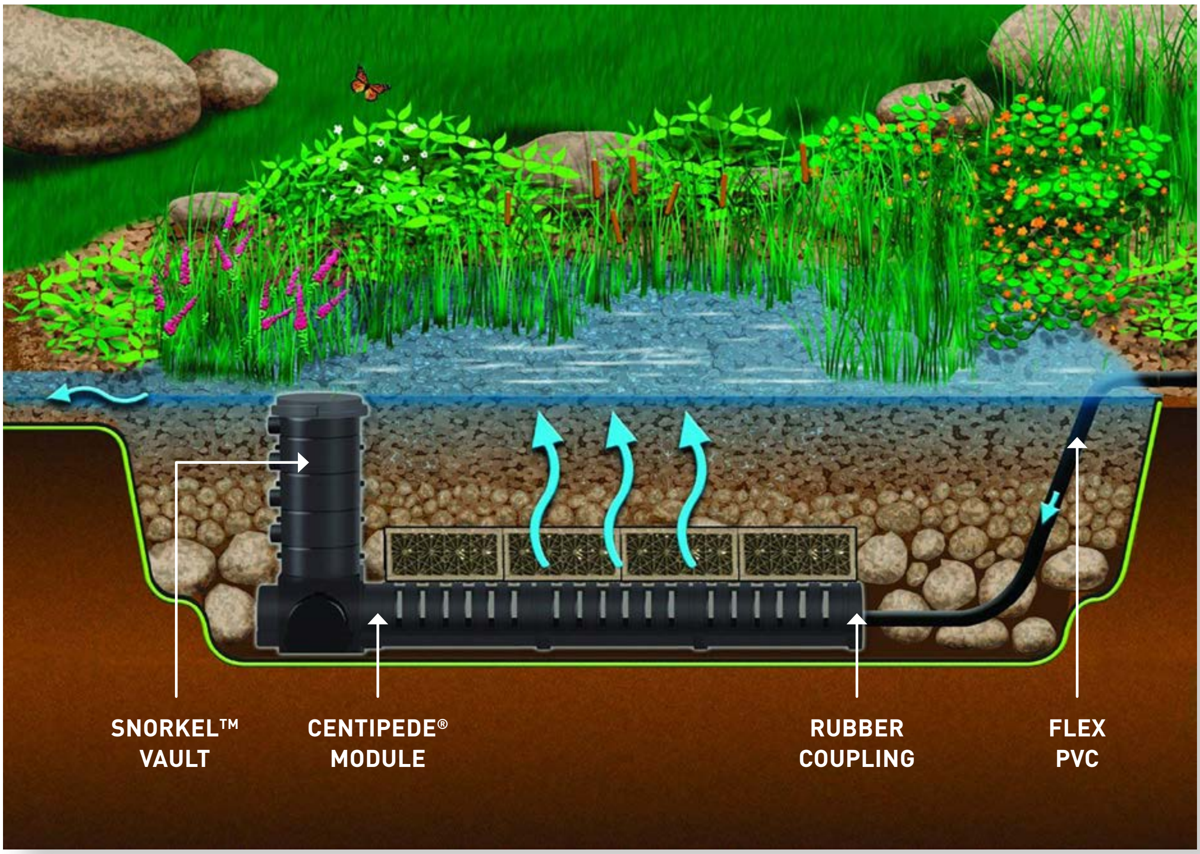
4.5.5. Full sewage treatment

A full onsite sewage treatment would include several of these elements: a trap for solids, a septic tank (for the primary treatment) and either a helophyte filter or a constructed wetland (for the secondary treatment). About 70% removal of organic matter (measured as Biological Oxygen Demand BOD5) can be expected using this system. Details and guidance on designs is available from FAO: www.fao.org/docrep/t0551e/t0551e05.htm.



4.5.6. Constructed filters and wetlands

Constructed wetlands are systems with careful engineering design to pass wastewater through a system of soil and plants that enables organic matter retention and treatment. Treated water from the wetland can be used for irrigation, provided that a water quality check has been conducted to test for pathogens, nutrients, or any other suspected potential hazard such as heavy metals.

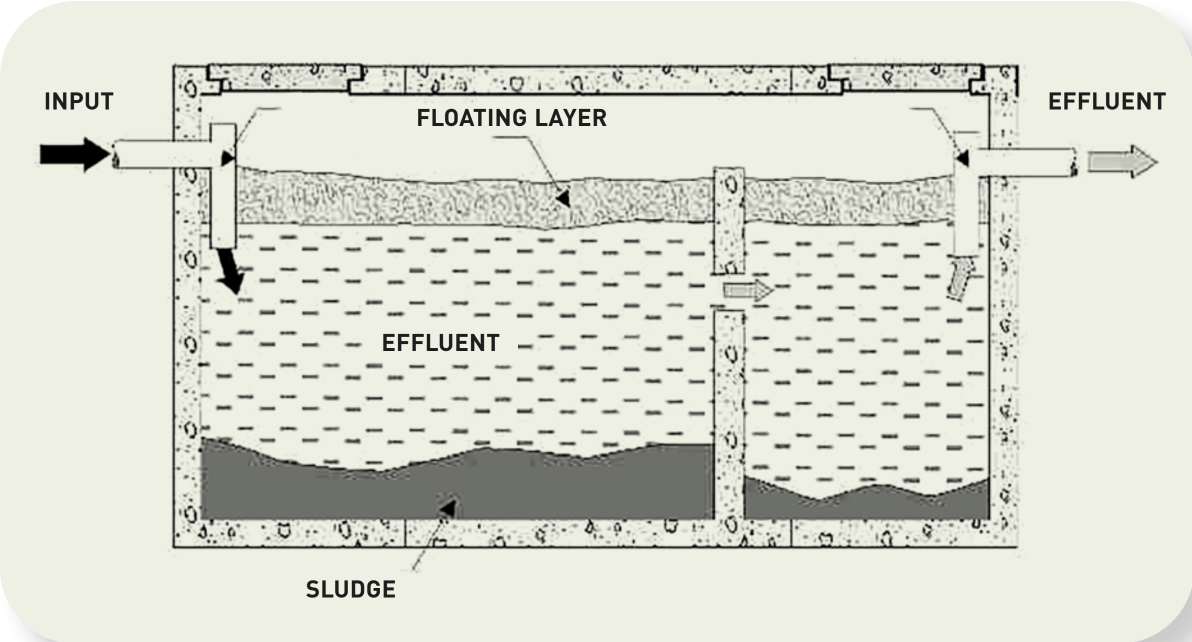


Constructed wetlands can be divided into two types:

- Subsurface-flow or reed bed systems, where plants grow in gravel or soil.
- Surface-flow or pond systems, where plants float in the water.

Surface flow or pond systems need a relatively large area, but can be situated on non-productive land and are mainly suitable for medium to large farms.

For smaller farms, backyard grey water wetlands can be constructed using reed bed systems in recycled containers such as bathtubs, steel barrels and plastic bins. These are filled with gravel, mulched with woodchip, and then planted with cattails, bulrushes, and other wetland plants. In these systems the water never rises above the mulch, so people and animals are protected from coming into direct contact with the grey water. There are many possibilities of creating simple and inexpensive grey water filters using old bulk bags and vertical filters. **However, inexpensive systems such as this are suitable for irrigation, but not for the washing of produce.**



Practical tips are:

- Plant a mix of wetland plants with rhizomatic roots to maximize wildlife benefit and treatment at a range of temperatures. Use native species, and seek advice from local experts.
- Weed out grasses and other plants with fibrous roots as they will clog the pore space in the gravel. Once a year, cut back the tops of wetland plants and use them as a crop mulch.
- After several years, it may be necessary to thin the wetland plants.
- Consider the risk of infestation by pests such as rodents, insects, as well as other side effects such as bad smells, before embarking on this kind of natural filtering.
- NEVER use toilet waste in these systems.

4.6. RECYCLING DIFFERENT TYPES OF GREY WATER

4.6.1. Irrigation water

If more water is applied to the field than can be retained by the soil, it will leave the field as runoff. With a drainage system to capture the runoff, this excess water can be collected, stored and pumped back to the field for irrigation. The following infrastructure would be needed:

- **Capture:** water can be captured from the drainage system. Pipes and pumps are needed at this stage. Details on the drainage system can be found in Chapter 6 of part 1 of this manual. A good source of advice on drainage systems design is given in the FAO report on agricultural drainage: www.fao.org/docrep/w7224e/w7224e00.htm#Contents.
- **Storage:** storage tanks may be needed to temporarily store drainage water. See Chapter 3 on storage tanks and resevoirs.
- **Transport:** Pumps and pipes are needed to take water to the storage tanks and subsequently to distribute it to the fields. Chapter 3 explains the types of pump that might be used.
- **Treatment:** Treating agricultural drainage water is generally one of the last management options to be considered. This is because of the costs and the complexity of its chemical characteristics. One option is to use helophyte filters or constructed wetlands before disposal. FAO is a good source of information on treatment of drainage effluents: www.fao.org/docrep/005/y4263e/y4263e0b.htm.

Pollutant concentration is an important consideration in the case of re-used irrigation water. If irrigation water is recycled a number of times, the concentration of pollutants in the water (salts and agrochemicals) will increase. It is therefore recommended that recycled irrigation water should either be treated to remove the contaminants (see above), or should be mixed (diluted) with water of higher quality from other sources. In the case of salts, stringent water quality monitoring is recommended because the efficiency of salt removal by helophyte filters or wetlands is very low. In this case, dilution of irrigation water is recommended. In the case of nutrients, it is recommended that they should be monitored, and then nutrient levels in recycled water should be integrated into the farm nutrient management plan. If there are high levels of nutrient in the irrigation water, fertilizer applications may need to be reduced.

4.6.2. Post-harvest washing and processing water

Water collected after post-harvest washing can be used for small-scale irrigation. The infrastructure needed at each stage is as follows:

- **Capture:** water can be captured from sinks and gutters through pipes.
- **Storage:** if the water is not required immediately, storage tanks may be needed. However, in many cases post-harvest water goes straight to the field for irrigation (after treatment, if needed). See Chapter 3 on storage tanks.

- **Transport:** pumps and pipes may be needed to take water to the storage tanks and to distribute it to the fields. Chapter 3 addresses the types of pump that might be used.
- **Treatment:** if the likelihood of contamination is low, this water is often discharged directly onto a field without treatment. In the case of wash water that contains sediment, use of a filter is recommended before it is pumped to the field. If there is a possibility of other contaminants, use of a septic tank or a helophyte filter is necessary to reduce the discharge of pollutants onto the field. If possible, and especially when recycling is taking place on a large scale, it is good practice to analyze the quality of re-used washing water periodically to check for the presence and concentration of pollutants. The pollutants to be monitored in each case will depend on the type of post-harvest processes and treatments, but generally may include plant pathogens, bacterial contamination, chemical cleaning agents.

The proximity of the washing and processing facility to cropped areas is important in deciding how practical, and how costly, re-using wash the water would be. The further apart they are, the greater the cost of installing, running and maintaining equipment such as pipes and pumps.

4.6.3. Household water

Water from some household activities can be recycled and used for irrigation in the following way:

- **Capture:** water can be captured use in small canals, gutters and pipes leading to a treatment system, after which it can be piped directly to the field or storage tank.
- **Storage:** a tank or reservoir may be needed if the water is not required immediately. See Chapter 3 on storage tanks.
- **Transport:** pumps and pipes may be needed to take water to storage tanks and to distribute it to fields. Chapter 3 gives an overview of types of pump.
- **Treatment:** solid trap, fat trap, septic tank, helophyte filter or constructed wetland.

Due to the risk of chemical and biological contamination, it is strongly recommended that at a least primary treatment is applied to household waste water (e.g. fat traps, filters, septic tank). Periodic water quality analysis is also recommended, especially for pathogens such as *E. Coli*.

Note that untreated sewage (from toilets) and water containing high levels of cleaning products, must never be used for irrigation. This is critically important in the case of fruit and vegetables that are eaten uncooked, as the risk of contamination and food poisoning is high.

4.6.4. Hydroponic wastewater

Hydroponic wastewater can be used for irrigation. The most important consideration here is the management of nutrients as hydroponic water has high nutrient content. If it is used for irrigation, this must be taken into account in the farm nutrient management plan.

4.7. THE BUSINESS CASE FOR RECYCLING WATER

4.7.1. Considerations

As with harvested water, the business case for water recycling needs to consider:

a. the quantity of water that can be recycled in relation to farm water needs;

b. the cost installing and maintaining the equipment and infrastructure needed (to collect, store, transport, treat...);

c. the cost of water quality checks (if relevant);

d. the potential increase in yield (and income) through ensuring that more water is available at critical periods;

e. the potential reduction in expenditure on water abstraction (fees, fuel, transportation costs...).

In addition to the immediate costs and benefits, as noted previously, the adoption of responsible water use practices can make a farm or company more attractive to buyers, especially when selling produce into global supply chains. In some cases responsible water use is becoming a requirement for market access; where this is the case, market access needs to be factored into the overall business case.

Is water recycling an option for the farm?

- What types of waste water effluent are produced and discharged on the farm? Can the farmer prepare a list of these effluents, with origin, and approximate volumes?
- Can the farmer identify potential contaminants in the different types of waste water?
- Does the farmer have enough data on the quality of farm waste water to decide if it is suitable to be recycled? If not, what are the data gaps?
- How could these effluents be recycled? What could the water be used for? Would treatment be needed? What type of treatment?
- Prepare a qualitative business case for water recycling taking into account:
  - amount of water that can be recycled in relation to overall farm water needs;
  - the current cost of water, and risks of water shortages;
  - the cost of materials and installation of a systems for capture, storage and transport (pumps, piping, storage tank, etc).
- Does this preliminary assessment suggest that water recycling may be an interesting option from a financial point of view?
- If at this stage water recycling does not seem feasible, discuss why among participants.
- If information is too limited to make an informed assessment, list the additional information that is needed to complete a business case.

4.8. EXAMPLE

4.8.1. Suzan and Kioko

After dinner, Kioko´s children wash the pans and plates they just used for dinner with rainwater from the tank next to their hut. When done with the dishes, they pour the dirty water around the plants in their nearby home garden. In the garden, their mother grows onions and capsicum, as well as some medicinal plants.

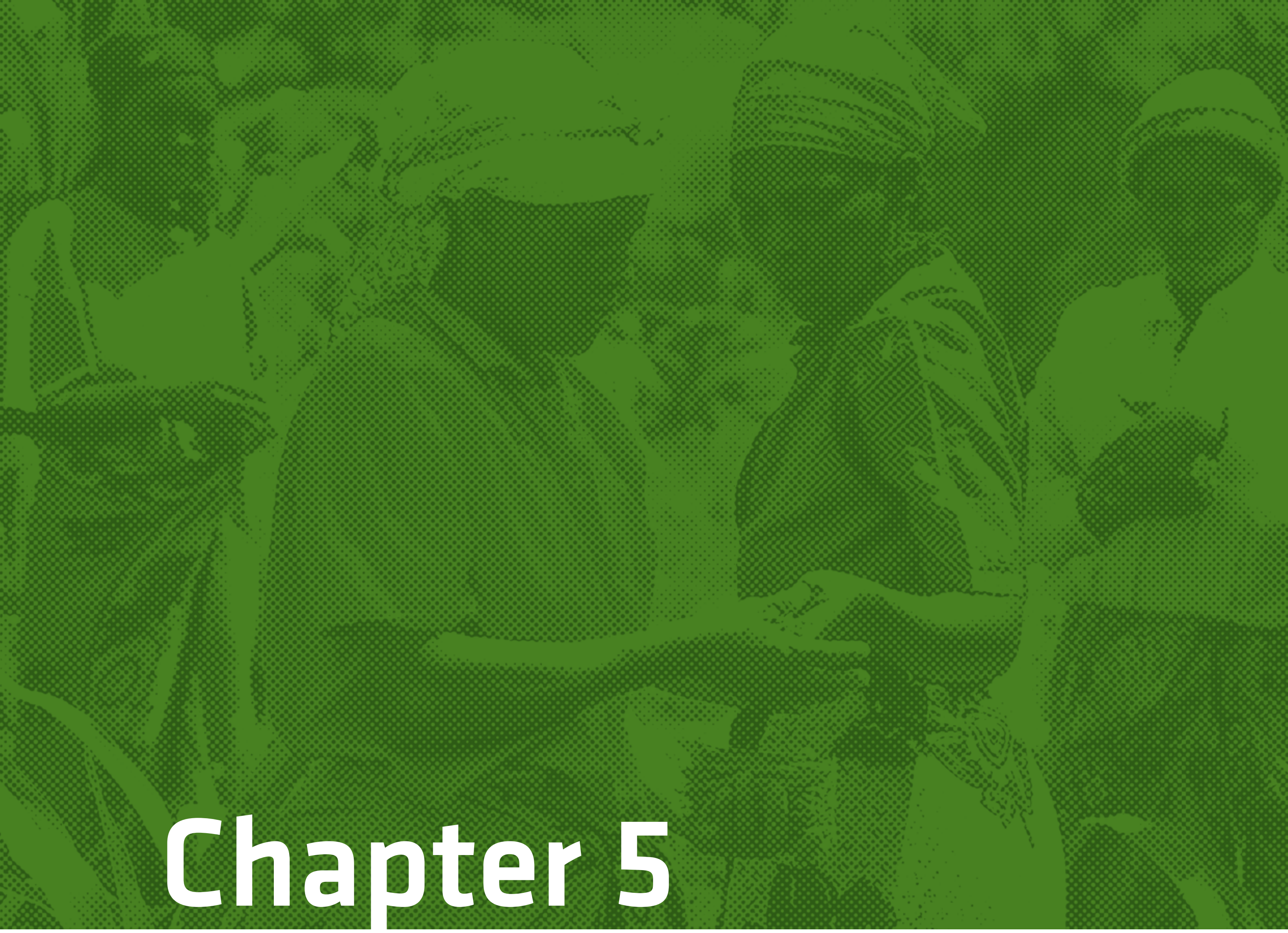
Susan´s tomato crop has a good yield this season. She planted 10 hectares and managed to harvest 200 tons. She also managed to buy a similar amount from her outgrowers. Pickups with tomatoes arrive at the washing and packaging facility on her farm. All tomatoes are washed by hand in large sinks by her farm workers. They are then sorted according to size and ripeness, and packed into boxes for transport to buyers in Nairobi that use them fresh or for processing.

Susan gets the water for washing from water trucks that bring potable water to the farm. When the washing water gets too dirty, her workers empty the sinks, from which the water flows through a concrete drain into the river. The water has no further use. However, close by she is preparing land to start cultivating green beans for export to the UK. To start off the green beans she needs a first irrigation to wet the soil for germination; she needs about 800 m^3 of water for that. Could she use the water from the sinks to supplement irrigation, in addition to canal water and leftover rain? She estimates the amount of water used post-harvest. To wash 100 kg of tomatoes she needs 250 l of water; so for 200 tons she estimates that she uses 500 m^3 of water, which is a little more than half the first irrigation for her hectare of beans. The problem is, she does not need the water yet. Where could she keep it in the meantime? Maybe in a pond nearby?

The water is quite dirty from the soil that is washed off the tomatoes, and she wonders if it is clean enough to use for irrigating the beans. The water may also have some leftover fertilizer and pesticides from the tomatoes. Maybe the pond can also clean the water: she knows that water plants can be used for that. Or she may dilute the water with water from the river, water harvesting, or the canal. As her beans are for export, she has GLOBALG.A.P. certification and wonders if using the recycled washing water may violate GLOBALG.A.P. water quality requirements. She assumes that GLOBALG.A.P. probably require the quality of water to be checked before using it for the beans. Or maybe she could just store it and assume it will clean itself? If not, she can always use it to supplement irrigation for her next season of tomato production. She should enquire with the local agricultural extension officer about this.

To go ahead, Susan needs to address the following questions:

- Where in her farm could she locate her pond? What dimensions should it have?
- What water quality levels does she need to have to irrigate GLOBALG.A.P. certified beans? For which parameters?
- Is there a business case for building a pond, collecting post-harvest wastewater, measuring pollutant levels and pumping the water for beans? Is it financially interesting?



Chapter 5

Using water efficiently

5.1. INTRODUCTION

5.1.1. Definition

Water efficiency can be considered from two perspectives. Firstly, it consists of producing more crop with less water. This element needs to be addressed though improved management of the production system as a whole including soils, crops, and water itself.

The second element is about avoiding water losses, and is the main topic of this chapter. It addresses, in particular, how to:

a. abstract the right amount of water according to what is needed; and
b. ensuring that as much as possible of the abstracted water is actually used, with minimal losses or wastage.

Water losses can happen during transportation (to the field or packhouse), at the storage point, in the field, or during post-harvest handling and processing. Although some losses are inevitable, it is important to consider how they can be minimised, and where and how water can be used more efficiently by following certain practices.

5.2. THE BUSINESS CASE FOR EFFICIENT WATER USE

5.2.1. Benefits

As noted in earlier chapters, using water efficiently can have a number of clear benefits:

- increase water availability during times of scarcity;
- increase yield (or reduced crop losses);
- reduced water abstractions;
- reduce dependency on external resources;
- reduced competition for water with other users;
- increased resilience to scarcity situations or to climate change;
- a positive image of the farm or company as a responsible user of water.

To assess water use efficiency, it is important to know approximately how much water is abstracted and how much water is actually used for different purposes (e.g. ield irrigation, greenhouses, washing and processing, etc.).

If a farm or company can estimate the volume of the water they lose, and the cost of abstracting and transporting this amount, and then compare this to the cost of rationalizing abstractions (extracting only what is needed) and pro-active measures to reduce losses (e.g. better maintenance of irrigation systems), it is generally very clear that improving water use efficiency not only prevents wastage, but also results in financial benefits.

5.3. INCREASING WATER EFFICIENCY DURING TRANSPORT

Water efficiency during transportation refers to how much of the water abstracted from a source actually reaches the point where it will be used. In the case of irrigation, for example, high water efficiency implies that most of the water abstracted reaches and is applied to the field. The same thing is true in hydroponic systems or any other water use.

5.3.1. Assessing water use efficiency during transport

If the farmer wants to assess water losses during transport, he needs to measure how much water is abstracted (e.g. from a canal or borehole), and how much water is delivered at the point of use (e.g. distributed onto the field during irrigation). Chapter 2 outlined methods that can be used to do this including mapping water sources, measuring water abstracted, and measuring volumes applied to the field.

5.3.2. Actions to increase water use efficiency during transport

Losses during transportation occur, for example, when irrigation canals are permeable (infiltration), are open to the air (and therefore evaporation occurs), where pipes are not watertight, or where spills or leaks occur.

To minimise such losses, it is important to visually inspect the water transportation system on a frequent basis to check for leaks, spills or any damage to the infrastructure. It is also critical to invest, as a priority, in repairs and regular maintenance, especially of irrigation systems.

Some options to improve water use efficiency are listed in Table 1.

Table 1. Options to increase water efficiency during water transport

Visual inspection and maintenance of water transportation systems: canals, pipes, irrigation systems like pipes, canals, sprinklers or drippers.	Check water transport infrastructure frequently. Ideally the farm should have an inspection plan or schedule, with individuals given responsibility for checking particular sections at particular times; this will make sure that all elements of the system are covered on a regular basis. Pipes for water transport and irrigation (in the field, green house and pack house) must be examined for leaks, and any damage repaired promptly. Irrigation canals should be checked for excess debris, weeds, damage or leaks; debris should be removed, and damage repaired promptly. In the case of shared infrastructure, it is helpful to draw up a plan between all users to cover the canal and pipe inspection and maintenance.
Lining of irrigation canals	Losses from irrigation canals due to infiltration can be reduced by lining with a less permeable type of soil, or by adding an impermeable layer (e.g. cement)
Pipe conversion	Losses due to evaporation can be reduced by converting open canals to pipelines. This includes transporting to the farm from the water source, as well as transporting to and around fields. However, while this will increase water efficiency, if water from the canals is no longer open this could have an impact on the environment (animals and vegetation) and livelihoods of others. Any potential negative impacts must be assessed and discussed with other users before carrying out this measure.

5.4. INCREASING WATER EFFICIENCY DURING STORAGE

Water efficiency during storage depends mainly in the condition of the storage facilities.

5.4.1. Assessing water use efficiency during storage

The farmer can use simple measures to assess water efficiency during storage by measuring water losses due to leaks or evaporation. This can be done by using a gauge, or marking the water level in storage tanks or reservoirs, and noting any change. Water capture and water abstraction from the tank or reservoir would need to be stopped (or remain constant) while the assessment is taking place.

5.4.2. Actions to increase water use efficiency during storage

- It is important to ensure frequent revision and maintenance of all water storage facilities, fixing cracks, and generally maintaining them in a good condition. This will avoid water losses and also potential contamination from external sources.
- When possible, cover water tanks and storage facilities in order to avoid not only evaporation, but also the possible intrusion of plants, debris or organic matter from birds or other animals, as this may also affect water quality.

5.5. INCREASING WATER EFFICIENCY IN THE FIELD

Water efficiency in the field refers to how much of the water applied to the crop is taken up by it, and thus used productively. Losses happen because water runs off the field without penetrating the soil, or it is lost to drainage or evapotranspiration without being taken up by the crop.

5.5.1. Assessing water use efficiency in the field

To assess water use efficiency in the field, it is necessary to measure the volume of water applied to the field and the volume of drainage water. The difference between these two will be the water that was evapotranspired by the crop.

If it is not possible to measure drainage water, a qualitative indication of water use efficiency can be obtained by:

1. assessing soil moisture content (Chapter 11), and ensuring that this is not excessive and
2. monitoring runoff. If the right amount of water is being applied during irrigation, there will be no runoff. Irrigation efficiency is covered in more detail in Chapter 8.

5.5.2. Actions to increase water use efficiency in the field

Paying careful attention to when and how much water is applied ensures that as much as possible of this water is retained by the soil for crop growth. Losses can be minimized by timing applications properly using well-planned irrigation scheduling. This includes:

- Applying water to the soil only when it reaches a certain threshold of soil moisture content, which will depend on the type of crop, type of soil, and climatic conditions.
- Applying just the right amount of water above this threshold to recharge the soil to field capacity. Water applied after this point will be lost to runoff or drainage.

While sophisticated systems are available for irrigation scheduling, where this is not possible, a simple schedule can be developed by using qualitative estimates of soil moisture content on a daily basis. In Part 1, also in Chapter 11 of Part 2, simple methods of estimating soil moisture content are explained.

Improving the ability of the soil to retain water is also critically important to water use efficiency (see Part 1 Chapter 6, and Part 2 Chapter 11).

Table 2. Increasing water use efficiency in the field

Irrigation scheduling	It is essential to know when and how to irrigate. It is more efficient to irrigate when the soil water content is low (critical depletion). The goal of irrigation scheduling is to avoid under or over irrigation, while providing enough water for the crop. Complex computer based-models are available (e.g. FAO CROPWAT) to determine crop water needs, and develop a complete irrigation schedule. These sophisticated irrigation scheduling tools use information collected daily and are thus fine tuned according to the weather, relative humidity etc. on anyone day. In low-input systems many simple measures can still be taken to increase efficiency. As well as visual monitoring of soil moisture and runoff, a general recommendation is to avoid irrigation during the warmest/sunniest hours of the day to minimise evaporation.
Agricultural practices	Practices to increase soil water retention are critically important, and include conservation tillage, cover crops, or conservation crop rotation
Type of irrigation	Choosing the most appropriate type of irrigation will improve the efficient use of water. Sprinkler and especially drip irrigation are the most efficient, as will be seen in Chapter 8.

5.6. INCREASING WATER USE EFFICIENCY IN THE POST-HARVEST PHASE

5.6.1. Assessing water use efficiency in the post-harvest phase

In order to assess water efficiency during post-harvest activities, it is necessary to know the volume of water used, and the volume of effluent, in relation to a given volume of produce (e.g. per 100 kg of produce washed). The goal is to minimize losses (for example due to evaporation or spills) and to maximize volumes of product treated with the same amount of water.

5.6.2. Actions to increase water use efficiency in the post-harvest phase

Recommendations to increase water efficiency in the post-harvest phase include:

- Make the working area impermeable. Inspect infrastructure (notably pipes and water storage facilities) regularly and repair promptly to avoid leaks and infiltration.
- Divert used water to storage devices such as water tanks, for sedimentation, and for later use in irrigation (taking into account water quality recommendations provided in Chapters 3 and 6).
- Consider if more produce can be washed with less water, while maintaining the same produce quality.

Are you using water efficiently?

- Why is it important to make efficient use of water?
- Where and when could water efficiency be improved in your farm/enterprise?
- How can water efficiency be assessed?
- How can water efficiency be improved in the transportation and storage phase?
- How can water use efficiency be improved in the field?
- Explain why it is important to execute general inspections and maintenance of infrastructure in where water use takes place?

5.7. EXAMPLE

5.7.1. Suzan and Kioko

After the failure of his tomato crop, Kioko asks himself if he is using the water that he can access to the utmost. He once learned from the extension service that in Kenya the crop requires an average of 6 mm of water per day to grow well. On his half hectare, with a growing season of 145 days, that would mean the crop needs 870mm of water. For his 0.5 hectare, this would be 4350 m^3 of water. This is total – and does yet account for the rain. He thinks that for his crop grown during the rainy season, the rain can take care of half the amount of water that is needed by the tomatoes. That means the crop needs 2175 m^3 of irrigation. He calculated that last year he only applied 1440 m^3 from the spring, and this is probably why his crop failed.

He has also checked his land and realizes that when he irrigates, he lets water flow out from the other end of the field. This means that the crop got even less than the water he pumped and applied. He sees that he needs to improve the way he is using the water.

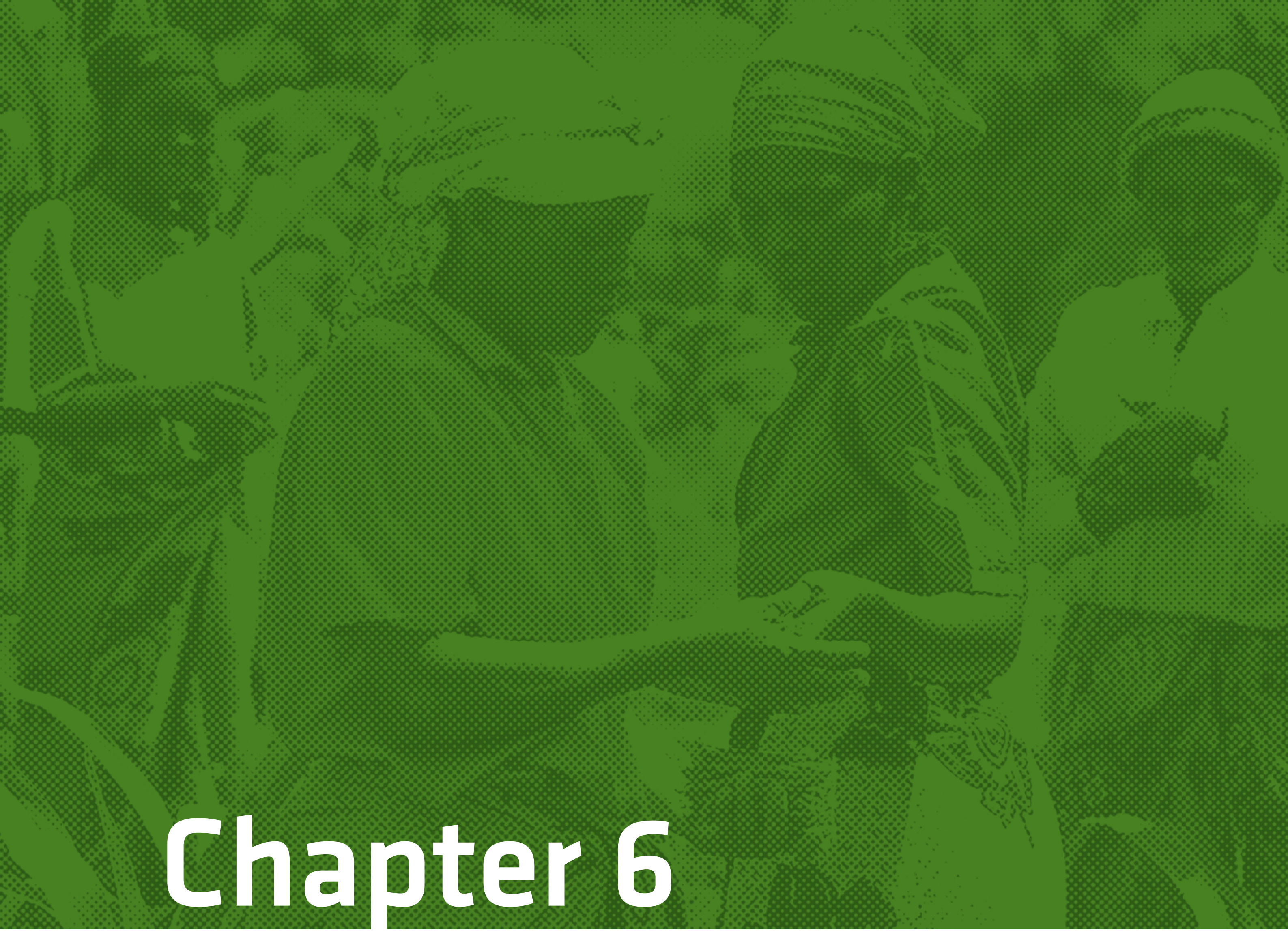
Firstly, he decides to take better care and not let the water flow out of his field. He also knows that it would be better to create furrows, but this requires a lot of extra work. But he knows that if next season he has the same amount of rain, but doesn't change his current practices, his crop may fail again. He is considering only growing tomatoes on a smaller part of the field, which would reduce the amount of work on furrows. This would help him improve his water use, and also his yield/unit area. It would leave the rest of the field where he could grow another, perhaps less water sensitive crop.

Susan thinks about the reliability of her access to water and understands that she should make the most of the water that is available. She has been looking at alternative sources of supply but these are also limited. It is time to look at the use of water. She decides to figure out what type of cropping pattern and use of technology is economical and efficient from the water use as well as productivity perspective. She cannot do this herself and decides to find a person who can help her with this. This should be an expert in agriculture and water that is able to calculate the crop water needs but also the efficiency of water use and productivity of the current practice in her farm. But especially she would like to know what are the simple actions she can take to increase productivity and at the same water use efficiency. She realizes that she needs a better picture of all the water that goes into her farm and all the water that she uses. If she has that, she would have the full information needed to decide on different options to optimize her water use. This is what the trainer called a water balance. She knows some farmers that have switched from furrow irrigation to sprinkler irrigation for green beans. She feels that it might be worthwhile putting up a greenhouse for her green beans as she has heard this will further increase yields as well as decrease the amount of water and other inputs that she has to use. But first she needs the overview on the water balance and productivity.

In addition to the information that will be provided by the expert, Susan would like to know:

- What can she do to increase soil water retention?
- How can she immediately and in a simple way start testing soil water content to help decide when to irrigate?
- What is the minimum amount of water that she needs to add besides irrigation to make sure salts are washed away?

PERSONAL NOTES



Chapter 6

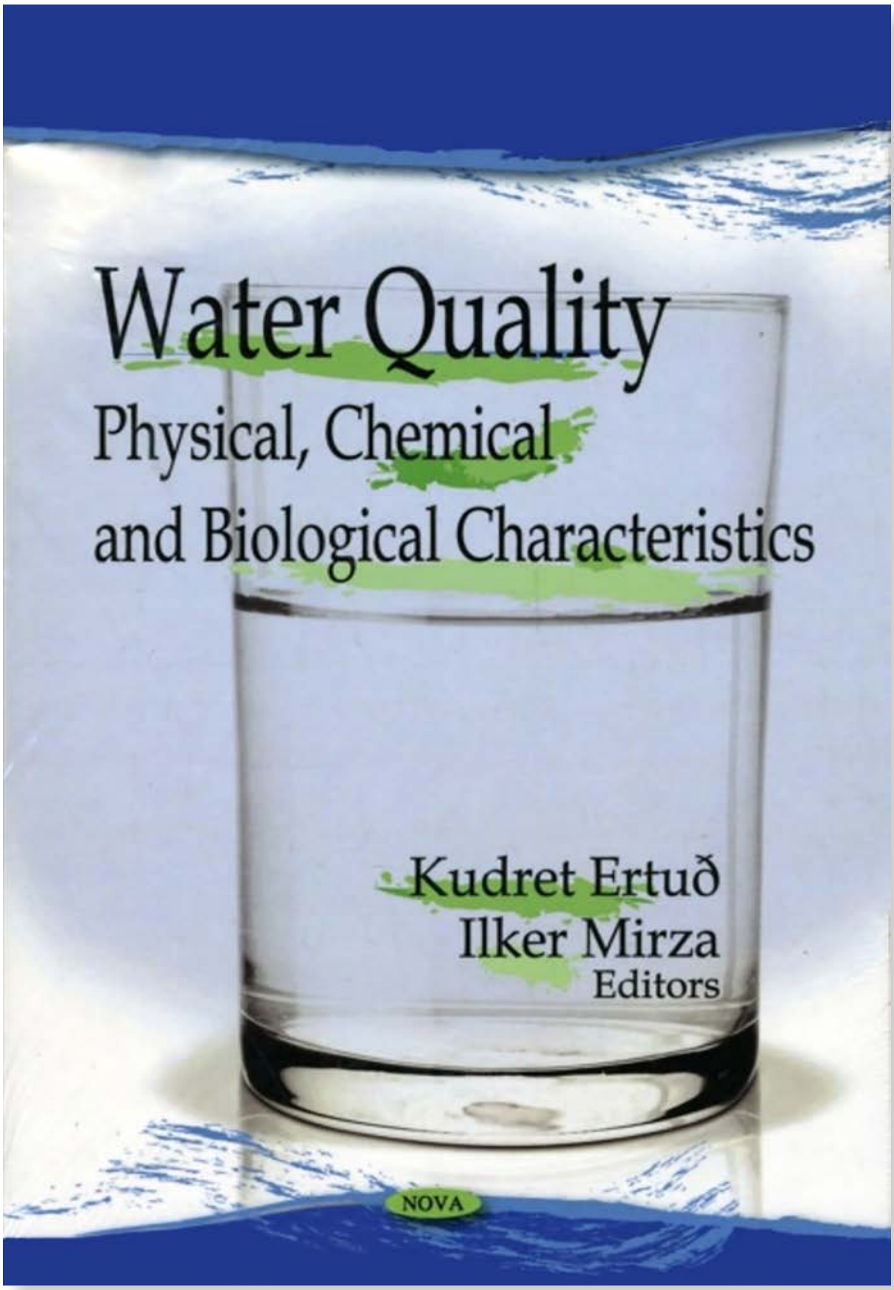
Water quality

6.1. CHARACTERISTICS DEFINING WATER QUALITY

While it is essential to ensure sufficient quantities of water are available, it is equally important to ensure that water is of the right quality for its intended use. Poor water quality can have a serious impact on short and long term productivity and, in horticulture in particular, it is a critical factor in terms of food safety.

Water may be polluted by physical, chemical or biological contaminants. The risk of these contaminants being present varies according to the source of the water. For example, as we saw in Chapter 4, recycled water from domestic uses can be a source of water for irrigation, but it can have high salt content and be potentially high risk in terms of food safety due to microbial contaminants. It is essential therefore to understand and monitor water quality on a regular basis, and to ensure that the use of water, and the application of water treatment, avoids any potential problems.

Water quality is determined by its physical, chemical and biological characteristics.



6.1.1. Physical

The physical characteristics of water include: suspended solids, temperature, color, taste, and odor. These characteristics will vary according to water source, and are affected by natural influences (e.g. rock or soil type) as well as potential sources of physical contaminants.

These characteristics can fluctuate. For example, the presence of suspended solids in lakes or rivers generally increases following rainfall, especially where soils are exposed and prone to erosion.

6.1.2. Chemical

Chemical characteristics of water refer to substances present in dissolved form, or adsorbed onto soil particles. This can include salts and heavy metals, as well as pollutants.

Chemical characteristics are determined by a variety of factors:

- **Natural chemical contamination.** The soil and rock the water has been in contact with are a major influence, especially in the case of water from springs and boreholes.
- **Human and animal waste.** The chemical characteristics of river water depend on natural factors, but also on the human and animal wastes from domestic use, agriculture or livestock. Lakes, rivers, and grey water will also be affected by activities on the farm. Runoff may contain nitrates from fertilizers and manure, heavy/metals from animal manure (Zn, Cu, Ni), as well as pesticide residues from tank washing and field applications.
- **Industrial.** If there are mining activities, or the river receives urban or industrial wastewaters, the river may contain pollutants.

6.1.3. Biological

Water is in contact with and contains a great variety of living organisms. Some are visible, such as plants, algae or fish, while others are invisible to the human eye, such as bacteria. While some organisms are beneficial or harmless, others can have a negative impact on water quality, in particular pathogenic bacteria.

Pathogens are generally present in domestic effluent (especially that containing untreated sewage), animal effluent, and other wastewater. There is a high risk that where such wastewater has been discharged into lakes or rivers, water quality will be affected by microbial contamination.

6.2. WATER QUALITY AND WATER SOURCE

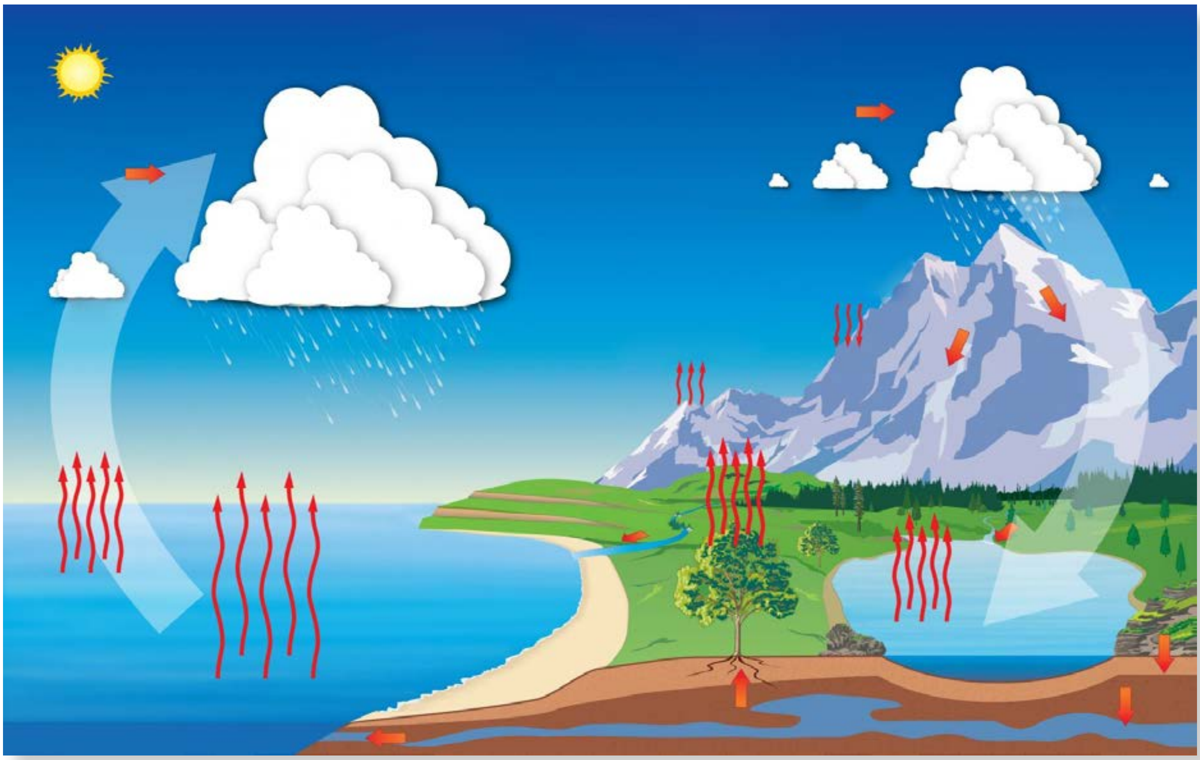
6.2.1. Impacts

The source of the water will influence the likelihood of physical, chemical or biological contamination. This is an important consideration when deciding what water sources can be used for different purposes on the farm, as well whether farm water sources should be analyzed, how often, and for what characteristics.

Blue water from springs and boreholes may contain high levels of salts or heavy metals, but is likely to be the least at risk from microbial contamination.

Blue water from lakes and rivers is likely to carry sediment, especially following rainfall. As well as salts and heavy metals, it may also contain chemical pollutants, especially if the extraction point is downstream of mining, industry, or a large habitation. Agricultural pollutants such as nutrients and pesticides may also be present. Finally, it may contain microbial contamination; this will depend on: the uses of the water upstream, the discharge of human or animal effluent, and whether animals (domestic or wild) have direct access to the water.

The quality of grey water will also depend on source or use. Recycled washing water may contain high levels of disinfectant, for example, as well as bacteria. Recycled irrigation water is likely to contain pesticides and nutrients. The way in which grey water is stored can influence quality, especially if debris or animals are allowed to enter and accumulate.



6.3. WATER QUALITY AND WATER USE: IMPLICATIONS FOR HORTICULTURE

The quality of water used during the growth of the crop and post-harvest is critical, and will directly affect production as well as the quality and safety of the final produce. In terms of yield, prolonged use of poor quality water for irrigation can have a damaging impact on the soil and long-term productivity. Furthermore, as many fruits and vegetables are eaten raw, contamination with pathogenic bacteria is a high risk and can be extremely dangerous; it is one of the main causes globally of serious and fatal food poisoning.

The following are some important considerations regarding water quality for production and post-harvest activities.

6.3.1. Irrigation

Poor quality of irrigation water can affect infrastructure and equipment, short-term crop growth, long-term health and productivity of the soil, and the safety to consumers of the final product. Some of the most important considerations are described here, differentiating between physical, chemical and biological contaminants.

6.3.1.1. Physical

- Pipes and canals can become blocked by suspended particles or impurities. River water or other sources containing sediment or suspended particles may need to be filtered, especially when using drip irrigation.
- Excess sediments can clog the soil and impede drainage.

6.3.1.2. Chemical

- The presence of certain plant pathogens, and contaminants such as salts, may affect plant health and hinder crop growth. Prolonged use of irrigation water containing high levels of salts will result in salinization, with a serious impact on long-term soil productivity.
- A sudden change in the color or smell of water can be an indicator of physical or chemical pollution. If water changes color, is very turbid (cloudy), or has a strange or different smell, it should not be used for irrigation without first analyzing for potential contaminants.
- High levels of heavy metals can damage soil and long-term production. They can also affect consumers as these substances are, by nature, persistent and may be taken up by crops. Arsenic is of particular note as it is naturally occurring in groundwater in many locations.

6.3.1.3. Biological

- Microbial contamination of irrigation water is a critical concern, especially where there is a high risk of direct contamination such as crops where the edible portion is in contact with the soil (e.g. lettuce); or where a sprinkler irrigation system is used. This is particularly important in the case of fruit and vegetables that are eaten raw.
- Water that may contain untreated human sewage or animal waste must never be used for irrigation.

6.3.2. Post-harvest activities

The quality of water used in post-harvest activities must be carefully managed to prevent contamination of produce. Most important is to ensure consistently high (potable) quality of the water used for washing fruit and vegetables prior to packing or shipment.

6.3.2.1. Physical

- Physical contamination (e.g. with suspended soils, dirt or debris) of post-harvest water can affect both the product and the facilities used for handling and processing. The quality of water quality used to wash the product, equipment, and handling facilities as well as for personal hygiene (pack house staff), must be controlled to avoid cross-contamination.

6.3.2.2. Chemical

- Chemical contaminants that should be controlled and monitored in water used post-harvest include pesticides, fungicides, machine lubricants, heavy metals, industrial toxins, and compound used to clean or sanitize the facilities.

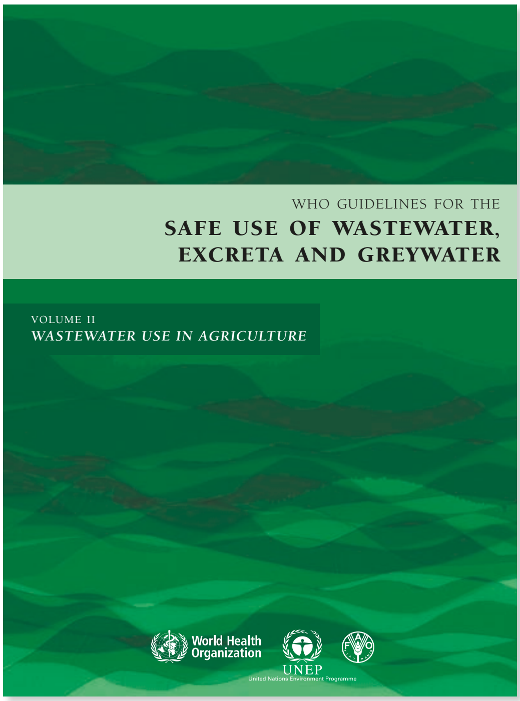
6.3.2.3. Biological

- Microbial contamination is the most serious concern during the post-harvest handling of fruit and vegetables. Soil-associated pathogenic bacteria, faecal bacteria, pathogenic parasites or viruses must be monitored and avoided during the post-harvest and storage of fresh produce.

6.4. MEASURING WATER QUALITY

Each farm should identify potential sources of contamination of the water they use, and assess whether this is high or low risk, in order to decide:

a. which water sources should be tested;
b. what tests should be carried out (depending on the source of the water, and what it will be used for);
c. how often tests should be carried out.



Guidance is available from the World Health Organization (WHO) on acceptable water quality for different purposes. For example, WHO[274] guidelines stipulate water quality and maximum allowable concentrations of key parameters in waste water, so that it can be used safely on farms (e.g. for irrigation). WHO[275] provides more general guidelines and health standards of water used for drinking, irrigation or recreational purposes.

To test water quality, samples should be collected on-farm using recognized and recommended sampling methods, equipment, and transport, and then taken to a laboratory for analysis. It is important to establish if suitable laboratory testing facilities are available locally to conduct the various analyses needed, and to compare prices between labs. Some certification schemes specify that analyses must only be conducted by an accredited lab.

Guidance on sample size and method can generally be obtained from the laboratory conducting the analysis, and will vary according to the type of analysis being carried out. However, in terms of frequency, while general guidance can be given on how often water quality should be tested, it is very important to identify high risk situations where testing should be done more frequently. For example, private water supplies generally should be tested for bacterial safety at least once a year, but frequency should be increased:

- when a new borehole is constructed;
- when an existing borehole is returned into service;
- whenever a component of the water system is opened for repair;
- whenever the water source is inundated by flood waters or surface runoff;
- whenever bacterial contamination is suspected (e.g. in the event of illness, or the appearance of a bad odor);
- when a laboratory test shows high nitrate levels, indicating possible contamination from human or livestock waste.

6.4.1. Water for post-harvest use

In order to comply with private standards (certification schemes) such as GLOBALG.A.P., any ice or water used in direct contact with produce, such as cooling or washing water, must meet the microbial standards for potable (drinking) water, and be handled under hygiene conditions and procedures to prevent contamination.

According to GLOBALG.A.P. guidelines, re-circulated water used for washing should be filtered (using a system effective for solids and suspensions) and disinfected. Disinfectant and pH levels should be routinely monitored.

274 WHO, *Guidelines for the safe use of wastewater, excreta and greywater*, vol. 2, *Wastewater use in agriculture*, Rome, WHO, 2006, www.who.int/water_sanitation_health/wastewater/wwuvol2intro.pdf.

275 WHO, *Water quality: Guidelines, standards and health*, 2001, www.who.int/water_sanitation_health/publications/whoiwa/en.

- **What**

  WHO (2011)[276] provides guidelines for drinking water quality. The EPA Maximum Contaminant Level (MCL) for coliform bacteria in drinking water is zero (or no) total coliform per 100 ml of water.

- **When**

  Water sources used for produce washing must be analyzed at least every 12 months. The key parameters must meet WHO thresholds, or the levels accepted as safe by the food industry (if more different).

- **How**

  Simple (although not highly accurate) drinking water quality kits, that can test for *E. Coli*, are available in the open market and inexpensive (USD$10-15). However, while these can give a general picture of water quality (Figure 1), it is advisable to back them up with laboratory analysis.

Figure 1 - Example of simple drinking water test
Source: www.firstalert.com

276 WHO, *Guidelines for drinking-water quality*, 4th ed., who.int/water_sanitation_health/publications/2011/dwq_guidelines/en.

6.4.2. Irrigation water

Knowing the levels of key substances present in a water source (particularly salts) is essential to assess whether the water is suitable for irrigation. A list of key parameters and measurement guidelines is given below.

6.4.2.1. Salts

- What

  Moderate parameters should be between 0.7-3 dS/m for EC and 450-2000 mg/l for TDS.

- When

  In normal conditions, levels should be checked at least twice a year at blue water abstraction points. However, the frequency should be adapted to the water source. Salts should also be checked when grey water (wastewater or recycled water) is used for irrigation. Assessing salt levels is part of the routine maintenance of drip or sprinkle irrigation systems. If boreholes or springs are near coastal areas, salts need to be monitored in order to detect saline intrusion.

- How

  Electrical conductivity (EC) or Total Dissolved Solids (TDS). This can be done by a laboratory, using portable kits, or through evaporation.

6.4.2.2. Microbial Contaminants/Pathogens

- What

  Various pathogens can be present in water (e.g. faecal coliforms, helminths, viruses), but testing generally focuses on coliform bacteria and E. coli. Coliform bacteria do not themselves normally cause disease, but they are good indicators and show the likely presence of other more harmful organisms; by monitoring coliform bacteria, the levels of many pathogenic bacteria can be estimated. GLOBALG.A.P. recommends a maximum of 1000 cfu/100 ml for E. coli.

- When

  According to GLOBALG.A.P., the quality of irrigation water should be monitored and tested at regular intervals. Frequency of testing should be adjusted according to the risk of contamination of a water source. Grazing land, livestock farms, septic tanks, and wastewater are common sources of contamination by pathogens. Where there is a higher risk of contamination, frequency of sampling should be increased accordingly. Also seasonal samples should be taken to obtain representative data, and to allow for variation in water quality according to climatic conditions. Additional measurements should be taken after storm events.

- How

  Analysis of microbial contaminants is complex and must be conducted by an appropriate laboratory.

6.4.2.3. pH (Acidity)

- What

  pH levels should normally be between 6.5-8. Measurements outside this range can be a sign of abnormal water quality. pH of green water is primarily influenced by the composition of surrounding rocks, but can be altered by a range of factors such as industrial and mining runoff, wastewater and acid rain.

- When

  Measurements should be taken monthly at extraction points, and weekly in warmer seasons (pH decreases as water temperature rises). It is important to measure pH when drip systems are in place (see Part 1, Chapter 6).

- How

  pH pocket meters can be obtained for around US$50, and give immediate results with a high degree of accuracy.

6.4.2.4. Heavy metals

- What

  Water normally contains a certain level of heavy metals, influenced by the surrounding rocks. However, occasionally levels can be raised to the extent that they pose a threat to water quality. It is particularly important to monitor lead and arsenic, which are among the most harmful heavy metals, and also the most commonly found in water. A recommended maximum concentration for arsenic in irrigation water is around 0.10 mg/l, and 0.5 mg/l for lead.

- When

  As with pathogens, the sampling frequency depends on the water source and use. For example, in water from a spring or a borehole, sampling can be less frequent as the variation over time is likely to be small. Heavy metals should be monitored in all urban and industrial wastewaters, but more frequently if mining activities are taking place in the area or upstream.

- How

  The complexity of analyzing for heavy metals means that samples need to be sent to a laboratory.

6.4.2.5. Nutrients

- What

  Nitrates are present in natural waters, but their concentration is significantly higher in runoff coming from fields that are fertilized, in areas with livestock, or in wastewater and industrial discharges. If wastewater or drainage water is used for irrigation, analyzing nutrient content is important to manage nutrients efficiently and avoid overloads. As a minimum, the following parameters should be tested: ammonia, nitrites, nitrates, total nitrogen and total phosphorus. Water nutrient content can be reported simply as total nitrogen (TN: the sum of ammonia, nitrites and nitrate content); 5-30 mg/l is considered a moderate value of TN.

- When

  Ammonia, nitrites, and nitrates should be tested monthly during the irrigation season; total nitrogen and total phosphorus should be tested twice yearly.

- How

  Nutrients can be measured in the field with portable kits or strips. However, for a more precise result, it is recommended that samples be sent to a laboratory.

6.5. WATER TREATMENT

As outlined in Part 1, Chapters 4 and 7 of this manual, various water treatment measures are available to address different types of contamination and/or to improve water quality.

6.5.1. Physical

Filters can be used to remove large solids, and primary sedimentation treatments remove inorganic matter and suspended solids.

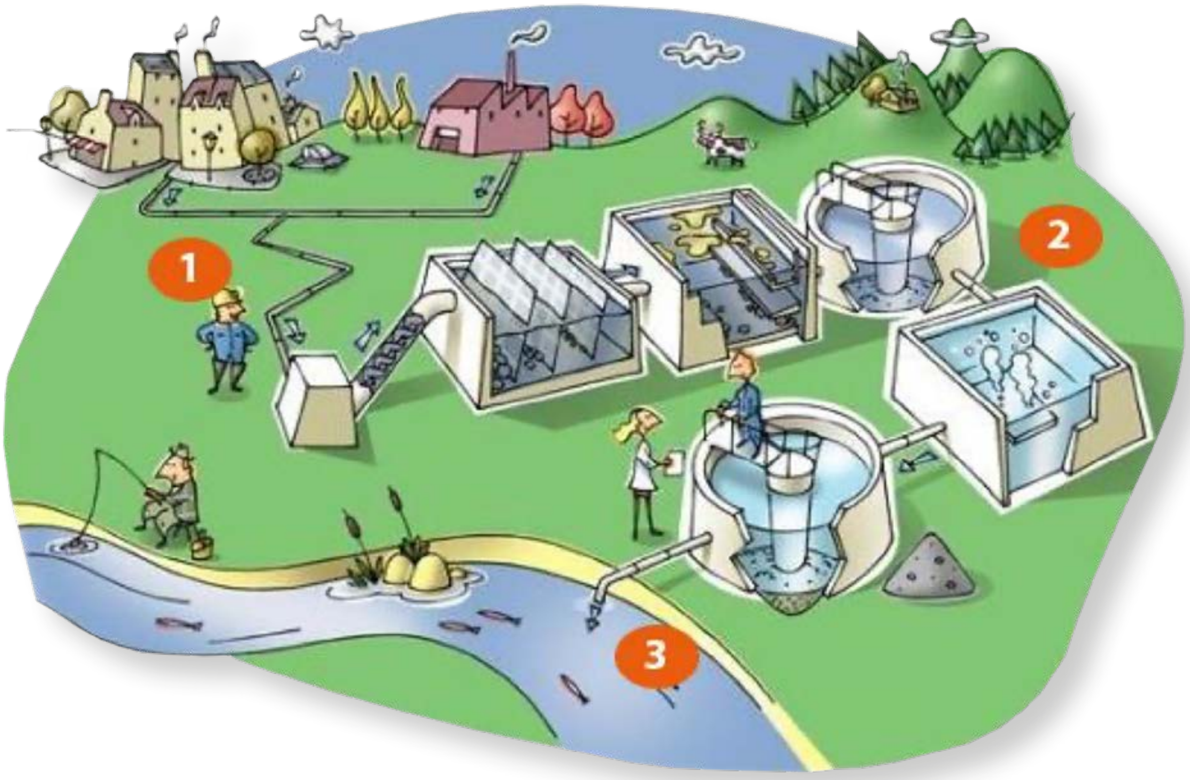
6.5.2. Chemical

Some treatments for removing chemicals from water use water tanks and chemical precipitants (known as coagulants or flocculants). These increase particles size through aggregation, allowing the contaminants to then be removed by physical methods, such as clarification and filtration.

Phytoremediation is also used to remove chemical contaminants, but without the need for expensive or complex facilities or chemicals. It involves the use of terrestrial or aquatic plants to remove pollutants. For example, hydrangeas absorb aluminum, and water hyssops absorb other heavy metals such as lead or cadmium.

6.5.3. Biological

As primary treatments, sedimentation can be used to remove organic solids, and skimming to remove floating materials. These simple treatments can remove a high percentage of biochemical oxygen demand (BOD5), suspended soils, oils and greases.



6.6. WATER QUALITY AND ITS IMPORTANCE FOR HORTICULTURAL BUSINESSES

6.6.1. Critical points

The quality of water used both during production and post-harvest will directly affect the quality and safety of horticultural produce, as well as the quality and productivity of the soil. Managing water quality effectively is critical to:

- protect and maintain yield;
- avoid the risk of costly damage to infrastructure;
- ensure that produce is safe for the consumer;
- meet the demands of buyers/clients (exports and high-end local markets increasingly require evidence that water quality is being monitored and managed responsibly).

Assessing the quality of water on a farm

- Do you have any concerns about the quality of water used on the farm? Do you think there a difference between the quality of water needed for irrigation and post-harvest uses?
- Can you give a qualitative assessment of the water used for (a) irrigation and (b) postharvest purposes? For example, are there salt problems? Excess sediments? Does the water have a smell, a color?
- Have any tests been made of on-farm water sources? If yes, what have they shown? Did these look at physical, chemical and biological quality parameters?
- Are there any activities upstream that could affect on-farm water sources? Mining? Industries? Villages or towns discharging wastewater to the river?
- Have you taken any action to improve the quality of water used for irrigation and post-harvest activities?
- If wastewater or recycled water are used, have you considered that they may have a high nutrient content? If levels are high, you taken action to reduce nutrient applications on the field?
- What is the nearest place where water samples can be analyzed? Is it an accredited laboratory? Do you know the cost of sampling, transporting and analyzing water?
- Have you considered buying a portable kit to measure salts and pH? Is there potential for several farmers to group together to buy and share such equipment?

6.7. EXAMPLE

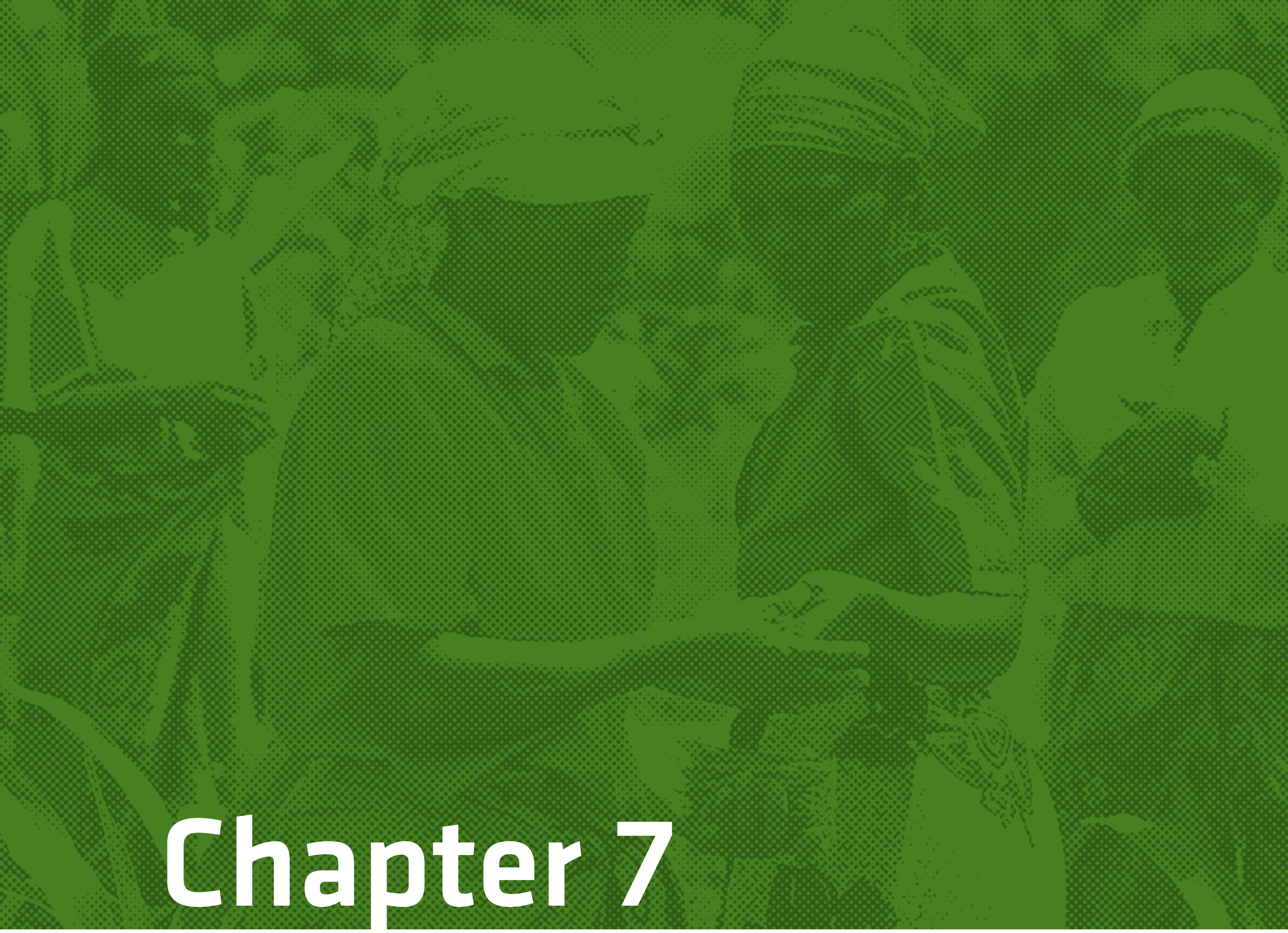
6.7.1. Susan and Kioko

Yesterday one of Susan's workers told her that in the far part of her farm the soil is becoming white. Susan knows what this means: there are too many salts in the soil and soil water. When the water evaporates from the soil, the salts crystallize on the surface. She knows this is not good and could lead to the land being totally lost. She wonders what to do. The canal water maybe contains too many salts, and the volume of water she is using may not be enough to wash the salts out. She has never checked the salt content of the irrigation water. Also, in that part of the farm, there is little water in the irrigation canal, so washing out the soils is difficult. In the next meeting of the irrigation water user association, she plans to bring this issue up. She wants:

- to hear if other people have the same problem;
- to get the irrigation water quality checked for salt content; and
- to arrange for some extra water in the short-term to wash out the salts.

Kioko is at the spring he uses to take water to irrigate his tomatoes. There is a clear smell of cows and he sees cow tracts near the spring. He knows that pastoralist herders sometimes water their livestock at the spring, often in large numbers. After that the water flowing from the spring is murky, and dung is lying around everywhere. He knows that the water is now not good to drink. He wonders if it good for irrigation; there may be cow dung in the water that carries disease. He decides to not take water now but to wait until the murky water settles a bit and the fresh spring water washes the dirt away. He wonders if it would be possible for the livestock to water further away from the spring. Maybe a pipe with a trough could be installed? But, for now, he can only wait for the spring to clean itself before he can use the water for his crop.

PERSONAL NOTES

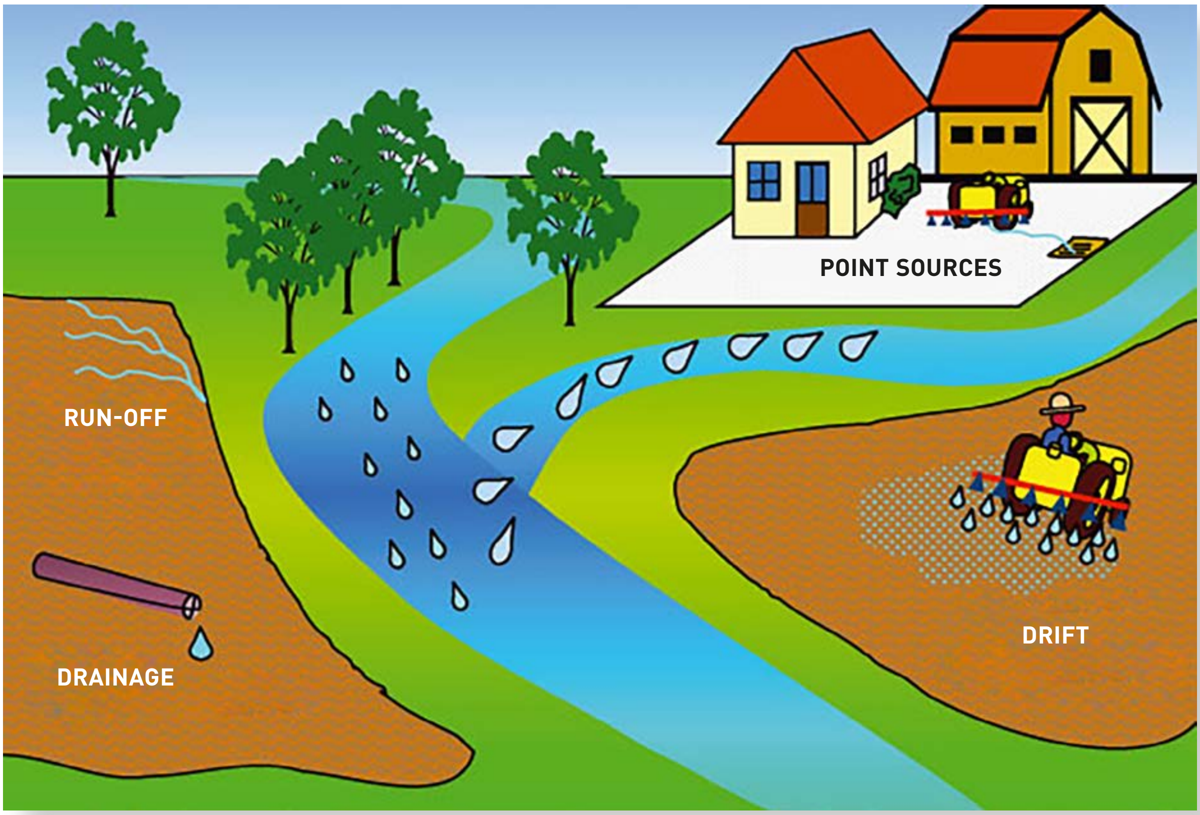


Chapter 7

Horticulture and pollution

7.1. SOURCES OF WATER POLLUTION

The previous Chapter addressed water quality, and explained why high quality water is essential for irrigation and post-harvest use in horticultural production. In this chapter, horticulture is instead considered as a potential source of pollution: a sector that can be responsible for discharging pollutants into the environment. As we saw in Part 1 of this manual, agriculture is a major cause of surface and ground water degradation worldwide. In recognition of this, governments and markets are putting increased emphasis on pollution control to protect the environmental and ensure safe food. Agriculture and horticulture supply chains are increasingly having to respond by identifying and controlling sources of pollution, and providing evidence of responsible practices.



On the farm, the main sources of pollution are:

1. **Runoff and drainage water:** Water used for irrigation will evapotranspire, run off, or drain. Farm runoff and drainage water are in contact with soil and plants, carrying with them pollutants that may be present in the field such as salts, nutrients, pesticides, pathogens and sediment. This happens not only because water is a universal solvent, but also because water carries substances in a suspended form (e.g. sediments). Pollutants such as chemical or biological nutrients or pesticides also leach into the water.

   Runoff and drainage water, as well as all the substances they carry, will eventually end up in ground and/or surface waters. If these substances become concentrated and reach harmful levels, they can have negative impacts on the environment, wildlife, and people living or working nearby.

2. **Post-harvest wastewater** may contain high levels of disinfectants, debris, or nutrients, among others.
3. **Household water**, if untreated, may contain high levels of pathogens, debris, nutrients, salts, and many other substances used in the home such as detergents, soap, oils and fat.
4. **Spillages of hazardous substances** such as pesticides, liquid fertilizers or fuels, will either infiltrate into the soil and eventually reach groundwater, or be carried away in runoff water.
5. **Organic manure** contains nutrients such as carbon, nitrogen, and phosphorus, and may also contain contaminants such as pharmaceuticals and personal care products (PPCPs) and pathogens from both humans and animals.
6. **Sewage works** are used to treat large quantities of waste, for example in septic systems. Without proper management, they can become a source of nitrogen and phosphorus pollution.
7. **Discharge water points** may be a source for the release of pollutants from farms, industries, domestic water, or any other activity. The pollutants depend on the type of activity generating the discharge water.

7.2. WHY IT IS IMPORTANT TO MANAGE POLLUTION ON THE FARM

As will be explained in Chapter 12 ("Water Risk Assessment"), controlling the discharge of pollutants is an essential element of a farm water management plan. Irresponsible practices that give rise to pollution create risks at various levels, both for the farm and business, as well as the neighboring community.

- **Watershed risks**

A farm needs high quality water for its operations. However, a farm doesn't function in isolation, but forms part of a watershed, and controlling the release of pollutants into the environment is essential to maintain the health of the watershed as a whole. It has an impact on the quality of water available to the farm and the wider community. For example, when high loads of pathogens are discharged into the environment, this can reach water sources that are used for irrigation and household use, leading to health problems for both consumers, and for households within and downstream of the watershed.

- **Regulatory risks**

Governments and public bodies are becoming increasingly strict over the control of pollution, and new policies and regulations are being introduced around the world (e.g. NEMA in Kenya). Controlling pollution is an essential element of being a responsible business, but is also becoming mandatory to avoid legal action, fines and even, in some cases, the closure of the company.

- **Market-related risks**

International (and high-end local/regional) consumers and markets are becoming increasingly concerned about healthy and safe food, social responsibility, and environmental stewardship. Private industry standards for Good Agricultural Practice (such as GLOBALG.A.P.) include criteria that assess the safe and responsible use of water on farms, as well as waste and pollution management. From a commercial perspective, addressing environmental protection and pollution control is becoming essential in some segments to gain and maintain market access.

- **Reputational risks**

Managing pollution is an essential element of good practice in the context of corporate social responsibility. Farmers and companies increasingly need to be able to provide evidence that they are taking measures to prevent pollution, and to show that they are running a responsible business. This is important for individual farms/companies, as well as at sector level. Negative press about pollution incidents, ecosystem damage, or non-compliance with regulations resulting from the actions of one operator can affect the reputation of the entire sector.

- **Financial risks**

Optimizing the use of chemical inputs on a farm will not only help to avoid pollution, but will also reduce production costs. However, as well as being an opportunity to save money, paying pollution fines or managing pollution incidents can be very costly and represents a significant financial risk for companies.

- **Biodiversity / environmental risks**

Pollution can damage the surrounding environment, biodiversity and natural resources. As well as having a negative impact on the health and well-being of neighboring communities, it will have an indirect impact on the long-term productivity of the farm through the degradation of soil and water resources.

7.3. HOW TO PREVENT AND MANAGE POLLUTION

In order to implement appropriate water pollution control measures, potential sources of contamination need to be identified. Farm maps (developed in earlier Chapters to show water sources) can also be used to identify and locate potential sources of pollution. Linking the sources with the risk of pollution (e.g. according to farm activities, time of year, among others) can give farmers a clearer picture of their situation.

Once sources of pollution are identified, appropriate preventative and control measures can be put in place. Some examples are described in Table 1.

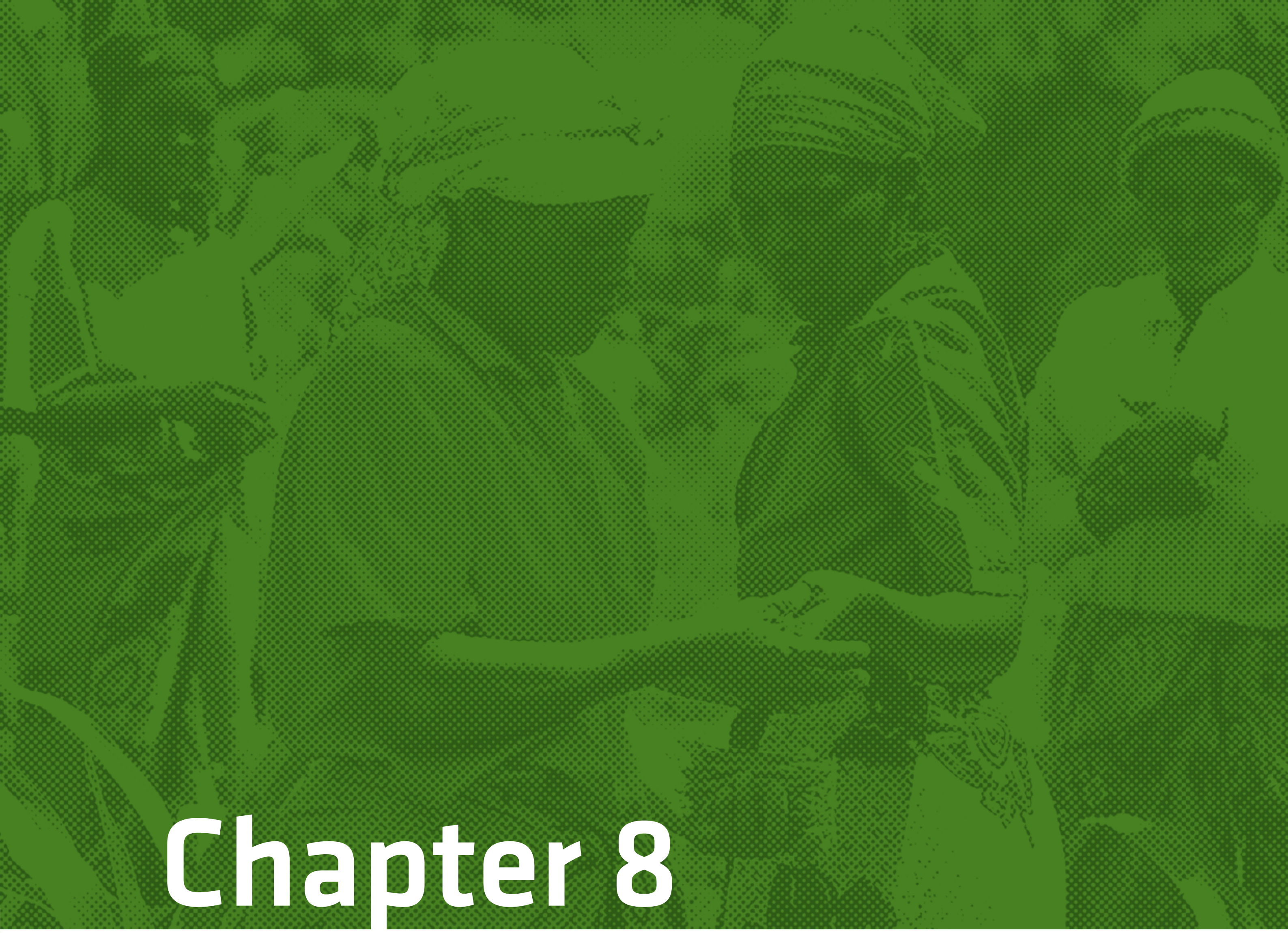
Table 1. Measures for pollution control

Control measures	Comment
Finding out about relevant regulations and bylaws	Gather information on the regulations in place governing maximum allowable concentrations of pollutants in discharged effluents. These may be set at a local, national or global level depending on the pollutant and regulatory framework in place. For example, the maximum allowable nitrate content in drinking water is 10 mg/l according to WHO guidelines.
Market requirements (GLOBALG.A.P.)	GLOBALG.A.P. requires waste minimization. This includes identification of waste sources on the farm, and development of a pollution action plan. Guidance is given on what should be included in the action plan. In terms of waste water, GLOBALG.A.P. requires growers to collect and dispose of waste water in a way that ensures minimum impact on the environment, health and food safety.
Sampling and analysing wastewater	Samples should be sent to a laboratory to identify any critical pollutants in water that is used on the farm. A sampling plan should be implemented to monitor their levels on a regular basis, consisting of: a) identification of waste water sources b) sampling interval and c) water quality indicators to be assessed. This forms an integral part of the water risk analysis presented in Chapter 11.
Identification of waste and pollutants	List all the possible sources of pollution on the farm (e.g. excess fertilizer, pesticides, cleaning products, pathogens in irrigation water, etc.)
Pollution prevention plan	Prepare a pollution reduction plan. For example: Apply only the amount of fertilizers and pesticides actually needed by the crop. Use integrated pest management practices COLEACP, Training Manual, Integrated management of bioagressors. Use nutrient management planning and practices, as described in Part 1 Section 4.4 of this manual.

Incident management plan	Records (see Chapter 14) should be kept of any pollution incident to help identify high risk points on the farm. Farms should also compile an action plan describing what should be done in the immediate and longer-term if they experience a pollution incident, such as spillage of a dangerous substance. In areas identified as high risk, farms can take precautions to minimize the impact of a possible pollution incident. For example, an earth or debris bund built around a settling pond would contain the spread of contaminated water in the event of a breach. If there is a spillage of fuel, oils, fertilizers or pesticides, to prevent the pollutant from spreading, the area around the spillage should be closed off with bunds to decrease any runoff into surface water, or seepage into groundwater. Pollution incidents should always be reported to the authorities. They should also be followed up with testing of the affected area (soil and water) to determine the level of any remaining contamination. This will indicate if any additional mitigation measures are needed, and identify any potential risks from using the affected soil or water.
Recycling water	Water recycling and re-use practices (see Chapter 4) can help to reduce effluents and potential pollution.
Treat effluents	Farms could consider the possibility of introducing wastewater treatment, for example, using septic tanks and stabilization ponds (see Chapters 4 and 6).

Managing pollution on a farm

- Can you list the potential sources of water pollution on the farm (resulting from production, irrigation, postharvest and domestic activities)?
- Do you know the type of pollutants from these sources?
- Do you take samples to check the levels of pollutants in water from these sources? How?
- Are you already treating the pollution that is coming from these sources? If yes, how? If not, how could you go about treating the pollution?
- Has the farm experienced any pollution incidents? Is there a plan to manage possible pollution incidents?
- Does you keep records of any pollution incidents on the farm?
- What is the nearest place to the farm where water samples could be sent for analysis? Is this laboratory certified?
- Are you aware of the local regulations (laws) on permitted levels of pollutants in discharged effluents?
- Do you have a plan to address waste water minimization (for example, as required by GLOBALG.A.P.)?
- Does the farm have a pollution management plan? If yes, does this specifically address water? If not, this aspect could be developed as part of the overall water management plan (Chapter 13).



Chapter 8

Irrigation

8.1. INTRODUCTION

As any farmer knows, the aim of irrigation is to fulfil crop water requirements when there is insufficient rainfall for optimal crop growth. Irrigation has been practiced for centuries, but today, with big strides in research and technology development, opportunities are opening up as never before to improve water use efficiency by adopting smart and appropriate irrigation methods.

As in the case of agriculture in general, irrigation uses different practices and systems around the world. Topography has a big influence, as does soil type, water source, climatic conditions, and crop. Depending on all of these factors, and taking into account economic viability and feasibility, choosing an appropriate irrigation method, and managing it well, are among the most important elements of responsible water use.

8.2. TYPES OF IRRIGATION

Recent improvements in technology now provide farmers with a wide range of options so that they can find the most efficient and appropriate method for their needs.

As explained in Part 1 Chapter 5, irrigation methods can be roughly grouped into:

- Surface gravity irrigation, based on the principle of using soils as a conduit, and gravity as a conductor.
- Pressurized irrigation, based on the use of devices to apply water under pressure through pipes and hose systems.

8.2.1. Surface gravity irrigation systems

- **Basin/flood**

  This involves the application of water onto relatively flat land, where it spreads uniformly and is contained (preventing runoff) by surrounding dykes. The system can be used for many crops and requires little labor for its management. The main limitation is that it is only suitable for flat fields and soil types with medium to low infiltration rates, and medium to fine textures. In some cases it can also be used in terraces. This system is used for example in banana, tobacco, or in the early growth stage of citrus, as well as for horticulture, where loamy soils are preferred.

- **Border**

  This also requires surrounding dykes; the difference is that in this case the aim is not to contain the water, but to release it at one (slightly elevated) side of a field, and allow it to spread uniformly across. It is important to have some understanding of the extent to which water infiltrates the soil in order to apply the correct amount of water, and avoid over or under irrigation.

- **Furrow**

  This involves digging furrows or trenches between crop rows, and releasing water so that it flows down the furrows by gravity, wetting the soil. This method is more flexible, as water can be applied and controlled individually along each furrow. It requires smooth slopes and is suitable for most crops.

- **The quarter time rule**

  The quarter time rule is a 'rule of thumb' commonly used in surface gravity irrigation systems. It says that the stream size applied to irrigate a field should be large enough for the water to reach the end of the field (in border or furrow irrigation) or for the water to cover the entire field (in the case of basin irrigation) in a quarter of the time needed to fill the root zone with sufficient water.

8.2.2. Pressurized irrigation systems

- **Sprinkler**

  With a system of hoses and sprinklers, this method aims to simulate rain. It is flexible and suitable for most crops and soils, and, it is more efficient than surface irrigation systems as it produces less water losses through runoff or deep percolation. In hot climates, this system can be a major cause of hard pans and problems with soil structure.

Figure 1 - Sprinkler irrigation in South Africa. Source: National Geographic

- **Drip**

  A drip irrigation system consists of hoses, valves and emitters that apply water at specific points in the fields, delivering water directly to the base of the plant. The system can be placed on the soil surface or underground (subsurface drip). Its adaptability to all surfaces and crops is very high. It is also the best option in terms of water use efficiency.

Figure 2 - Drip Irrigation system
Source: www.farmsolutionsafrica.com

- **Mixed Systems**

  Many smallholder irrigation systems use gravity feed, but are distributed using pipes and drip irrigation. In this case the pressure is given by gravity, not from an external power source. Figure 3 shows an example of a combined gravity-pressure irrigation system.

Figure 3 - Irrigation system in Africa using a bucket as a water reservoir and simple plastic hoses for distribution (Standish, 2009 and Infonet-biovision 2010)

8.3. THE PROS AND CONS OF DIFFERENT IRRIGATION SYSTEMS

As mentioned, many factors influence the choice of irrigation method, and the systems vary considerably in terms of their complexity, cost and benefits.

Surface gravity systems are low technology, low maintenance, and often the most achievable and accessible in low input smallholder farming systems. However, they also tend to be the least efficient in terms of water use. Furrow irrigation allows some degree of control of the water applied but, in general, in all gravity systems, it is difficult to apply the amount of water actually needed with any degree of accuracy, or to avoid wastage. As a very general comparison, surface irrigation has an efficiency of around 50%, sprinkler 70%, and drip irrigation 90% (though there are exceptions to this rule).

Given these limitations with surface gravity systems, it is particularly important to be able to plan and implement a sound water scheduling plan. There are ways to make it more efficient, especially if soil and crop characteristics are known. Efficiency of these low technology systems can also be improved if the water is recycled, though this requires some investment in infrastructure.

Pressurized irrigation systems are far more efficient, and drip irrigation is best of all in terms of enabling as much as possible of the water delivered to actually reach and be used by the crop. Little water is lost to drainage, runoff or evapotranspiration. There are clear advantages in terms of water use efficiency, and all the associated benefits described earlier. There are also significant benefits in terms of general crop and soil management and productivity. With the higher degree of control provided by the pressurized systems, it becomes possible to ensure that the crop receives sufficient water at the right time for optimum crop growth, but avoids applying too much water so that valuable (and expensive) nutrients are lost to runoff and leaching.

Weighing against these benefits are the high cost of pressurized compared to gravity feed systems. This is in terms of the investment to purchase and install the pipes, pumps, sprinkler systems etc., as well as the ongoing costs of running and maintenance. Also, a greater degree of technical knowledge and skill is required to operate and maintain the systems. This is in contrast to gravity feed systems, which at field level can be installed and operated with minimal expenditure.

The main characteristics of different irrigation systems are summarized in Table 1.

Table 1. Irrigation methods and characteristics

Method			Water use efficiency (%)	Topography	Suitability according to soil type	Cost of installation, infrastruc-ture and fuel	Labor for operation and maintenance
Gravity	Surface	Basin	60-65	Flat land	Fine texture, low/ medium infiltration rate	Low	Med-high
		Border		Gently sloping field			
		Furrow		Sloping fields			
Pressurized	Sprinkler		80-87.5	Medium	Medium/ high infiltration rate	Med-high	Medium
	Drip		95	High	Medium/ high infiltration rate	High	Low

Choosing an appropriate irrigation system means taking into account many factors including crop, climate, soil type, water availability and source, topography, labor availability and technical capacity, among others.

Of overriding importance, however, is the business case for the individual farm or enterprise. This is especially the case for the more expensive pressurized drip and sprinkler irrigation systems.

In terms of selecting an irrigation system on the basis of crop:

- surface irrigation can be used for all crops;
- sprinkler and drip irrigation are mostly used for high value crops because of the economic investment required;
- drip irrigation is especially used for watering individual plants and crops that grow in rows such as vegetables, strawberries.

Table 2. Overview of factors and the most recommended irrigation method for each case (adapted from FAO, 1988)

Factors			Recommended method	Comments
Natural conditions	Soil type	Low infiltration rate	Surface	Surface irrigation works better in low infiltration rate soils, whereas sprinkler and drip methods are suitable for high infiltration rates
		High infiltration rate	Sprinkler/drip	
	Slopes	Irregular	Drip	Flat slopes are suitable for surface irrigation methods. Also in higher slopes by building terraces. Drip irrigation is more flexible for irregular surfaces
		Flat	Surface/ sprinkler	
	Climate	Rainy	Surface	For dry areas, sprinklers or drip irrigation are more water efficient. In windy areas, sprinklers are not recommended
		Dry	Sprinkler/drip	
		Windy	Surface/drip	
	Water availability	Constant	Surface	In areas with reliable water sources, surface irrigation is adequate. In water scarce or seasonal regions sprinklers or drip are recommended
		Seasonal	Surface/ sprinkler	
		Scarcity	Sprinkler/drip	
	Water quality	Salty	Sprinkler/drip	Salty waters are easily dissolved through sprinklers, but if water is high in sediments, they are not recommended as they can clog emitters
		High in sediments	Surface	
Type of crop	High value crops		Sprinkler/drip	As drip or sprinkler irrigation are more efficient, high value crops such as fruit trees or vegetables are suitable to cover the costs. For individual trees or vegetables, drip irrigation is recommended. Sprinkler irrigation is commonly used for seed germination and ground cover establishment for crops like lettuce or alfalfa. Surface irrigation is suitable for most types of crops, bur preferably for close growing crops like rice.
	Individual plants or trees (vegetables, sugar cane…)		Drip	
	Seed germination and groundcover establishment		Sprinkler	
	Close growing crops		Surface	

Technology	Strong technological knowledge	Sprinkler/drip	Sprinkler or drip irrigation require higher level of complex technology, and people able to use and maintain the equipment. They also need a permanent energy supply. Surface irrigation requires less technology but more labor for construction and maintenance
	Regular energy supply	Sprinkler/drip	
	Availability of labor	Surface	
	Low maintenance	Surface	
Tradition and culture in irrigation	Introducing a new and unknown method inappropriately may cause new and unexpected problems. Sometimes farmers are reluctant to accept the new method until it really shows results. It is sometimes easier and more logical to improve traditional irrigation methods than to introduce a totally new method.		
Economics	Costs and benefits	Higher costs in drip irrigation systems, but also high benefit possibilities	Irrigation and energy efficiency, type of sprinklers or drip irrigation systems, material, operation costs, human resources costs and market variations of crops have a strong influence in this analysis. A cost/benefits analysis must be done in detail, studying all possible options and having the most recent data on prices and markets.
	Labor inputs	More human labor required for construction and maintenance for surface irrigation methods	

8.4. HOW TO INCREASE IRRIGATION EFFICIENCY

Optimum water use efficiency relies on combining an appropriate irrigation system with a good irrigation management plan. This takes into account the amount and frequency of water available, crop water requirements, and the optimization of water use through agricultural practices that increase soil water retention.

Once an appropriate irrigation method is in place, there are numerous ways to improve, maintain and increase water use efficiency, and reduce waste. This requires rigor and discipline by the farmer to apply good practice during operation of the system. Some examples of good irrigation practice are outlined in Table 3.

Table 3. Low- and hi-tech good practice to increase water use efficiency in irrigation

Low-tech options	• Know the farm in terms of climatic conditions, surface area, topography, and soil type, and adopt (as far as possible) an irrigation system that is appropriate. • Have a maintenance plan. It is essential to maintain all irrigation infrastructure in good condition. This includes regular checking, cleaning, and repairing of damage to dykes, canals, pipes, pumps, sprinklers, etc.). For sprinkler or drip irrigation, regular and careful maintenance is critical as these contain delicate and calibrated equipment. • Drainage system. Monitor and maintain the drainage system to avoid problems such as salinization or groundwater depletion. • Irrigation scheduling: develop an irrigation plan according to crop water needs. • Increase soil water retention (see Chapter 11 for guidance). • Use water storage when possible (see Chapter 3 for guidance). • Use the Quarter Time Rule: In furrow irrigation, the stream size should be large enough to cover the entire field in a quarter of the time needed to fill the root zone with water.
Hi-tech practices	• Laser Land levelers (LLL) can be found in the market at a range of prices depending on size. Farmers can group together to split the cost and share the use of the LLL equipment. • Advanced irrigation techniques. For high value crops, consider investing in modern drip micro-irrigation to achieve high levels of efficiency in the use of water • Computer technologies. Modern IT software such as CROPWAT can help improve irrigation scheduling, and GIS (Geographic Information Systems) can be used to map the area accurately and improve irrigation planning.

8.5. IRRIGATION MANAGEMENT PLAN

The objective of an irrigation management plan as outlined in Part 1, Chapter 6 is to:

- minimize water loss and maximize yields with the available water;
- manage drainage water and salinity;
- minimize negative environmental and social impacts.

An irrigation management plan should be integral part of the farm water management plan (see Chapter 13). Below is a list of headings and topics that the plan should include. It should be completed with an action plan that lists time-bound activities.

8.5.1. Basic details about the irrigation system (see Part 1, Chapter 5)

- Is the farm is part of an irrigation scheme? If yes, describe how the management, operation and maintenance of the scheme is organized, and the involvement of the farm in this. Provide a map of the scheme and the location of the farm/fields within it.
- Describe the irrigation system currently used (gravity, flood, basin, furrow, pressurized drip, sprinkler, other).
- Describe the operation and maintenance activities carried out on the irrigation system.
- Map the sources of water used for irrigation (see Section 2.2).
- List any concerns about water quality and availability (Section 2.3).
- Provide an estimate of water use (Section 2.4).
- Describe the soil types, and any potential issues affecting irrigation and drainage (Section 11.2).
- List the crops that are irrigated, and the irrigation requirements (IR) of each crop over the course of the year. Document crop yields and value.
- Assess if the irrigation water received is sufficient to meet total irrigation requirements. In other words, calculate an irrigation water balance (the difference between irrigation water coming into the farm and irrigation requirements of all crops).

8.5.2. Efficient transport of water (See Part 1 Section 6.2.2)

- Describe how irrigation water is transported from the source to the crop.
- Consider the volume of water lost during transport (including evaporation from a canal, or seepage into the ground, or leaking pipes). If measurements can be taken of the volume of water extracted from the source, and the volume reaching the field, they can be used to calculate the Conveyance Efficiency (ec: the ratio of water reaching the field divided by water taken from the source).
- Describe any actions taken to improve transport efficiency. For example, regular checking and maintenance of pipes and joints; inspections for leaks; removal of blockages and debris from canals; maintenance of canals; lining or covering canals to decrease seepage and evaporation.
- Is the conveyance infrastructure (canal, pipe) is used by others as well. If yes, describe how water users work together to implement actions (e.g. through an irrigation water user association).
- Are records kept of volumes abstracted and volumes reaching the field? If not, consider including measurements and record keeping in the action plan (Chapter 14).

8.5.3. Efficient and productive use of irrigation water (Part 1, Section 6.2.3)

- Describe the method(s) used to determine when to irrigate the different crops during the growing season. (For example, by estimating/measuring soil moisture content, and/or by observation of the crop). Include details of any equipment or method used (e.g. look and feel method, tensiometer, gypsum block, root zone depletion based on modelled evaporation and rainfall, CROPWAT, other). Explain if climate data is used to plan irrigation timing and volumes. Are there any problems with the quality of irrigation water? If yes, what problems, and what can be done about it?

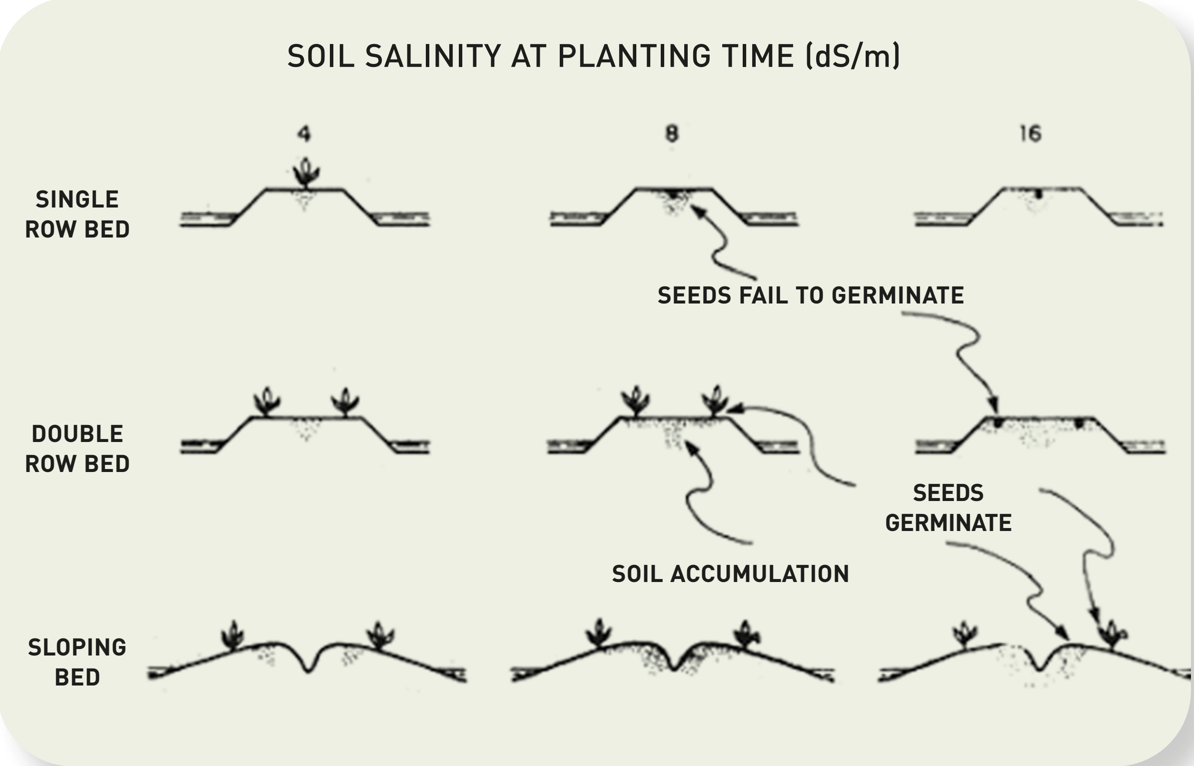
- Record the amount of water used for irrigation and the volume used by the crop (Crop water requirement, see Part 1 Section 3.2). Use this to calculate the field application efficiency (ea) = amount of water used by the crop divided by amount of water applied. For surface irrigation, the ea is approx. 60%; sprinkler and drip can reach an ea of 70-90%).
- Describe any practices used to increase the efficiency of field level irrigation. This could include, for example, conservation tillage, cover crops, windbreaks, improved soil water holding capacity, other agricultural practices.
- Assess the business case for increasing water use efficiency (see Chapter 10). Savings in the amount (cost) of water used and increased productivity (yield) need to be set against the costs of installing and running more water-efficient infrastructure.

8.5.4. Managing drainage and salinity (Part 1, Section 6.3)

- Is drainage currently included in the farm irrigation management? If not, is it needed? Does water run off the fields during or after irrigation? Is the groundwater table rising? Is there any indication that salinity in soils and water is increasing? Has this been measured, or observed (e.g. salt crusts on the soil)? These all indicate that improved drainage may be required.
- Consider the different types of drainage that may be put in place:[277]
    - Surface drainage systems - these can be relatively simple structures such as dug out field drains
    - Subsurface systems using a network of pipe drains
- Describe if drainage water from fields is (or could be) captured, and how.
- Assess if drainage water could be reused. This includes checking if the levels of salts are acceptable for the crops cultivated.[278]
- Assess if and where the drainage water could be stored, and how it could be transported for re-use.
- Assess if salinity (EC) of the soil and irrigation water is suitable for the crops grown. Electrical conductivity (EC) is good indicator of salinity and can be measured using an EC meter. An EC lower than 0.7 dS/m gives good yield potential for most crops; but most crops display severe yield reduction if water is applied with a dS/m of more than 3.0.

277 Information on the components of drainage system and technical design can be found on www.fao.org/3/a-ai587e/ai587e01.pdf.

278 www.fao.org/DOCReP/003/T0234e/T0234E03.htm gives a good overview of the tolerance of different crops to salinity in soil and irrigation water.



- If salinity is too high, calculate the Leaching Fraction required to flush the salts. The leaching fraction depends on the salinity of the soil and the irrigation water. It can be estimated by:[279]

LEACHING FRACTION =
(ELECTRICAL CONDUCTIVITY OF IRRIGATION WATER/
PERMISSIBLE ELECTRICAL CONDUCTIVITY IN THE SOIL)
X 100%.

- If water harvesting takes place on the farm, this can be used to dilute the salinity of irrigation water.

8.5.5. Minimising negative environmental and social impacts

- Consider any environmental impacts from the farm irrigation system and water use. For example, water quality and availability to downstream users, environmental water requirements to sustain biodiversity.

279 If soil EC is higher than the permissible EC, a different equation should be used, for this see: www.publications.qld.gov.au/en/dataset/salinity-management-handbook/resource/529b12b0-8e23-4cd3-a1cd-7659d0b9b3b4.

- If the farm or business intends to make changes to their irrigation system or infrastructure, check if local environment regulations or bylaws require an Environmental and Social Impact assessment prior to implementation.
- Check for any pollution problems associated with irrigation water use, such as runoff of nutrients, pesticides, sediments, and other pollutants (see Chapter 7).
- Describe any actions taken to mitigate environmental and social impacts

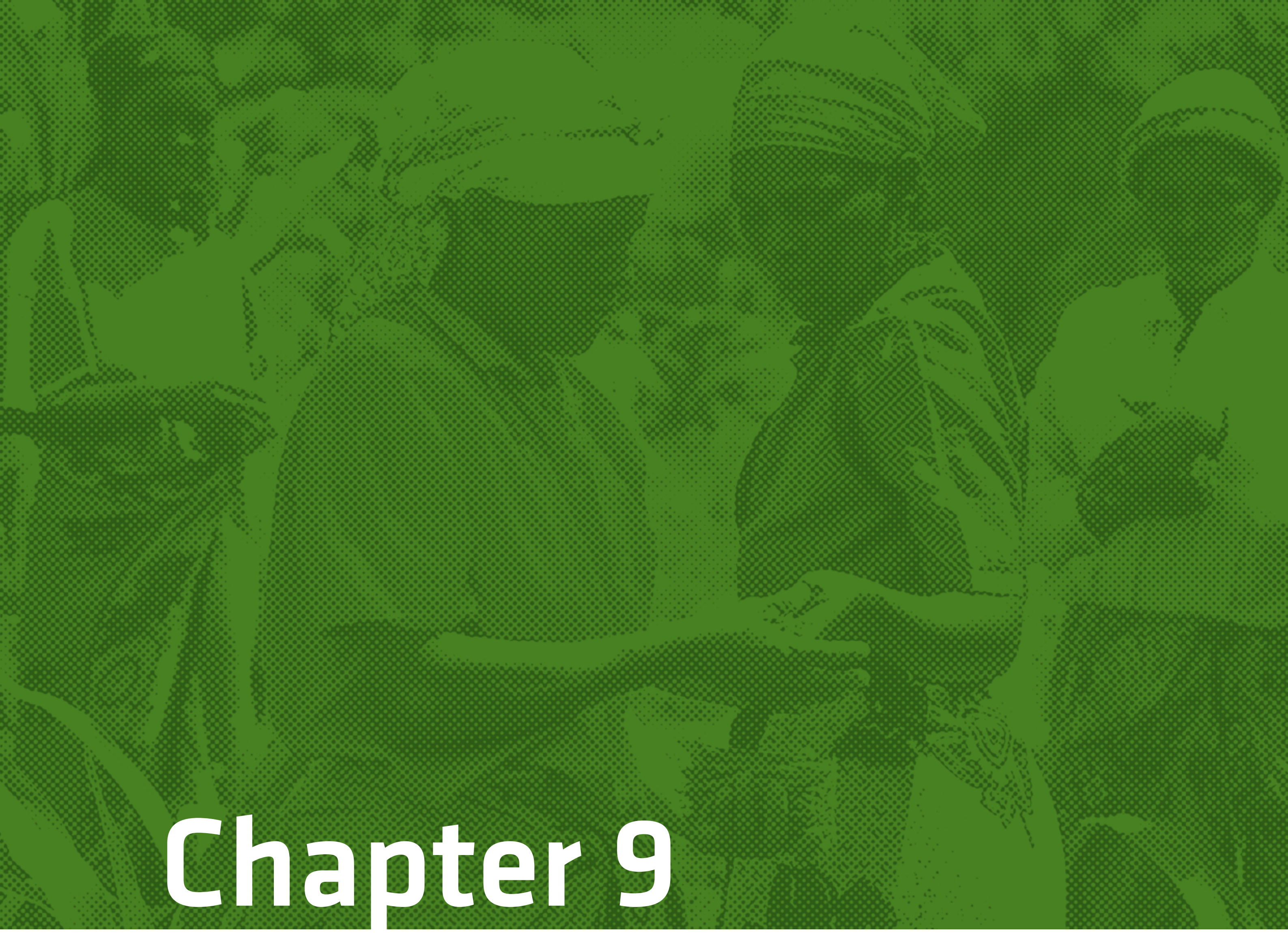
8.5.6. Monitoring and review

- Monitoring of the irrigation management plan should be done to assess if it is being successfully implemented.
- The irrigation management plan should be reviewed annually in terms of outcomes, in particular concerning:
  a. efficient and productive irrigation;
  b. drainage and salinity; and
  c. environmental and social impacts.
- Data collected on the irrigation system, in particular on water volumes abstracted and used, will provide a baseline to plan and improve irrigation management. A record keeping system should be part of the action plan (see Chapter 14 Record Keeping).

Managing irrigation

- Can you list the main elements of the irrigation system on your farm (water transport, irrigation scheme, irrigation type, drainage…)?
- Do you maintain the irrigation system and related infrastructure and equipment in good condition?
- Can you list actions you could take to improve the irrigation system?
- Does the farm have an irrigation management plan?
- Can you list the elements that should be included in an irrigation management plan?
- Do you know how to prepare an irrigation water balance for the farm?

PERSONAL NOTES



Chapter 9

On farm climate data

9.1. CLIMATIC FACTORS

9.1.1. What climate factors are important

If there is one nearby that can be reached easily or has easily accessible records, farmers can use data from the nearest weather station. Alternatively, other sources of climate information generally include TV, radio, newspapers, or mobile weather data providers like aWhere (www.awhere.com).

Farmers can also use simple methods to make their own measurements of the most important climate factors including:

- **Precipitation (Rainfall)**

  Precipitation is the most crucial climatic factor to measure. Rainfall determines how much water the crop is obtaining naturally. Knowing the rainfall will help the farmer assess how much additional water is required for irrigation. Knowing precipitation with precision will also help the farmer to evaluate his/her potential to harvest rainwater.

- **Temperature**

  This factor is also of considerable importance as temperature influences all plant growth processes in relation to water. For example, water absorption is inhibited when temperatures are low in the soil because water is less mobile and more viscous at low temperatures. Photosynthesis, respiration, evaporation, transpiration, seed germination, protein synthesis, and translocation are all influenced by temperature.

- **Wind**

  Wind has a direct influence on the level of evapotranspiration. Strong winds can cause excessive water loss through transpiration and also lodging or toppling of plants. This may result in a decrease in the rate of photosynthesis, growth and yield. Additionally, if sprinkler irrigation is used, wind is an essential parameter to take into account as it will affect the spread of the water onto the crop.

- **Light**

  Light (sunshine hours) and water determine production of chlorophyll and photosynthesis. Both the duration and intensity of sunshine (solar radiation) affect the level of energy available to the plant for growth.

- **Humidity**

  Humidity (the amount of water in the air) affects turgor pressure (see Part 1 Chapter 2), which is an indicator of the amount of water inside plant cells (or, more correctly, water flow in and out of plant cells). In dry conditions when humidity is low, moisture evaporates quickly; plants therefore lose water, decreasing turgidity, and causing them to wilt. This will decrease productivity and yield if plants suffer prolonged or extreme wilting.

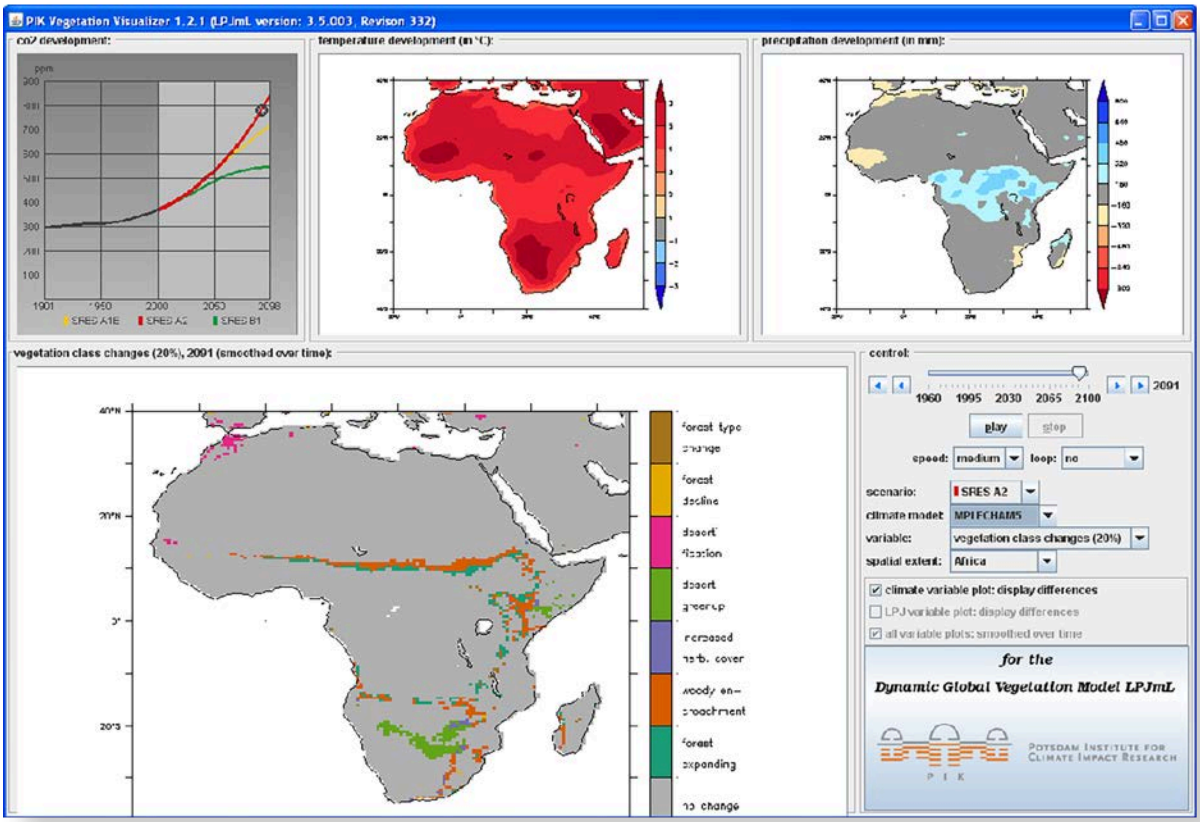
  When humidity is high the rate of transpiration (and plant water loss) goes down, thus increasing turgidity. This may lead to the overheating of plants in extreme cases. It is also important to take into account as it can affect the onset of different plant diseases.

9.2. WHY RECORDING CLIMATE DATA IS IMPORTANT

9.2.1. Key criteria

- Rainfall, solar radiation (and number of hours of sun), temperature, relative humidity and wind speed are the main climatic factors influencing crop evapotranspiration. To prepare a detailed irrigation schedule, these factors need to be measured on a daily basis to estimate crop evapotranspiration, and therefore irrigation water needs, with any precision.
- Measuring rainfall in combination with soil water content will indicate how a crop uses water. This will provide a baseline to plan all water-related activities (irrigation, water harvesting and recycling, drainage, etc.). Improved management of these aspects will have an impact on productivity and profitability, reduce the risks and impacts associated with climate incidents, and result in a more resilient farm.
- A good knowledge of climate data, in particular temperature and rainfall, help to plan general cropping programmes and crop husbandry. While farmers have in-depth knowledge and experience of local climatic conditions, it is becoming increasingly important for them to start keeping records so that they better understand changing climate patterns, and can assess risks related to climate change. The benefits of record keeping are further explained in Chapter 14.

- Recording exceptional climate events (e.g. drought, floods, storms) systematically is also valuable. It provides data that can be used to identify patterns or changes in local climate, and to predict trends. In the short-term this data can be valuable in the case of insurance policies, or finance applications to install flood prevention measures (such as dykes) and water harvesting facilities (for example).
- In the long-term, on-farm precipitation and temperature data provide evidence of climate change, helping to guide future farm planning. For example, the size of rainwater storage tanks can be better adapted and designed if they take into account rainfall patterns and trends.

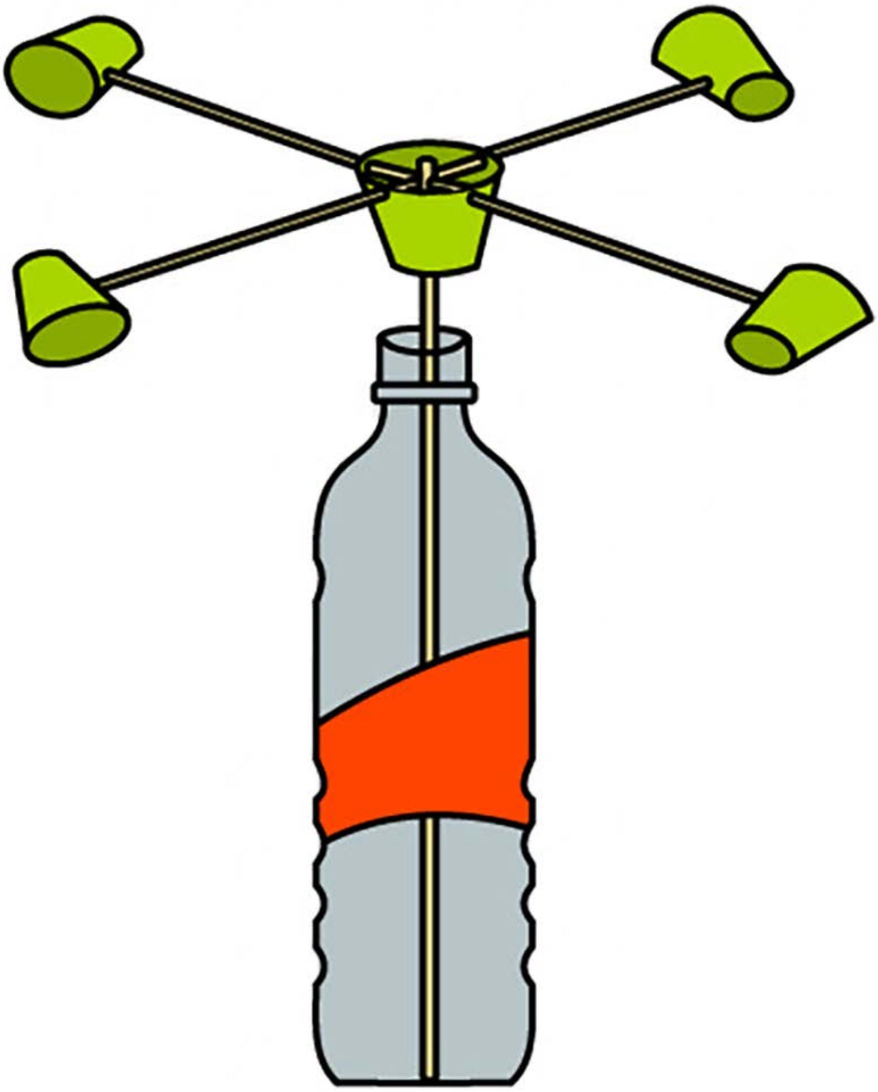


9.3. HOW TO RECORD AND USE CLIMATE DATA

9.3.1. Methods and equipment

Table 1. Low- and hi- technology practices and tools to record climatic data

Low-tech	• **Rain gauges**: These are simple vessels to collect and measure rainfall, and to calculate rainfall in mm (1 mm = 1 litre of water per 1 m^2). Gauges are normally cylindrical, with marks showing the water level. They have to be monitored and recorded daily in order to monitor rainfall over a period of time. After recording the data, they must be emptied each time. A basic rain gauge can be made in an artisanal way with a 2 litre soda plastic bottle with flat bottom and uniform vertical shape; measures are marked by placing a ruler vertically on the side (Note: always fill the bottle with water up to the zero mark of the scale). The bottle is then placed it in a clear open space. An example of a basic rain gauge is shown below:  A simple rain gauge made from a plastic bottle *Source:* rainwaterharvesting.wordpress.com/2013/06/08/how-to-make-a-cheap-rain-gauge
Low-tech	• **Thermometers**: These are affordable and easy to use to measure temperature. Minimum and maximum daily temperatures should be recorded. Thermometers should be located in the shade in a well ventilated place at least 1.5 m above any surface. The thermometer should be placed so that it does not receive any direct light. It should also be placed at least 15 m away from paved surfaces as these can reflect heat.

Low-tech	• **Wind**: Basic wind meters or anemometers can also be handmade (see below), with four hemispherical cups, each mounted on a horizontal arm. The speed at which the cups rotate is proportional to the speed of the wind, so average wind speed can be calculated by counting the turns of the shaft over a set time period. A wind meter provides basic information on the strength of the wind, but also wind direction if a vane is added. To calibrate the wind meter, sit on the back of a motorbike that drives at 15km/hr and count the number of rotations the meter makes in, for example, one minute. Wind direction should also be recorded.  A simple handmade wind meter (www.education.com/science-fair/article/make-anemometer)
Low-tech	• **Wet/dry bulb hygrometer**: These can be purchased from specialist suppliers but also made using two thermometers and a small piece of wet cloth. • Record all climate data in a notebook or agenda, and use the records to chart the data over time.

Hi-tech	• **Barometers:** These record atmospheric pressure. The most advanced record data in a computer and provide a forecast of weather conditions. A rising barometer indicates sunny and dry conditions, while a falling barometer indicates stormy and wet conditions • **Computer climate models** using GIS software. Computational tools are available to help farmers add climate data to CROPWAT to give more precise water irrigation scheduling, as well as for weather forecasting • **Complete on-farm weather stations** can be installed to measure temperature, relative humidity, rainfall, wind speed and sunlight. Small portable weather stations can be acquired and shared between a group of farmers or a community

9.3.2. Keeping records

Climate records can be kept in a variety of ways, depending what resources are available. The simplest method is to record data in a note book. If a computer is available, data can be uploaded into spreadsheets or dedicated software packages, allowing data to be plotted and studied over time.

A combination of electronic and paper methods is also an option. Daily records can be recorded on paper and later put into a computer, or taken to someone who has access to a computer to process the data (see Chapter 14 for more details). Data can also be recorded and kept using online and offline smartphone applications. An example is the free and open source 'GEOodk collect' (www.geoodk.com).

9.3.3. How to use climate data

Once climate data is gathered and recorded, it can be processed an analyzed. This will allow practices such as irrigation and soil management to be adapted according to real data, rather than estimates and guesswork. For example, if data gathered shows a trend towards decreasing rainfall after a certain time, or in a particular season, decisions can be made to adapt practices accordingly, such as increasing the volume of irrigation water, changing the crop, changing planting dates, or a combination of these. Such decisions can help the farm make more efficient use of water, increase productivity and profitability, and mitigate against the effects of climate change.

How do you manage climate data?

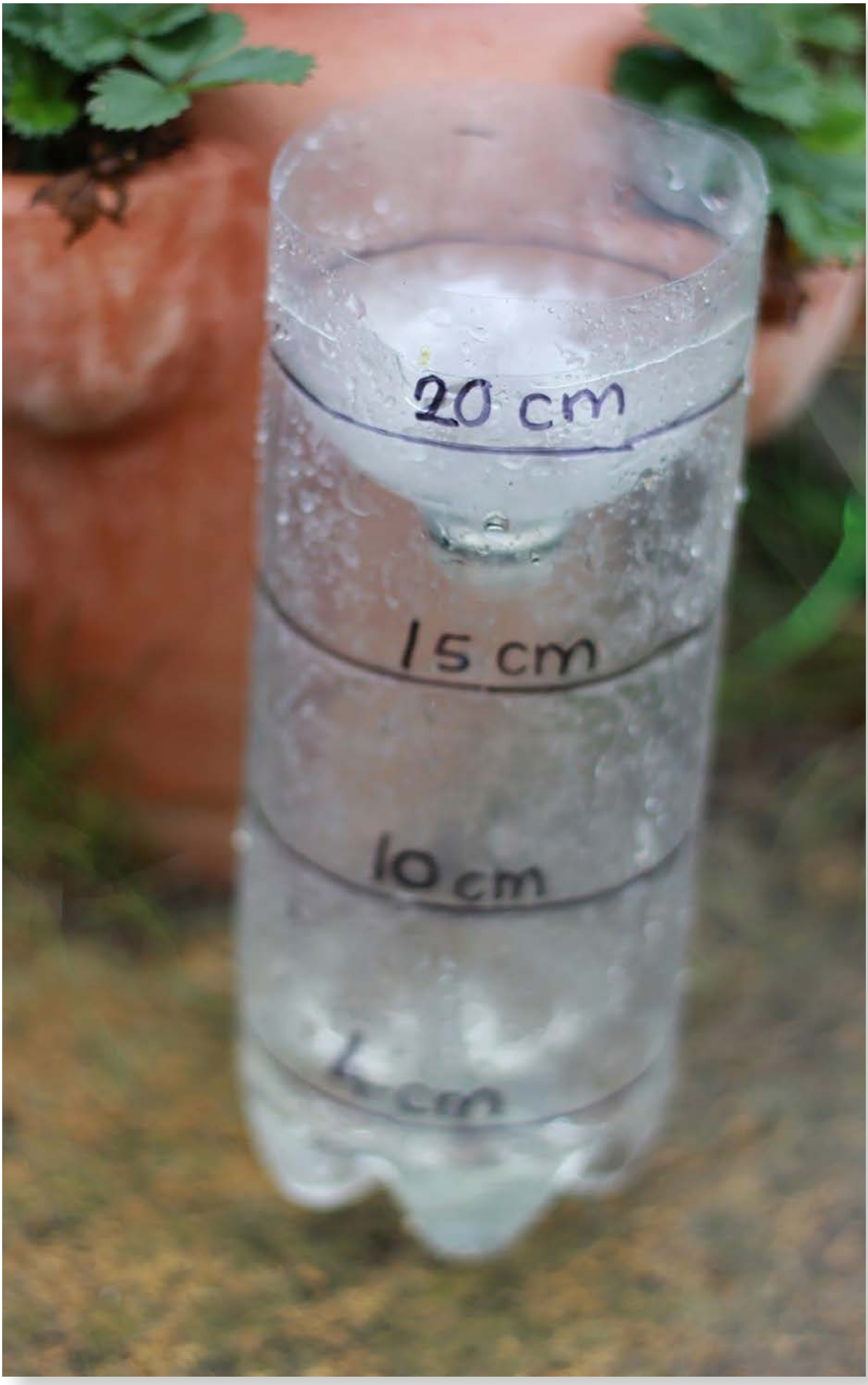
- Just from memory, list any occasions in recent years when your crop has suffered and yield was lost due to climate conditions.
- Can you describe (qualitatively) the local climate over the course of an average year?
- Do you record climate data on your farm? If yes, what information do you collect? What methods and equipment do you use?
- If not, do you know of any simple methods that can be used to measure rainfall, temperature, wind speed and humidity?
- List sources of weather forecasts that you have access to.
- Is there a weather station near your farm? Do you have contact with local weather stations? Can you access their data?
- If there is nothing available locally, would it be worth investing in a small weather station on your farm? Or could you join with neighboring farmers to install and run a weather station?
- Do you feel that the climate in your location is changing? If yes, how? Do you think this will affect your farming in the future? In what way? What can you do about it?

9.4. EXAMPLE

9.4.1. Suzan and Kioko

By thinking more about how to manage water, Susan has come to a better understanding of the topic. She now knows that not all water use is efficient and productive, both in the field for growing crops, as well as in the packhouse during grading and packing. After monitoring the different activities, it is now clear that by far the largest amount of water used on her farm is for irrigation. By recording precipitation data, she knows that she could have a more precise and better targeted irrigation schedule. There is a weather station in the village nearby, and she plans to ask for access to their climate records. She is also thinking about buying an affordable device to measure soil moisture, after seeing an advertisement in the latest horticultural fair in town. With daily information on precipitation and soil moisture, she would know with more precision how much water is needed to irrigate her crops.

Kioko builds a small rain gauge from a plastic bottle that he cuts the top off. He creates a scale next to it so that he can take daily readings and relate these to the daily average of 6 mm of water needed by his crop. Now he needs to find a way to assess the moisture content of his soil, and will ask a local trainer, who he knows can tech about some simple methods.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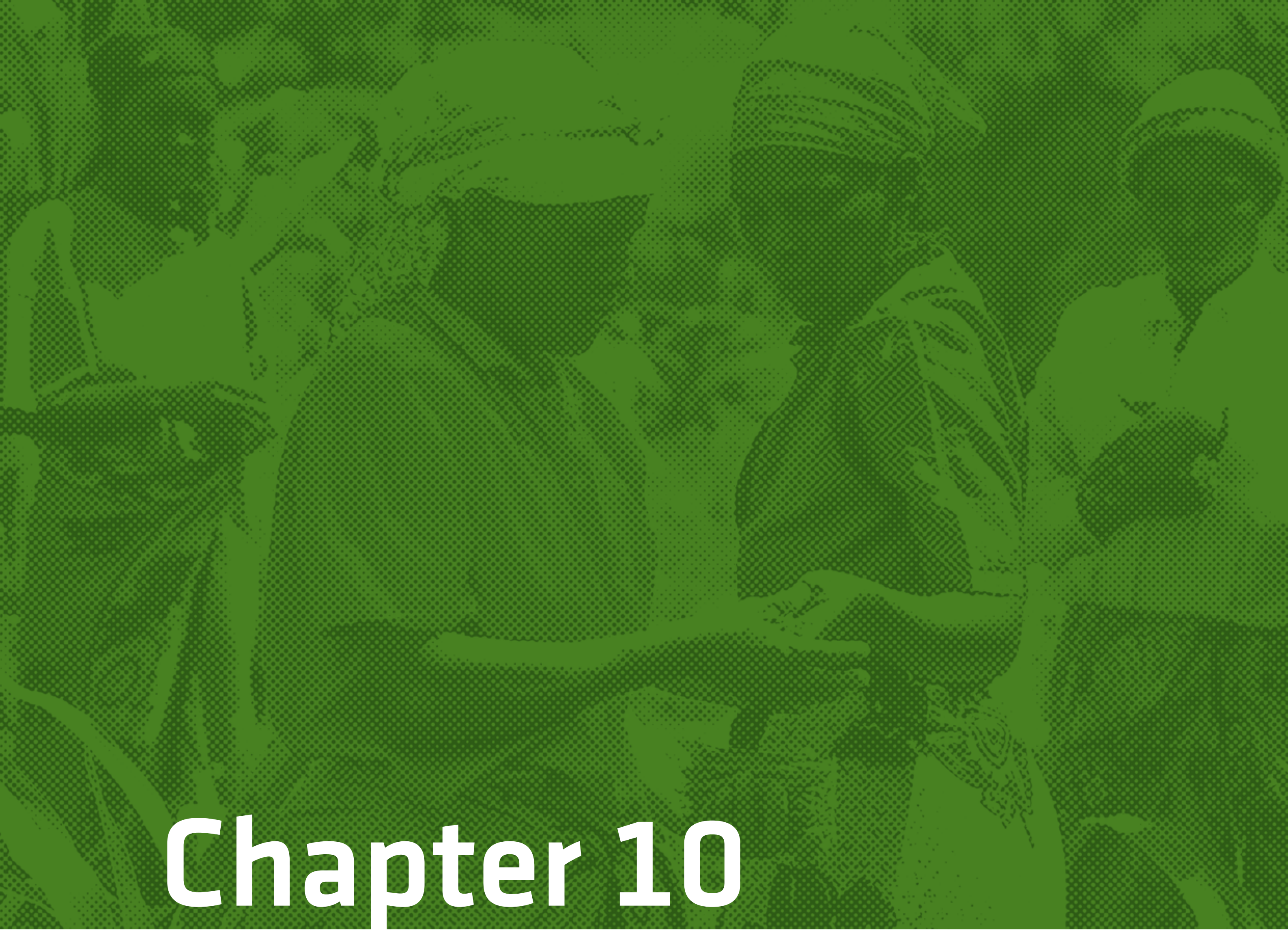


Chapter 10

Putting a price on water

10.1. PRICING WATER

10.1.1. Overview

This Chapter is about assigning a price to water. The price of water is not only the price paid for abstracting it, but also includes all the costs associated with making sure that the right quantity and quality of water reach the point of use on the farm or enterprise. These include:

- abstraction cost;
- irrigation cost;
- treatment before and after water use;
- indirect water costs.

Pricing water means putting an economic (financial) value on all of these associated activities from abstraction to pumping, infrastructure, and treating or cleaning the water before and after use.

Indirect water costs should also be included, for example, water-related administrative costs (e.g. paying membership of a water platform, paying workers for repairing canals, eco-taxes for releasing polluted waters). Values can also be assigned to any positive or negative environmental impacts, or to the potential benefits of managing water risk (e.g. avoiding losses due to water scarcity).

Once the price/cost of water is calculated, its financial value can be analyzed by comparing cost against the economic productivity (crop yield and sales) associated with its use. In short, this is the financial/monetary gain per cubic meter of water consumed.

10.2. WHY PRICE WATER IN THE HORTICULTURAL BUSINESS?

10.2.1. Objective

The objective of water pricing is to establish the business case for efficient water use, and to help enterprises identify opportunities for increasing their profitability and competitiveness through better water management.

By knowing the cost of water in financial terms, and by comparing this with the productivity of the farm per unit of water used, it is possible to translate any increase in water use efficiency into improved financial performance (and increased profit).

Increased water efficiency can increase productivity, reduce abstraction costs, and mitigate water risks. However, achieving increased water efficiency will generally involve investment in new methods, equipment and infrastructure.

Being aware of the real cost of water (which is generally significantly higher than the price actually paid for water), the farmer will have a clearer financial picture that will help to decide what and how much it is worth investing.

In the GLOBALG.A.P. Guidance Document, estimating the price of water is one of the recommended practices to manage financial risk. The following questions should be considered:

- Does the producer pay for the water usage?
- How is this price/tax/tariff fixed?
- Does the price include operational costs and (environmental) externalities?
- Is the pricing system stable, foreseeable and transparent?
- How likely it is that water prices will be increased on a regular or irregular basis?

10.3. WHY AND HOW TO PUT A PRICE ON WATER?

10.3.1. Data on the cost of managing water

The first step is to identify and add up all the costs on the farm/enterprise associated with water use. All of these costs should be calculated in terms of €/year (or relevant currency). These may include:

- cost of water abstraction rights or permits;
- cost of new pumps;
- cost of fuel for pumps;
- cost of irrigation equipment;
- cost of maintaining the irrigation and drainage systems (especially in terms of labor costs);
- cost of maintenance works for abstraction and irrigation equipment (canals, pumps, pipes or any related infrastructure);
- cost of any water treatment, before or after use;
- cost of municipal water, especially for post-harvest operations;
- cost of water-related legal procedures, if applicable;
- cost of producing a water management plan;
- cost of actions to increase water efficiency and resilience, and impact studies;
- cost of environmental externalities (these are the uncompensated costs of the environmental impacts of production, such as pollution. They are difficult to estimate and generally left out of the cost calculation. They are also often referred as "social" costs, and may result from the activities of several users within a given watershed);
- cost of taxes associated with water.

10.3.2. Estimating the price

The first step is to know how much water is abstracted and taken onto the farm, to get a figure for total cubic meters (m^3) of water/year (see Chapter 2).

Using the figure for total m^3 of water abstracted per year, and the total cost of managing water in €/year (from item 10.3.1. above), the financial cost of the water can be calculated in €/m^3.

10.3.3. The economic productivity of water

The real price of water as estimated in the previous item, in €/m^3, can be compared with the economic productivity of water, also in €/m^3.

This comparison will give the farmer clear information on the added value of water, and its importance for the financial sustainability of the business. Increased water use efficiency will improve the economic productivity of water, and can substantially reduce overall costs (and increase profit) by cutting the amount of water that is abstracted.

To estimate the economic productivity of water, the following information is needed:

- **Crop yield** in tons/ha.
- **Blue water consumed** by the crop in m^3/ha (this refers to 'consumptive blue water use': irrigation water that was taken up and evapotranspired by the crop, and did not return to the system (the watershed). Water that returned to the system (for example through runoff or drainage) is considered as a 'loss', as it was not given any productive use).
- **Blue Water Footprint** of the crop. This is calculated as the ratio between the blue water consumed by the crop (m^3/ha) and the crop yield (tons/ha). The blue water footprint of the crop is expressed in m^3/tons of blue water.
- **Crop economic productivity:** the income obtained by selling the crop. It is expressed in €/ton (or any other relevant currency).

The economic productivity of water represents the income that is generated by the farm per cubic meter of water consumed (consumed water means that it is no longer available for any other use).

This is calculated as the ratio between the crop economic productivity (€/ton) and the blue water footprint of the crop (m^3/ton). The economic productivity of water is expressed in €/m^3.

Actual and potential economic productivity will depend on the crop, irrigation, and many other agricultural practices, as described in earlier chapters. Economic productivity is evidently not only dependent on water, but on many other factors also. Thus the figure calculated for the economic productivity of water is not intended to be a complete financial analysis; it simply gives a good indication of the value of water for crop production, and considers the performance of the farming system in relation to water use.

Water pricing exercise

- Read carefully the examples provided at the end of this chapter.
- Based on the information provided in this Chapter on how to price water and how to work with the price of water, check the figures given in the examples.
- Analyse the differences between water prices and economic water productivities for both Susan and Kioko.
- Based on this analysis, what would be your recommendations be for Kioko?

Conclusions

For Susan the price of water is about 7% of her economic water productivity (and this ratio may even decrease for her after converting to greenhouse and drip irrigation).

In Kioko's, case this ratio is about 16%. Also, note that the water price calculations only include the price actually paid for the water, plus operational costs.

The major recommendation in Kioko's case is to plan irrigation more effectively by knowing when it is best to irrigate.

In the example, Susan produces French beans and estimates the price of water at 9 KES/m^3, which includes the price she pays for the water plus operational costs. She estimates the current economic productivity of water in 130 KES/m^3 (the price of water is 7% of this economic productivity), and estimates that with the investment in greenhouse and drip irrigation, she will increase it to about 300 KES/m^3.

The situation for Kioko is more complex.

Both examples demonstrate how water pricing allows the farmers to assess and demonstrate the business case for more efficient water use.

10.4. EXAMPLE

10.4.1. Suzan and Kioko

Susan is thinking of converting to greenhouse polytunnels for growing beans so that she can increase the productivity of her crop. She has understood that by using the greenhouse, together with drip irrigation, she could manage water and other inputs better. She wants to calculate the economic benefits of growing French beans in the greenhouse. She also wants to understand what her savings would be in terms of the cost of water.

Her average yield for French beans is 5 tons per acre. Last time, she sold them at 60 KES per kg. She only could sell 40% of the crop to the UK Company as the rest was damaged by the weather, and had to be sold in the local market. She made a total of 200,000 KES.

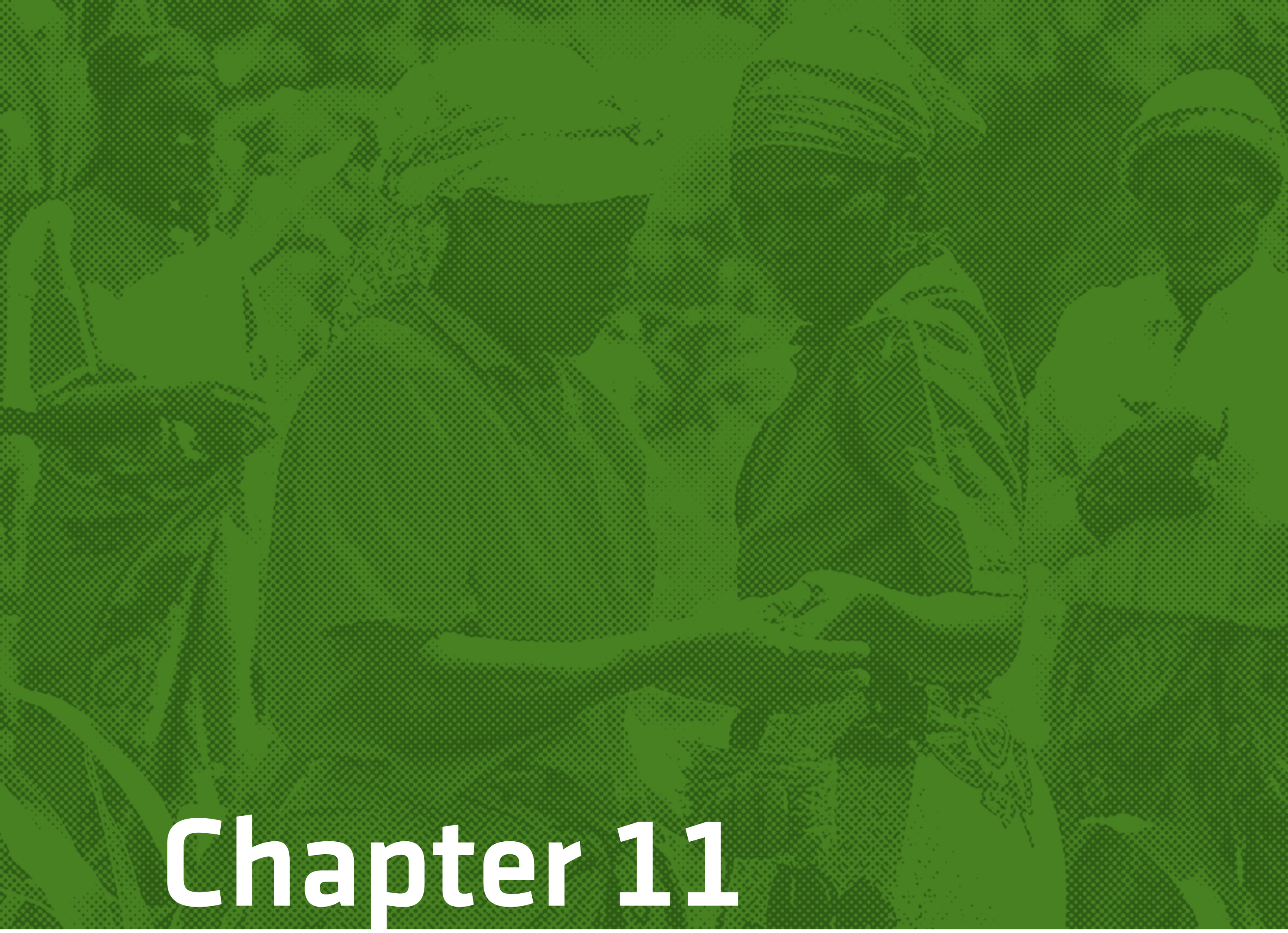
In terms of water use, in a normal field she uses about 1,500 m^3 of water per growing season. The irrigation water that she got from the canal cost about 8,000 KES. She also pumped additional water, which she estimates at another 5000 KES. This gives a total water costs of 13,000 KES, or about 9 KES/m^3. She calculates the economic water productivity of her French beans as follows: 200,000 KES/1,500 m^3 = 130 KES/m^3. Compared to other production costs, her greatest costs are farm laborers and seeds; water comes at third place.

She expects that the greenhouse will help her to increase productivity, manage the quality of her crop better, and decrease labor and water costs. She heard that the greenhouse could increase crop yield by 40% and when managed well, 98% of the crop has the quality required by UK importers. Susan also knows that by increasing water use efficiency, instead of needing 1500 m^3 for her field, she will need less, therefore increasing the economic productivity of water.

By converting to drip irrigation, water use is expected to go down by 30%. This means that she may improve her economic water productivity up to ~300 KES/m^3, as well as reducing other farm inputs. She will need to assess the cost of the greenhouse tunnels, as well as drip irrigation equipment, but she expects with this productivity increase, she will easily be able to recover the required investments.

Kioko thinks that the cost of pumping irrigation water from the spring to his tomato crop is a large part of his total production costs. If he could decrease this, he could get a higher income from his crop. He also knows that by minimizing the cost of water, he could perhaps increase the productivity of this crop, because crop productivity and efficient use of water are strongly related.

He calculates that for fuel and hire of the pump, he spent about 20,000 KES for 1,440 m^3 of water last year. This is a cost of about 15 KES/m^3. His tomato crop yielded barely 4 tons. He sold his crop at around 120,000 KES. He calculates the economic water productivity by 120,000/1,440 = ~83 KES/m^3 and realizes that the water cost is about 1/6th of his total revenue. He feels this is way too high. He decides that he needs to improve his yields while using less water to earn more from his hard work.



Chapter 11

Soil management for water retention

11.1. WHY MANAGING SOIL TO INCREASE ITS WATER-HOLDING CAPACITY?

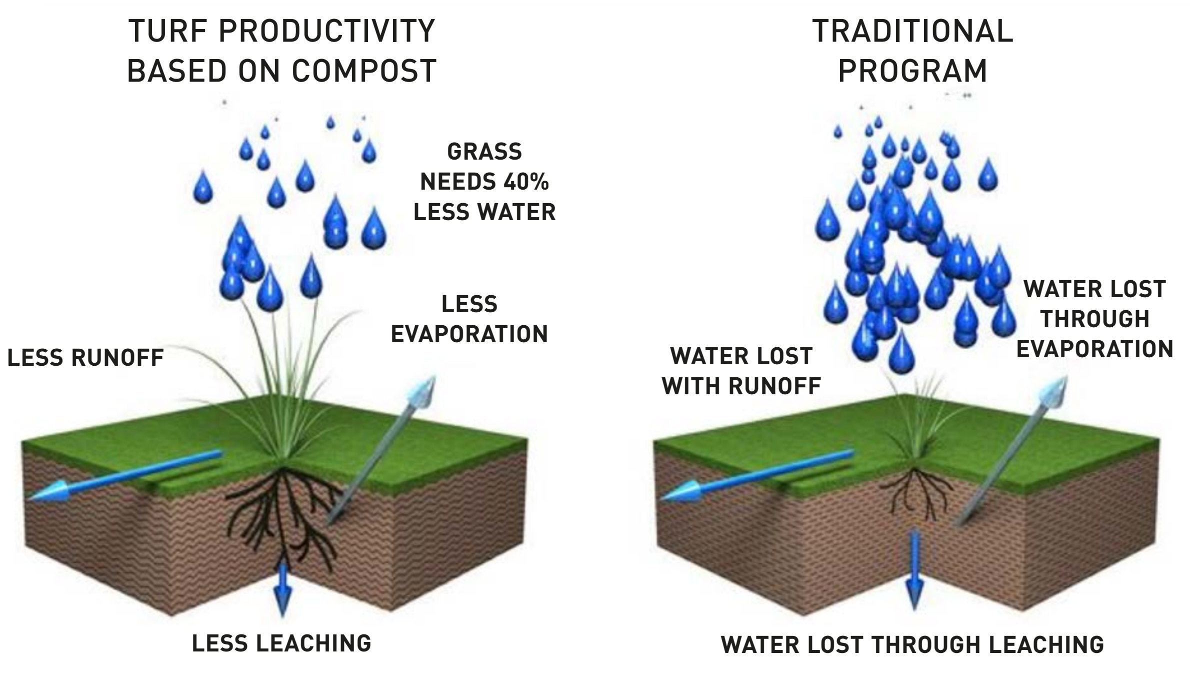
11.1.1. Overview

In previous Chapters we have seen the importance of managing water to increase productivity and profitability, improve climate-resilience, and limit dependency on external water sources. A key elements to achieving effective management and use of water is the soil; indirectly, the condition (health) of the soil affects the way in which water is captured, retained, and available for crop growth.

A healthy soil:

- is fertile, with the right balance of organic matter and nutrients;
- has a loose structure, with adequate aeration;
- has strong and diverse populations of soil organisms including microbes;
- can retain sufficient water so that it is readily available to the crop.

How well a soil can retain water depends on a number of factors, including soil texture both in the upper and sub-soil layers. The more permeable the top soil (e.g. sandy soils) the less water it will retain. Less permeable soils (e.g. clay and silt) may retain more water, but are associated with poorer infiltration and more runoff. In all soil types, the amount of organic matter (OM) present is a critical factor as it improves soil structure, allowing it to filter into the soil, and acting as a sponge to hold and retain it. Farmers can use a variety of techniques to increase the capacity of soil to capture and retain water.



At the same time, poor agronomic practices can damage soil health and water holding capacity. Of particular importance is the development of hard pans. These are compacted layers of soil below the surface. They restrict plant root growth and make it difficult for water, air and other gases to move through the soil. Panning causes waterlogging which, in turn, causes serious damage to soil organisms, fertility, and crop growth. The most common cause of panning is repeated tillage to the same depth. Some implements are more likely to cause pans (rotary hoes, disk harrows and disk ploughs), particularly if used when the soil moisture is not right, but almost any mix of tillage tools used often enough at around the same depth will help create a hard pan. Repeated planting of the same, shallow rooted crop, shallow irrigation, and waterlogging, can also cause panning. Once developed, pans can be treated by planting deep rooted crops, deeper tillage, or (ideally) with inversion tillage to break them up.

Careful irrigation is also critical for soil health. Water applications should be timed, and drainage controlled, to avoid either under- and shallow-watering (causing panning), or over watering. Over watering can lead to leaching of nutrients as well as waterlogging. Also the application of poor quality water can lead to salt build up, which causes serious damage to soil microbial activity, nutrient availability, and crop growth.

Careful control of cultivation practices on hillsides is also very important in the context of water. Bare soil on hillsides leads to increased runoff (and water loss) during rainfall and irrigation. It can also lead to soil erosion, whereby the fertile topsoil is washed away down the slope. Practices such as mulching, cover crops, and contour planting can help to reduce runoff and erosion.

Farmers can look for signs where poor management is causing damage to the soil. Persistent puddles, patches of poor crop growth, green algae on the soil surface, and salt deposits, are signs of problems that need to be addressed. Channels in the soil surface, river and runoff water that is cloudy with soil particles, exposed roots, and soil deposits at the base of slopes, are all signs of soil erosion.

Figure 1 - Signs of soil erosion with the loss of topsoil and stunted crop growth

Part 1, Chapter 3 of this manual gives more in-depth information on the interactions between soil, water and to crop growth.

11.1.2. The business case

Cultivation on healthy soils, in particular those with a high water holding capacity, requires less water to meet crop needs compared with soils of poor quality. This increases water-use efficiency, leading to direct savings on the cost of water abstraction and pumping.

In addition, soils with good organic matter content, healthy microbial content, optimal nutrient cycling and availability, and good structure and aeration, are more productive in general; they give higher yields, reduce the cost of inputs (fertilizer and water), and give a better economic return.

11.2. MANAGING SOILS FOR EFFICIENT WATER USE

11.2.1. Soil surveys and mapping

As a starting point for improved soil management, it is important to develop a soil map showing the type of soils present in different locations around the farm. This gives the baseline information needed to develop a plan for improved soil management. A soil map is also valuable to implement a more precise irrigation plan and schedule.

Soil maps can vary from the very simple, to the very complicated, depending on the type of farm and resources available. The most basic consist of hand drawings, and the more sophisticated are based on digital mapping techniques.

The first step is to conduct a soil survey to record soil type and soil properties in different locations around the farm, particularly in the areas used for cropping. In the context of water management, the key criteria to take into account are soil texture, soil structure, and organic matter content. The various categories of soil found in the different locations can then be marked on the map.

Rather than preparing a new map just for soil, farms/enterprises (especially small-scale operations) may find it helpful instead to simply add this information to their existing farm water maps. As well as avoiding additional work, having everything on the one map helps to see soil type and characteristics in the context of fields/crops, landscape features (notably slope), water sources, runoff, water storage and transport systems, etc.

11.2.1.1. Conducting a soil survey

1. If possible, obtain existing information on the local soil types and characteristics from official sources. Most countries have national soil maps, and local Ministry of Agriculture or agricultural extension offices generally have information on the key soil characteristics of each region. If this is not available, a global soil map is available on the ISRIC Web site (www.soilgrids.org). This Web site gives the soil classification, soil texture (sand, silt clay), mean organic matter content as well as acidity or pH from around the world. Some knowledge on geographic information systems and data management is helpful to use this site effectively.
2. Either draw a map of the farm, or use the existing farm water map, and add the outline and a number for each field.
3. Do a rough survey of all the fields in the farm to identify the different soil categories (areas or groups of fields where soils are similar in terms of texture (see Box 1) and color); mark on the map the areas or fields with each of these soil categories.
4. For each of these soil categories, take a number of soil samples at rooting depth The number of samples needed for each category depends on the size of the area, and the variation within it (e.g. due to slopes, gullies). To get detailed information on soil characteristics, these samples should be sent to a laboratory for analysis. Alternatively, simple qualitative assessments can be made of the soil in each area (to a depth of 100 cm if possible) to assess basic soil texture (using the method in Box 1) and soil structure (Box 2).

Box 1. Soil texture

There are three main categories of soil texture: sandy, silty or clay soils.

The texture of the soil is the main factor determining its capacity to hold water. Sandy soils can hold less water than silty soils, and silty soils can hold less water than clay soils. Similarly, sandy soils may contain less organic matter then silty soils, and silty soils may contain less organic matter then clay soils.

To determine the basic texture of a soil, take a handful of moist soil from the root zone, and squeeze it into a ball. If it is not possible to create a ball, or the ball falls apart almost immediately, the soil texture is mostly sandy. If the soil remains in a ball, but breaks when tapped, it is mostly silty. If the soil remains a ball when it is tapped, it is mostly clay.

Box 2. Soil structure

Soil structure describes how the solid parts of the soil bind or clump together, leaving pores (or spaces) between them. A good soil structure will have clumps (aggregates) with adequate pores to allow the movement of air and water. Structure ultimately depends on what the soil developed from, but it is influenced by management factors including cultivation, irrigation, and organic matter content.

Soil structure is classified according to the level of loose aggregates. Normally there are four classes but, for simplicity, only three are used here:

0. No structure. This is either soil made up of a seemingly solid clay mass, or very loose (sand). It has low water holding capacity.
1. Weak structure. This has a small amount of aggregates (small clumps) within a soil which is mostly unaggregated. It has limited water holding capacity.
2. Moderate to strong structure. This is mostly made up of distinct aggregates that do not easily fall apart, and little unaggregated soil. It has good water holding capacity.

The following method provides a rough idea of soil structure:

- Dig a hole 60 cm deep and examine the side of the hole (or take a soil sample with a soil probe, if available). Observe whether the soil appears to be (a) entirely loose (sandy) (b) a solid block or (c) if clumps of soil (aggregates) can be seen.
- If not sure, take a lump and examine it closely.
  - If it appears solid (massive), or completely loose without any small clumps (aggregates), then the soil has no structure (Class 0).
  - If there is a limited number of aggregates, with either loose soil or compact solid soil in between, the structure is weak (Class 1)
  - If most of the soil is made up of small lumps and aggregates, it has a moderate to strong structure (Class 3).

11.2.2. Soil water-holding capacity

With the information obtained on soil texture and structure, soils on the farm can be classified and marked on the map according to their likely water holding capacity, using the classification given in Table 1.

Table 1. Water holding capacity of soils according to soil texture and structure

Soil texture	No structure	Weak structure	Moderate-good structure
Sandy	Very low	Low	Moderate
Silty	Very low to low	Moderate	Good
Clay	Low to moderate	Moderate to good	Good to very good
Peat/mainly organic	Good	Good	Good

Once a good understanding has been obtained of the various soils in the farm and their respective water holding capacities, soil moisture content can be monitored. This should be a routine part of management to ensure efficient and effective irrigation scheduling. Table 2 gives a simple and practical method to estimate soil moisture content.

Table 2. Simple method to estimate soil moisture
Source: Colorado State University Extension, Estimating Soil Moisture, Fact Sheet No. 4700

Soil moisture deficiency	Moderately coarse texture	Medium texture	Fine and very fine texture
0% (maximum = field capacity)	Upon squeezing, no free water appears on the soil, but a wet outline of the ball is left on the hand		
0-25%	Forms a weak ball that breaks easily when bounced in the hand*	Forms a ball that is very pliable, slicks readily*	Easily forms ribbons when pulled between thumb and forefinger*
25%50%	Will form a ball, but falls apart when bounced *	Forms a ball; will slick under pressure*	Forms ball, will ribbon out between thumb and forefinger*
50-75%	Appears dry; no ball formed when squeezed*	Crumbly, holds together under pressure*	Somewhat pliable, forming a ball under pressure*
75-100%	Dry, loose, flows through fingers	Powdery, crumbles easily	Hard, difficult to break into powder

*Squeeze a handful of soil firmly to make ball test

11.2.3. Improving the water-holding capacity of the soil

The objective for a farm is to minimize water losses through runoff, evaporation or drainage. This can be achieved by making the soil retain more of the water that it receives from irrigation or rainfall. Some methods to achieve this are:

- **Minimize evaporation.** By applying a mulch on the surface of the soil, or by using conservation or zero tillage, or minimal tillage with direct seeding. FAO (1998)[280] reports a reduction of 35% in water lost to evapotranspiration

280 www.fao.org/docrep/x0490e/x0490e00.htm.

by tomatoes growing under drip irrigation when a plastic mulch was used. The Texas Cooperative Extension (2006)[281] reports reductions of 25% in evapotranspiration when using organic mulches such as pine bark. Plastic mulches usually achieve higher evapotranspiration reductions than organic mulches; however, a good quality organic mulch can also contribute to soil organic matter content. Minimizing tillage also has a positive effect on the organic matter content of the soil.

- **Maintaining and managing soil structure and organic matter content.** As noted, a loose and friable soil with aggregates is the best soil structure as it allows water and air to rapidly permeate. There are two main methods to improve soil structure:

  a. loosening the soil; and

  b. maintaining a high organic matter content.

  Organic matter does not only absorb water itself, it also contributes to formation of soil aggregates that improve soil structure, and therefore its permeability and water retention capacity. Agronomic practices have a big impact on this, and levels can be increased simply by applying organic matter. This includes (for example) leaving crop residues and roots on and in the soil after harvest, applying organic manure, or sowing and incorporating green manure. Crop rotation can also be used to improve organic matter content; cereal residues add a lot of organic matter to the soil, while vegetables add very little. Drainage and management of waterlogging are also critical.
- **Minimizing runoff.** Conservation tillage or organic mulching help to minimize runoff as water is able to infiltrate into the soil.
- **Other agricultural practices:**
  - conservation crop rotations help to reduce runoff and improve soil structure;
  - field windbreaks help to reduce crop evapotranspiration (for more information, see Part 1, Chapter 6).

Managing soils to increase water retention

- Do you know the type of soils in your farm and if they are mainly sand, silt or clay?
- Can you draw a rough map of the soil types in your farm?
- Do you assess soil moisture on a regular basis?
- How can you improve the water-holding capacity of your soil? Do you practice any of these approaches on your farm?

281 aggie-horticulture.tamu.edu/newsletters/hortupdate/hortupdate_archives/2006/nov06/ScienceFair.html.

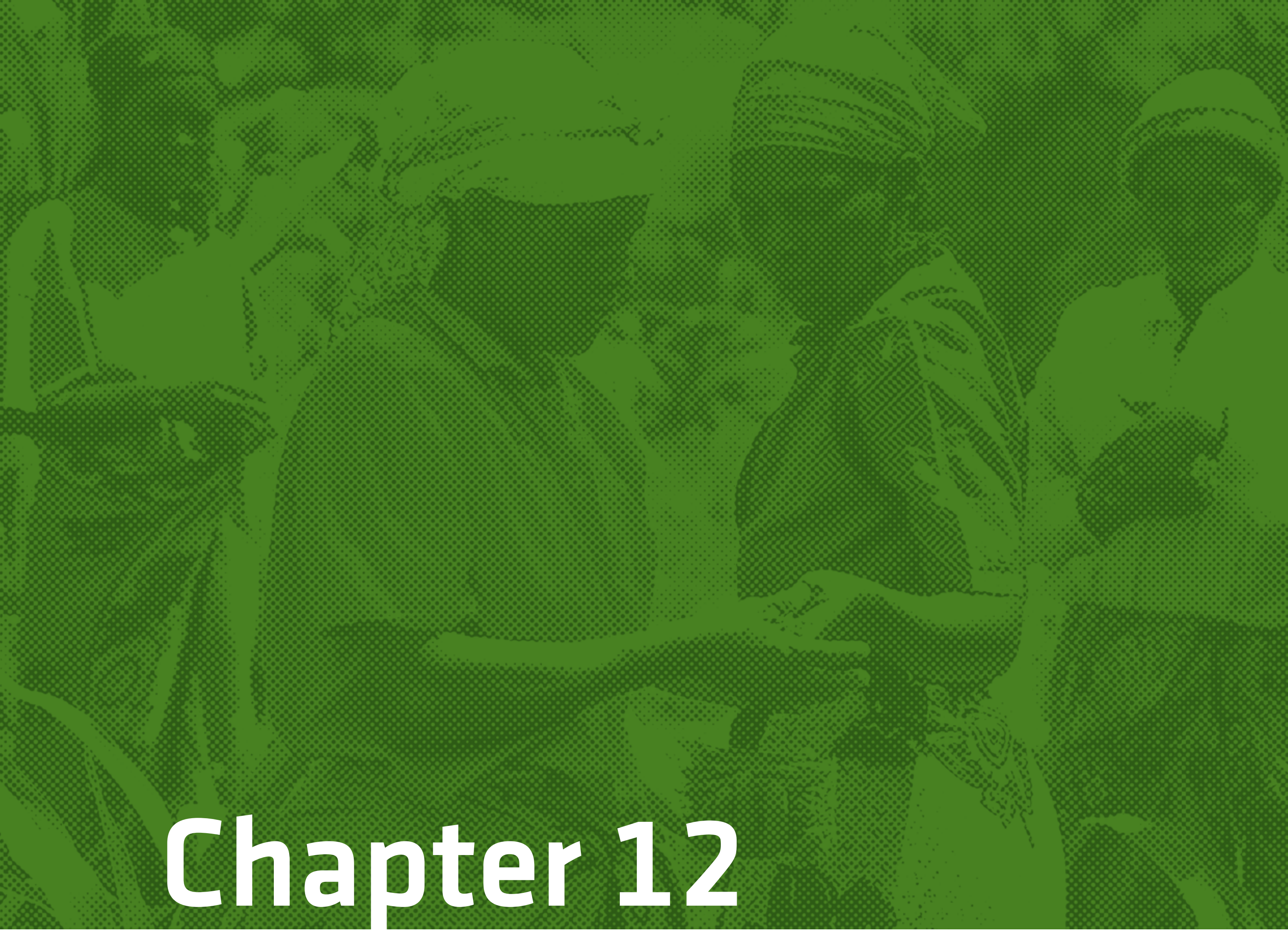
11.3. EXAMPLE

11.3.1. Suzan and Kioko

Kioko recently realized that for the same crop and same amount of water applied, some plants grew faster than others, depending on their location in the field. He recalls what they said in the AgriWaterProofs training about soil characteristics and water retention. Walking in his field and having a closer look, he also realized that soil texture is different for some parts of his field. He remembered that they mentioned this in the course, and that it was important to know about soil texture and soil water holding capacity. He decided to test some soil samples by taking handfuls of moist soil from the root zone and squeezing them into balls, as explained during the training. For some samples, the balls immediately fell apart, while others remained whole. After that, he decided to draw a rough map of the field, to locate the different soil textures (using Box 1 from the training course). He also realized that he can estimate the moisture deficiency in the soil by using a simple method that involves squeezing a handful of soil and feeling the ball formed (Table 2). With this information, he will know if his crop needs irrigation.

Kioko is now aware that he needs to take care of his soils and their structure, and should try to improve his soil. He decides to carry out conservation tillage by leaving the tomato residues from the previous season on the field, and only clearing and loosening narrow strips for the next planting. In the training course, they said runoff would probably decrease; this would be very valuable, as last time he had problems because irrigation water didn't permeate well into the soil, and much of it ran off his field and was wasted. Hopefully this method of conservation tillage will help him improve his soil and retain more water for his crop.

Susan has also experienced some problems with soils in parts of her field, and she is worried about getting non-conformities in the GLOBALG.A.P. audit. She wants to know more about the soil textures and structures she has in her farm in order to plant and apply water more efficiently. She decided to pay a visit to her sister in Nairobi, who has a friend that works as a GIS analyst. With his help, she downloaded a soil map where she found detailed soil information for the region covering her farm. With this information, she is able to survey and classify the soil water holding capacity for each part of the farm (Table 1). In order to know more about the soil structure, she gets her workers to dig 60 cm holes at certain points in the field. She finds that in some parts, soil aggregates are too loose. However, mostly the aggregates are uniform, meaning good structure and good water holding capacity. In the weak structure areas, she gets her workers to add plant residues to the soil to increase organic matter, and therefore water holding capacity. She is also wondering about mulching with dry hay from her neighbors (she could get it for a very good price), as well as rotating her crops. She does not know exactly how much water she will save with these practices; she needs to start keeping records to understand this better. She will definitely start accounting the water in- and outflows in her farm more systematically.



Chapter 12

Water risk assessment

12.1. WHY ASSESS WATER RISK?

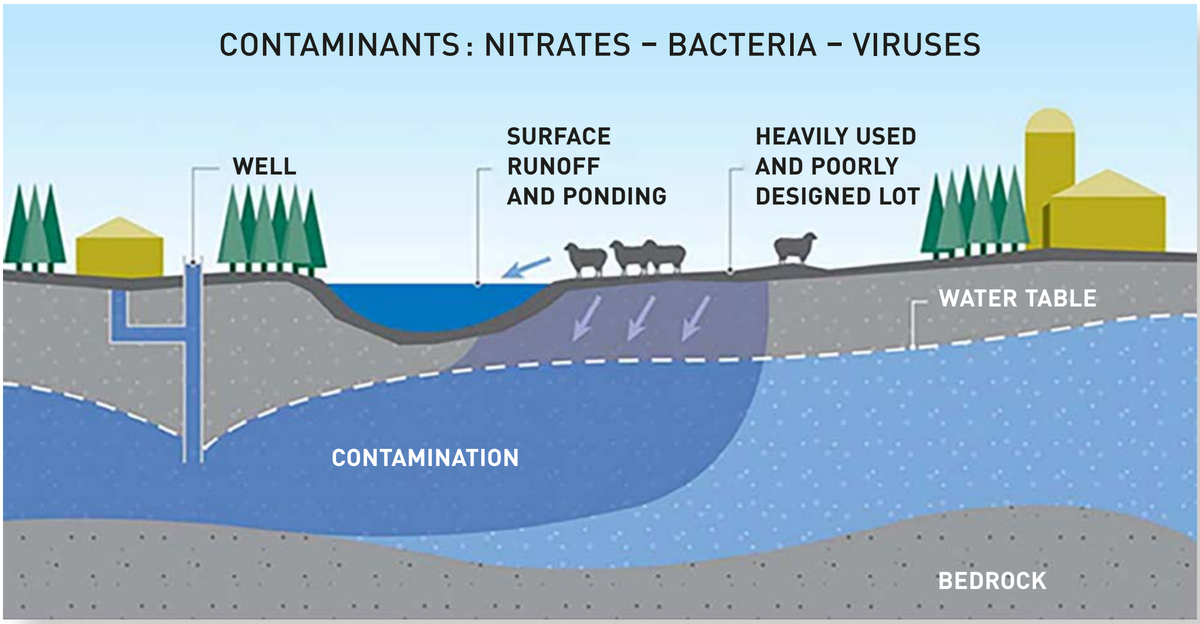
12.1.1. Overview

A risk assessment is simply a process to systematically think about the dangers (hazards) that could cause harm to people, the environment, the product, or your business, and decide whether you are taking reasonable steps to prevent that harm. The aim is not to create extra work and paperwork, but to identify sensible measures to control the risks in your business.

Water, as a crucial input, should be included as an integral element of an all-farm risk assessment. Other elements include soil, previous land use, legislations, access to land, among others, that can all have an impact on the business and associated stakeholders.

Assessing the water risks connected with a farm/enterprise and its surroundings help to:

- Understand the water challenges affecting the farm, as well as the surrounding area and community (*i.e.* the watershed in which the farm is located).
- Have first-hand information that will help to prioritize water-related actions at the farm and watershed levels.
- Manage water risks more effectively, by knowing how and where risk mitigation actions can be applied.
- Save unnecessary expenditure due to poor water management, and be more water resilient.
- Identify opportunities to manage risks and at the same time increase productivity, profitability and overall sustainability of the business.



12.2. PRINCIPLES OF A WATER RISK ASSESSMENT

12.2.1. Types off risk

For any water risk assessment, risks are assessed at two levels:

1. internal (the farm/enterprise);
2. external (the river basin or watershed).

In a horticultural company, internal water risks refer to those associated with production and post-harvest management of the crop/commodity. For example:

- Poor quality irrigation water creates the risk of crop contamination, damage to irrigation equipment, and salination. If a business does not measure the quality of irrigation water, this increases risk because the farm/business does not know if poor quality is affecting the produce, is not able to provide this information during inspections/audits, and does not take the necessary action to address (mitigate) problems.
- The more water a farm/enterprise needs to operate, the higher the risk as it is more sensitive and vulnerable to water shortages, water price, and water regulations. If the business takes no abstraction records, and does not asses everyday agricultural practices in terms of water use, it increases the risks.
- Lack of data is itself regarded as a high risk, simply because management decisions cannot be made on the basis of a sound understanding of the situation.

River basin risks relate to the water situation outside of the farm, but within the watershed where the farm is located.

- Examples of external risks are water scarcity at the watershed level (or predicted future water scarcity problems due to climate change), high levels of pollution, or ecosystems that are threatened by human activities.

A company can assess and manage its internal water risks relatively easily. However, managing external water risks can be challenging. At the watershed level, risks are shared by all farms and other users of water within it; these risks have to be addressed collectively, requiring dialogue and cooperation between all parties.

To conduct a water risk assessment, data on water quantity and quality are needed, as well as data on agricultural practices and climate, among others. Chapter 14 summarizes the data needed to assess water risks for the company's overall water management plan.

Both internal and external risks are classified into 4 categories: physical, regulatory, reputational and financial. Table 1 provides an overview of each of these.

Table 1. Water risks[282]

Type of risk	Description
Physical	Relates to water quantity, both too much (flooding) and too little (water shortages, drought). It also concerns water quality, particularly factors that can limit what the water can be used for (e.g. because of high salt levels, or contamination). Physical risk may mean that a farm or company does not have sufficient good quality water to cater for all its business operations. The impact of farm operations on the surrounding environment and ecosystems can also be considered as physical risks (e.g. pollution from waste water).
Regulatory	Relates to the imposition of restrictions on water use by government or by other regulatory bodies. This may include the pricing of water supply and waste discharge, licenses to operate, water rights, quality standards, requests for data reporting, and certification, among others.
Reputational	Relates to the impact on a company's brand and image, and can influence customer purchasing decisions. If a farm or business is associated with bad or irresponsible practice, this creates a reputational risk both for the business and any food company that buys from them. Examples from the horticultural industry include conflict around access to water (e.g. where intensive production of export crops causes water shortages for nearby smallholder farms or communities); and degradation of the local environment and water resources through discharge of polluted waste water. The media, consumers and European buyers (especially supermarkets) are very sensitive to reports of bad practice such as this, and increasingly require evidence of responsible water use from a farm/enterprise (e.g. certification) before buying their produce.
Financial	Relates to losses in productivity and profitability due to any of the above (including pricing of water).

12.2.2. Elements of a water risk assessment

The following elements should be considered in a water risk assessment (see Chapters in parenthesis for more details):

- **Water quality.** Irrigation water quality should comply with WHO Guidelines, and post-harvest operations such as produce washing must use water of drinking quality (WHO guidelines for potable water) (Chapters 6 and 7). The quality of waste (discharge) water should comply with local regulations or by-laws, and cause no harm to the environment or other users.
- **Water availability.** Availability of sufficient water to meet the needs of the farm/enterprise throughout the year (or at least during the growing season). (Chapter 2).

282 Based mainly on (with additions from the authors) WWF& DEG, "Assessing Water Risks", 2011, awsassets.panda.org/downloads/deg_wwf_water_risk_final.pdf.

- **Authorization to use.** According to local regulations, licenses, by-laws, customs, irrigation schemes, or protected areas (Chapter 2).
- **Flooding.** Unintentional flooding that results in microbial and chemical contamination of the produce (Chapter 2, Chapters 6-7).

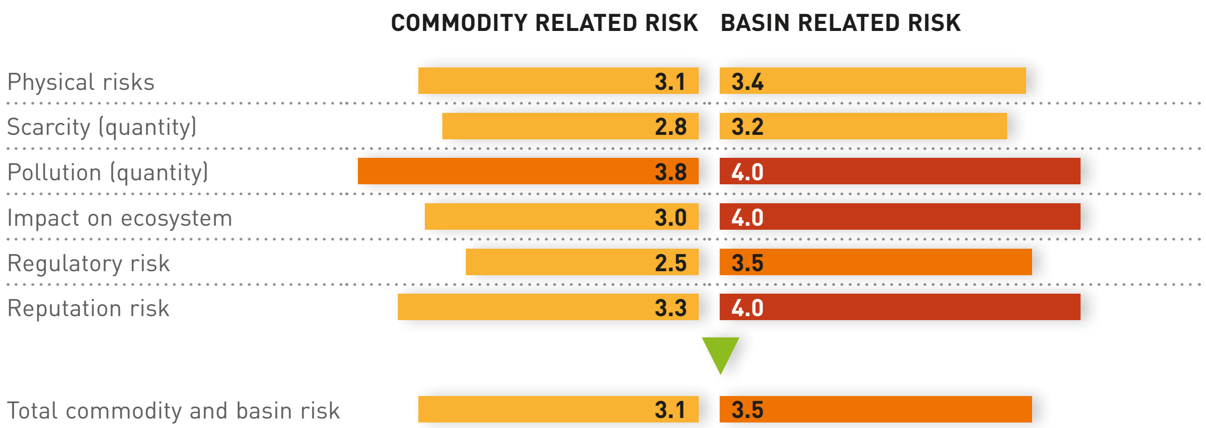
12.3. TOOLS TO CONDUCT A COMPANY WATER RISK ASSESSMENT

12.3.1. Different open-source possibilities

Several open-source tools are available to conduct a business water risk assessment such as the CERES Aqua Gauge[283] or the GEMI local water tool[284].

One of the most popular is the Water Risk Filter[285]. This scores and ranks water risks for a business in a straightforward and user-friendly format. The scores it generates help the company to identify and prioritize actions that should be taken to mitigate the risks. It has a dedicated Web site where any company is free to register as a user. Once on the Web site, the user locates the river basin/watershed where their company is located; they can then either use pre-set (default) global databases to conduct a preliminary mapping of water risks, or they can create a customized and more comprehensive assessment by completing a detailed questionnaire to enter their own company details. Figure 1 shows a typical output from the Water Risk Filter.

FIGURE 1 - WATER RISKS RESULTS GENERATED BY THE WWF WATER RISK FILTER FOR TOMATO PRODUCTION IN THE GALANA RIVER BASIN, KENYA



Risk scores from 1 to 5, where 1 is low risk, and 5 is the highest risk.
Default river basin data from global databases were used, and the questionnaire for commodity related risks was completed manually using estimated input data.

283 www.ceres.org/issues/water/corporate-water-stewardship/aqua-gauge/aqua-gauge.
284 gemi.org/localwatertool.
285 waterriskfilter.panda.org.

12.3.2. GLOBALG.A.P.

Version 5 of the GLOBALG.A.P. Integrated Farm Assurance (IFA) Crops Base, which came into force in June 2016, for the first time included several control points and compliance criteria (CPCCs) specifically addressing water. This recognizes the importance placed on responsible water use by global buyers in the food industry and retail, linked to reputational risk.

Attached to the IFA, GOBALG.A.P. have prepared "Responsible Water Use Guidance"[286] (Annex CB2) to explain the water-related CPCCs, and make it clear to farms and companies exactly what is expected in order to pass a GLOBALGA.P. audit.

One of the CPCCs addresses water risk assessment, and the guidance provides a useful summary to assess water risk. This presents specific questions for each type of risk, with the aim of guiding the farm towards responsible water use. For each question, the farm/enterprise is expected to indicate their current status, as well as listing any planned mitigation actions.

The following issues are covered:

- **Physical risks:** water scarcity, drought events, flood events, water pollution, alternative water sources.
- **Regulatory risks:** water allocation and management scheme, water usage permit, non-authorized water usage, priority usage.
- **Reputational:** water conflict, environmental issues, social issues, cultural issues, farm's water management.
- **Financial:** financing, insurance, water pricing.

286 www.globalgap.org/export/sites/default/.content/.galleries/documents/160630_GG_IFA_CPCC_FV_V5_0-2_en.pdf.

The GLOBALG.A.P. guidance does not provide a risk scoring method (such as the WWF Water Risk Filter), or guidance on which databases should be used. Instead, it lists a number of simple questions that can be answered by the farmer in a qualitative way. They serve as reflections to better understand the farm water risks.

EVALUATING FARM WATER RISKS.

Use the GLOBALG.A.P. Risk Assessment Summary to identify the main water risks on your farm/enterprise; prepare a list of the most urgent problems and mitigation actions needed to manage water risk on your farm.

Source: GLOBALG.A.P. IFA V5 July 16, Control Points and Compliance Criteria, Crops Base, pp. 79-82

Risk	Issue		Status	Action
Physical	Water scarcity	Does the river basin or area face water scarcity due to the over exploitation of water resources? Does water scarcity affect the current or planned water usage by the producer? Does the produce contribute significantly to water scarcity in the river basin or area, or might the producer do so in the future?		
	Drought events	Does the river basin or area face droughts due to irregular rainfall? Can this affect the producer's water availability or usage? How flexible is the farm's water usage? Can this have an impact on environmental, social or cultural issues?		
	Flood events	Does the river basin or area face floods due to irregular rainfall or water management? Can this affect the producer? Can this have an impact on environmental, social or cultural issues?		
	Water pollution	Does the river basin or area face water pollution? Are current or potential pollution sources upstream, or located in the same groundwater area, as the producer? Can the pollution affect the producer? Can this pollution have an impact on environmental, social or cultural issues?		
	Alternative water source	Do alternative non-overexploited and/or non-polluted water sources exists? Can this water be allocated to (or accessed by) the producer on a regular basis? Can this water be allocated to (or accessed by) the producer if they face extreme situations (drought, pollution, etc)? Are there (new) water storage facilities to address temporary extreme situations? What are the environmental effects of using the alternative water sources or storage systems?		

Risk	Issue		Status	Action
Regulatory	Water allocation & management scheme	Is the river basin or area managed according to a plan or scheme? Has this been consulted on with the public and interested parties, and approved by the relevant water authority? Is the plan being implemented and updated on a regular basis? Is the producer's water usage included in the plan or scheme? If not, is the producer's water usage coherent with the plan's allocation and management scheme? Does this plan consider adequately the environment, social or cultural issues?		
	Water usage permit	Does a procedure exists (or is there a requirement) to hold a water use permit? Does the producer hold a water use permit adequate for their water usage? Does this permit interact with other (water usage) permits?		
	Non-authorized water usage	Does the producer use water (partially) without the necessary permit? Do other users use water without the necessary permit? Can this non-authorized water use affect the producers' own water use permit or water use (availability)? Can this non-authorized water use have an impact on environmental, social or cultural issues?		
	Priority usage	Is the use of water prioritized in the river basin or area? What is the ranking of the producer in relation to other water users? Are specific regulations foreseen for extreme situations (drought, pollution etc.)? Considering current trends and scenarios concerning priority users and extreme situations, is there a risk to the producers water use? Can the permit be derogated in order to supply water to a priority water user?		
Reputational	Water conflict	Does the river basin or groundwater area cross national regional, local or cultural/ethnic borders? Are there conflicts over water in the river basin or area? What are the reasons? Are these conflicts dealt with by a conflict resolution/dialogue process? Is the producer involved in water conflicts in this particular area, or in any other geographical area where they operate? Are any similar water users involved in water conflicts in the river basin or adjacent areas?		

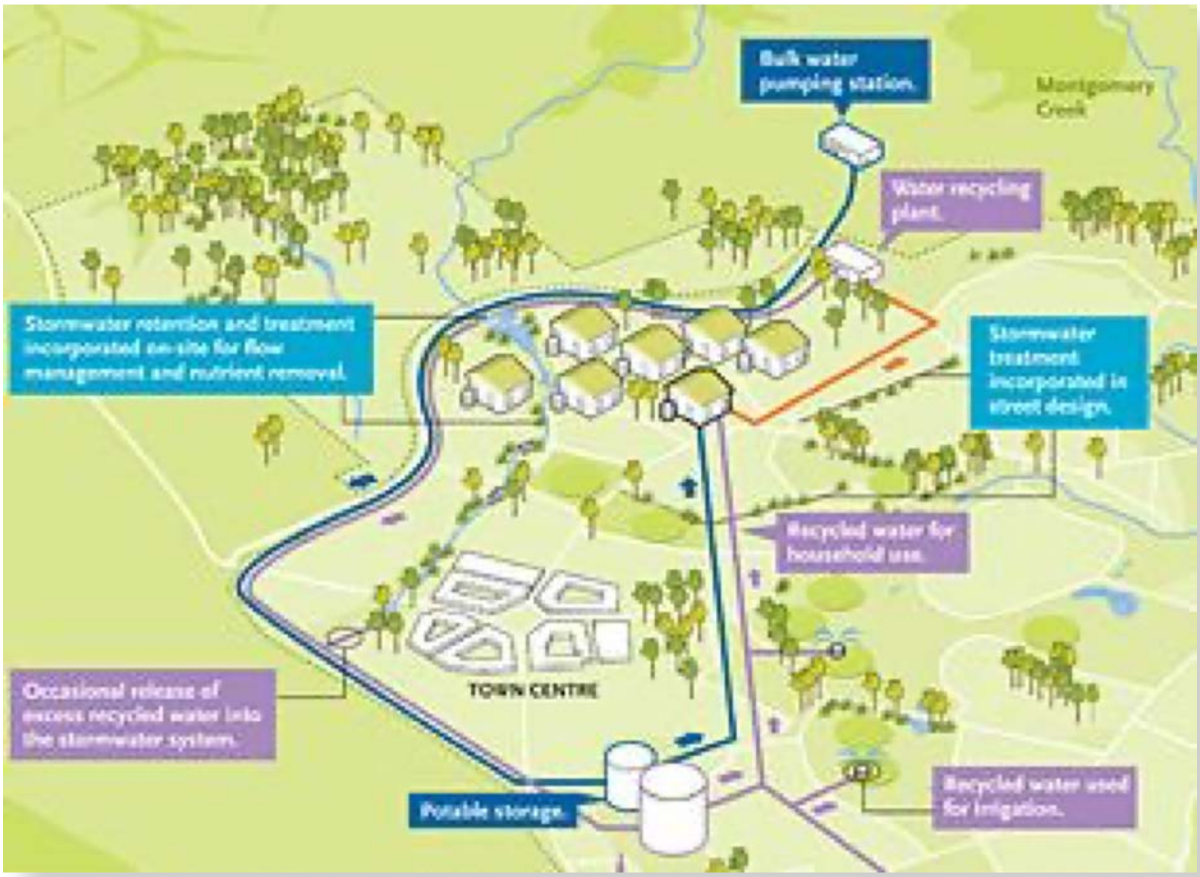
Risk	Issue		Status	Action
Reputational	Environmental issues	What is the current status of the freshwater environment in the river basin or area? What are the environmental or biodiversity trends for the river basin or area? Can these environmental trends affect negatively the farm's operations? Does the farm water usage impact significantly, either directly or indirectly, on key environmental or biodiversity features? Has the producer developed a (public) environmental statement or plan? Does this plan respond to any water-related environmental conflicts or concerns that have arisen? Is this plan implemented, audited and updated on a regular basis? Is this plan publicly available?		
	Social issues	What is the current social situation regarding water (access to drinking water, adequate sanitation, etc.) in the river basin or area? What are the trends in these aspects? Can social requirements or claims negatively affect the farm's operations? Does the farm's water use impact significantly (either directly or indirectly) on access to drinking water and sanitation by the inhabitants of the river basin or area? Has the producer developed a (public) statement and/or plan in this regard? Does this plan respond to any water-related environmental conflicts or concerns that have arisen? Is the plan implemented, audited and updated on a regular basis? Is it publicly available?		
	Cultural issues	What are the key cultural issues related to water in the river basin or area? How have they evolved? Can cultural trends, requirements or claims negatively affect the farm operations? Does the farm's water use impact significantly, either directly or indirectly, on cultural heritage in the river basin or area? Has the producer developed a (public) statement and/or plan in this regard? Does it respond to any water-related environmental conflicts or concerns that have arisen? Is it implemented, audited and updated on a regular basis? Is it publicly available?		
	Farm's water management	Is the water on the farm managed according to a plan? Does this plan include records of historical, current and future water use? Does it include provisions for the sustainable and efficient use of water? Does it respond to any conflicts or concerns that have arisen as a result of the farm's water management? Is this plan implemented, audited and updated on a regular basis? Is it publicly accessible?		

Risk	Issue		Status	Action
Financial	Financing	Does the producer require regular or periodic external financing? Do the (current and potential) investors consider water-related criteria in their funding evaluation? Are any specific items (e.g. water management plan, water usage permits) required by the investors? Do they establish thresholds for compliance with their water related criteria?		
	Insurance	Does the producer have insurance covering their operations? Do (current and potential) insurance companies consider water-related criteria in their evaluation? Are any specific aspects (e.g. water management plan, water usage permits) required by the insurance operators? Do they establish risk thresholds for compliance with their water-related criteria?		
	Water pricing	Does the producer pay for water use? How is the price/tax/tariff fixed? Does it include operational costs and (environmental) externalities? Is the pricing system stable, predictable and transparent? How likely is it that water prices will increase on a regular or irregular basis?		

12.4. EXAMPLE

12.4.1. Suzan and Kioko

Susan is checking the GLOBALG.A.P. documents to make sure she is taking control of everything and to make sure no new problems appear in the future. She realizes that having a risk assessment to evaluate environmental issues for water management on her farm is now a minor must, and will become a major must (compulsory) by July 2017. She wants her farm to be water-resilient and with efficient water use, as she is aware of the threat from climate change, and wants to ensure the future economy of the farm through improving productivity, quality and reputation.

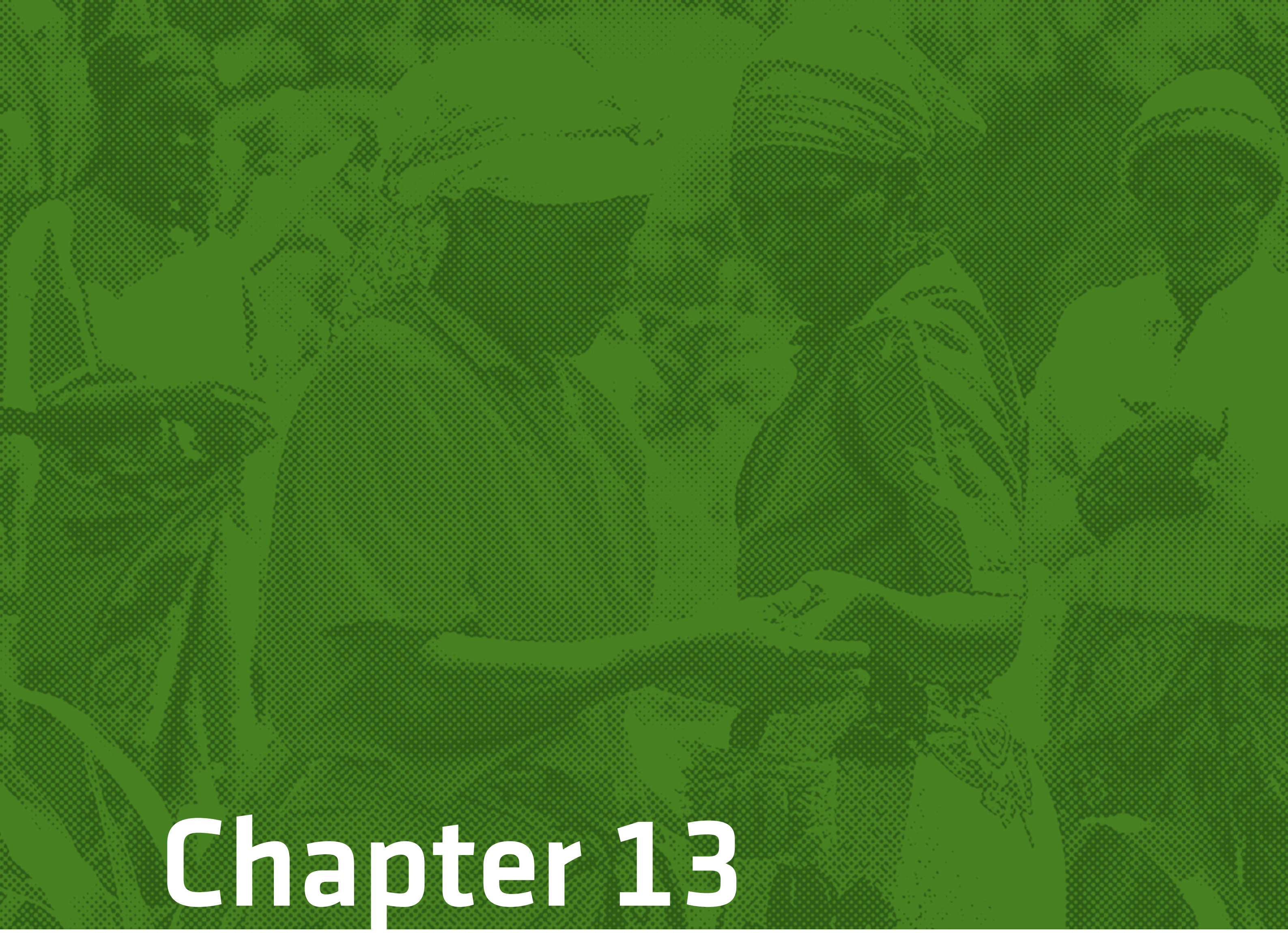


Susan knows the region well and has collected farm data for a couple of years on factors such as volume of water abstracted, crop yields, application of fertilizers and pesticides. Perhaps she does not yet have all the data needed for the water risk assessment, but she took part in some training and knows that she can already make a start on assessing her water risks with the information and knowledge she already has. She needs a framework to put all the information together, and to check what data are missing. In the training they mentioned the Water Risk Filter, so she sets time aside to sit in front of the computer and create a user profile. She selects her economic activity (agriculture), her commodities (tomato and French beans), and her geographical location (Galana River basin, Kenya). She fills in the information to the best of her knowledge (irrigation methods, irrigation data) and answers the questions related to soil moisture protection, water quality measurements, etc. When she is not sure, she selects an answer from the list of answers provided, based on her best judgement. She realizes she needs to collect more detailed information on all farm inputs to be able to answer accurately. With the information she provides, the Water Risk Filter gives her the highest risk score for water pollution, and realizes that it is because she doesn't know if she is complying with the regulations on effluent discharge. Measuring effluent water quality seems to be a priority. She also gets high scores for reputational risks and realizes this is because there have been multiple small disputes with other basin stakeholders (basically with the rice producers), also because she does not yet have a water strategy or a contingency plan prepared to respond to water risks.

After that, Susan fills the GLOBALG.A.P. Risk Summary (Annex in CB5), completing information on her current status for the physical, regulatory, reputational and financial questions. She finds there are some points for which she has little to no idea, and she lacks data. For example, she has no knowledge about potential upstream pollution sources, but now sees that this could pose a risk to her crop. By applying the Water Risk Filter and the GLOBALG.A.P. Risk Summary, she comes to realize that her own water risks are related to the general river basin water risks. She is now aware that in addition to her farm, she needs to think of her watershed. With all of this information, she is able to identify the most urgent actions that she needs to take in order to cover data gaps and mitigate risks. For this, she needs a clear water strategy and action plan.

Kioko, although having taken several actions and made improvements in his farm, is still worried about the future. He now understands much better the value of water and the water sources he has, as well as the changing climatic conditions, and he wants to ensure that his produce is a good enough quality for the company he supplies. His finances and his family depend on that, so he wants to try his best to manage any potential risks that could threaten his productivity and profitability.

Last time he went on a water training course, he was given a paper with the GLOBALG.A.P. Risk Summary; this gave a list of questions covering physical, regulatory, reputational and financial issues. He decides to try and answer the questions, but soon realizes that actually he does not know the answers to most of them. But three things he knows for sure: he does not hold the required permits to use water from the spring; his crop may fail again if he does not get enough water; and he does not really know his crop water needs. He thinks these three issues are his most immediate and urgent water risks. He understands he might be exposed to other water risks, as he learnt from the training course and GLOBALG.A.P. Risk Summary but, for now, he will concentrate on finding solutions for these three priority risks. He wants to do this because he knows that by addressing them, his production will be less erratic and there a better chance that he will increase productivity and income.



Chapter 13

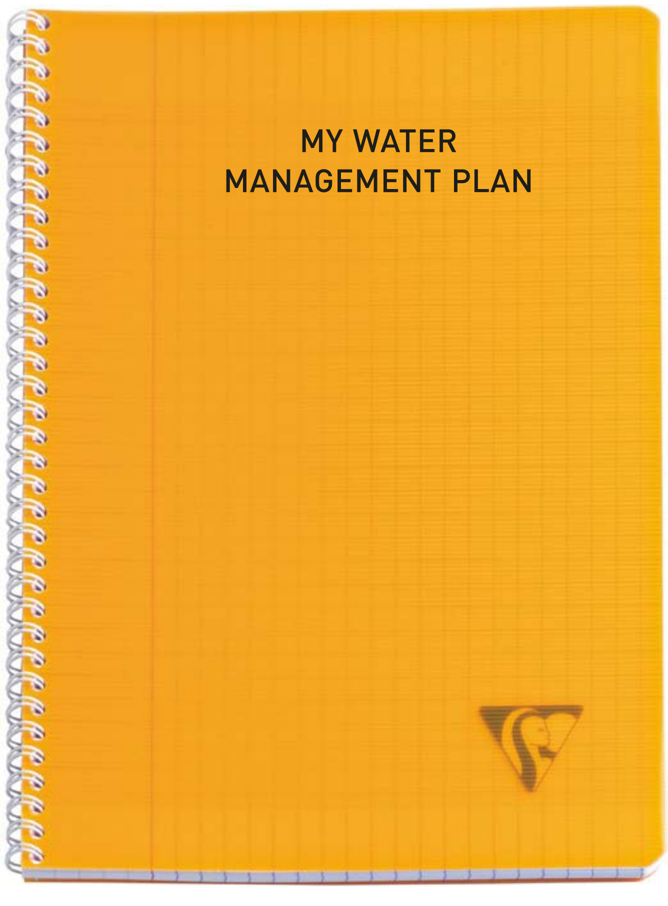
Water management plan

13.1. WHAT IS A WATER MANAGEMENT PLAN?

13.1.1. Definition

A water management plan is a written document that details all the actions that a farm or business will undertake in order to manage water risks, use water more efficiently, minimize water pollution, comply with water-related regulations and, for some companies, meet certification requirements.

The water management plan outlines a set of actions to be undertaken over a period of time. The correct and effective implementation of the plan should be monitored regularly, and adapted as needed according to the results. The plan itself should also be updated regularly (at least annually) to take into account any relevant changes in the farm or watershed.



Developing and implementing a water management plan requires the investment of time, money and human resources. An effectively implemented plan will pay back in increased production, reduced costs, and greater resilience; however, at the outset, it needs the foresight, buy-in, backing and drive of senior management to make the commitment and get the process underway.

It is also very important to nominate one or more people within the farm or business to be responsible for implementing and monitoring the various elements of the water management plan.

13.2. WHY DEVELOP A WATER MANAGEMENT PLAN?

13.2.1. Elements

A water management plan will help the farm or business:

- Focus on the key issues in terms of water risk.
- Prioritise actions that will manage or mitigate water risks most effectively.
- Carry out a risk/benefit analysis and identify the agronomic and management practices that can be changed, and will have most impact in terms of improving overall on-farm water use and water quality.
- Ensure efficient irrigation management, in an integrated and sustainable way, according to agricultural practices, factors in the watershed, the farm's water risks, and any relevant regulations.
- Enable an assessment to be made of the economic productivity of the farm in relation to water use (economic water productivity).
- Comply with regulations and buyer's requirements.
- Communicate its policies and actions related to the responsible use of water to its clients, investors, and neighbouring communities.

The food industry and retail companies increasingly require their suppliers to have a water management plan. As noted previously, GLOBALG.A.P. Version 5 has added specific water-related criteria, including the development and implementation of a water management plan. It defines a water management plan as "an action plan that aims to optimise water use on the farm, and to manage water as a scarce natural resource". Having a water management plan in place and operational is included as a GLOBALG.A.P. control point, and will be a Major Must (compulsory) from July 2017 onwards.

13.3. HOW TO DEVELOP A WATER MANAGEMENT PLAN

This section provides a basic outline and the steps needed to develop a water management plan for a horticultural farm or business. It brings into the forefront the fact that the farm alone does not have complete control over securing and managing its water risks, but operates within a watershed, and must work alongside other users and the environment.

The outline provides a framework that farms/enterprises can use to build their water management plan. It should be possible to complete the various sections using the information and methodologies outlined in earlier chapters.

The latter part of this section presents the specific requirements (expected content) of a water management plan according to GLOBALG.A.P. It is included here as an example of what is expected from a farm-level certification scheme in terms of responsible water management. These two approaches are aligned, but take a different angle on the subject. The first is designed to help a company incorporate water in its overall strategy to be a productive, competitive and sustainable business. The second is more related to market access, and reflects the expectations of buyers in global supply chains in terms of evidence of responsible water use.

13.3.1. Basic outline of a farm/business water management plan

1. **Express a commitment to the responsible use of water**. If the farm/business senior management are committed, they are more likely to assign tasks, allocate the necessary resources, and support the employees responsible for implementing the water management plan.
2. **Define the goals and scope of the water management plan**.
    - The scope can be set at different levels: (a) on the farm itself, and/or (b) the watershed, and/or (c) outgrower suppliers. It can focus only on crop production, or also on post-harvest washing, grading and packing.
    - Examples of goals are:
        - secure enough water for crop production;
        - recycle as much water as possible;
        - improve the irrigation system and increase irrigation efficiency;
        - help smallholder outgrowers improve their irrigation practices;
        - manage water risks in line with a risk assessment;
        - comply with national regulations, buyers' requirements, or certification schemes.
3. **Draw or obtain a map of the farm** showing its location within the watershed(s).
4. **Add water sources and users to the farm map**. Draw the location of blue water sources (Chapter 2.2). Indicate the location of other water users (upstream and downstream). Number the sources, and create a table listing their respective characteristics (including water quality, scarcity concerns, other users, and fluctuations in water availability, if any).

5. **Note records of climate data** for the farm, following the methodologies in Chapter 9.
6. **Note detailed information on the farm´s water use,** following the approach in Chapter 2.4. This includes crop water requirements, green blue water consumption, processing and packaging, etc. It should also include factors such as timing of water use (e.g. irrigation scheduling in the growing season), water treatment, recycling and re-use. Describe the 3-5 most serious water availability or scarcity concerns.
7. **Note information on water quality.** This includes water entering the farm, as well as waste water discharged as effluent (with possible pollution), using the methods described in Chapters 6 and 7. Identify the 3-5 main water quality concerns.
8. **Provide information on water regulations.** This should refer to any national regulations, local by-laws, or customs relevant for the catchment/s in which the farm is located (see Chapter 2.2 and Chapter 6). List any relevant public sector water management institutions or schemes, as well as any private irrigation schemes, existing processes or stakeholder platforms.
9. **Describe any social and environmental challenges.** This should focus on the watershed and surrounding area. It could include (for example) aspects such as soil erosion; fragile ecosystems or biodiversity management areas; land prone to flooding; municipal water supply and sanitation infrastructure; areas affected by water pollution. Does the farm contribute to these positively or negatively?
10. **Outline water risks.** Insert the prioritised water risks for the farm using the approach outlined in Chapter 12.
11. **Define focus areas for action** based on the prioritised water risks. For example, increasing overall water use efficiency (Chapter 5), irrigation efficiency (Chapter 8), soil management (Chapter 11), improved access to water by water harvesting and recycling (Chapters 3 and 4), improved water quality (Chapters 6 and 7), increased water allocation to the farm (Chapter 2), irrigation methods and maintenance (Chapter 8), using climate data (Chapter 9).
12. **Identify which measures are cost effective** for the focus areas, following the water economic productivity approach (Chapter 10). Use this to define an action plan (with schedule, targets, and actions).
13. **Collect information and data to monitor impact.** This includes any reduction in water risks after implementing risk mitigation measures. It should also note cost savings, and any changes in productivity and profitability (see Chapter 14 Record Keeping). Based on progress, impact, and any new challenges, update the water management plan annually.

13.3.2. Supporting outgrowers

If the scope of the water management plan includes outgrower suppliers, additional actions need to be defined such as:

1. Map the location of smallholder suppliers.
2. Support and train them to understand their water risks, how their activities impact the local water situation, and how their activities may contribute to water challenges facing their production site.

3. Develop an engagement strategy to help outgrowers develop and implement improved water management strategies.

In practice, the farm water management plan will most likely need to run a parallel processes of:

- applying concrete actions for water use efficiency;
- information gathering;
- planning;
- engagement;
- communication;
- monitoring and adaptive management.

13.3.3. Water management plan and GLOBALG.A.P.

The development of a water management plan is strongly recommended in the GLOBALG.A.P. guidance to optimize water usage and reduce waste[287]. For certification, the plan must be presented in written form, and can either be developed as an individual plan, or a regional activity if the farm is participating in and/or covered by a group or regional scheme. The plan should be based on the GLOBALG.A.P. summary water risk assessment (see Box, Chapter 12).

Some of the water-related GLOBALG.A.P. CPCCs provide a useful additional resource for the development of a water management plan (meeting a major must is compulsory to achieve certification):

- Systematic methods to predict crop water requirements should be used. Calculations and data records should be available, including soil maps and soil moisture content (Recommended).
- Avoid wasting water by using an efficient irrigation system (Major Must).
- Comply with any legislation about local restrictions on water usage (Recommended).

287 www.globalgap.org/export/sites/default/.content/.galleries/documents/160630_GG_IFA_CPCC_FV_V5_0-2_en.pdf.

- Keep records of irrigation/fertigation usage (dates, volumes of water, duration of irrigation) (Recommended).
- Untreated sewage is not used for irrigation (Major Must).
- An annual risk assessment for irrigation water pollution should be conducted (microbial, chemical and physical pollution of all sources of irrigation/ fertigation water) (Minor Must).
- Water quality analysis of irrigation water, and corrective actions and/or decisions are taken if required (Minor Must).
- Water abstraction from a sustainable source (Minor Must).
- Keep written communications with local authorities on advice for water abstractions (Minor Must).
- Good management of plant protection products and containers (Minor Must).

Create a draft water management plan

- Explain why you would want to develop and implement a water management plan?
- What would be your main goals? What would be the scope of the plan? Would it include outgrower suppliers?
- Following the steps given in 13.3.1, create a water management plan for your farm/business.
- Who in your farm/business would be responsible for developing, implementing and monitoring the plan?

13.4. EXAMPLE

13.4.1. Suzan and Kioko

Kioko is now much more aware of the imminent water risks his farm faces:

a. illegal water abstraction;
b. not enough water for his crop; and
c. not knowing how much water his crop needs. In his action plan, he decides to address these three areas.

- **Illegal abstraction of water.** His goal is to obtain water legally from the spring. He will schedule an appointment with the local administration office that provides water permits to find out what he needs to do. Also, he needs to bring the additional cost of the permit/abstraction into his accounting. He knows permits are scarce, so he must find out how much water he can actually get legally.
- **Not enough water for his crop.** He knows his 0.5 ha of tomatoes need 4,350 m^3 of water, and last year he only got 1440 m^3 from the spring, and the crop failed. Now he has more information; he knows rain can take care of half of the crop water needs (around 217 m^3), so he has a gap of around 735 m^3. Previously he considered growing tomatoes on a smaller part of his field, half of it, and to make furrows. In this way he can use all the water he gets to boost productivity in this smaller area. But can he apply conservation tillage to increase the water holding capacity of the soil, and use furrows at the same time? It actually shouldn't be a problem, as water will flow through the furrows, and crop residues can be left on the other areas of soil. If he plants 0.25 ha with tomatoes, he will need about 1,090 m^3 of irrigation water, and perhaps less with the new techniques (furrows, conservation tillage). He will also harvest some water from his roof and store it, and use this in case of drought. He decided not to use household effluents after hearing that these shouldn't be used without any treatment.
- **Not knowing how much water his crop needs.** Kioko will start writing down how much water he applies to the field. But he will also start checking soil moisture content using the simple method explained in the training. He will

use this information to decide when to irrigate. Above all, he will go back to his records at the end of the growing season to get a better idea of crop water needs versus water applications. He will compare this information with the yields obtained. He will also incorporate into the analysis precipitation (rainfall) data obtained from the rain gauge he installed.

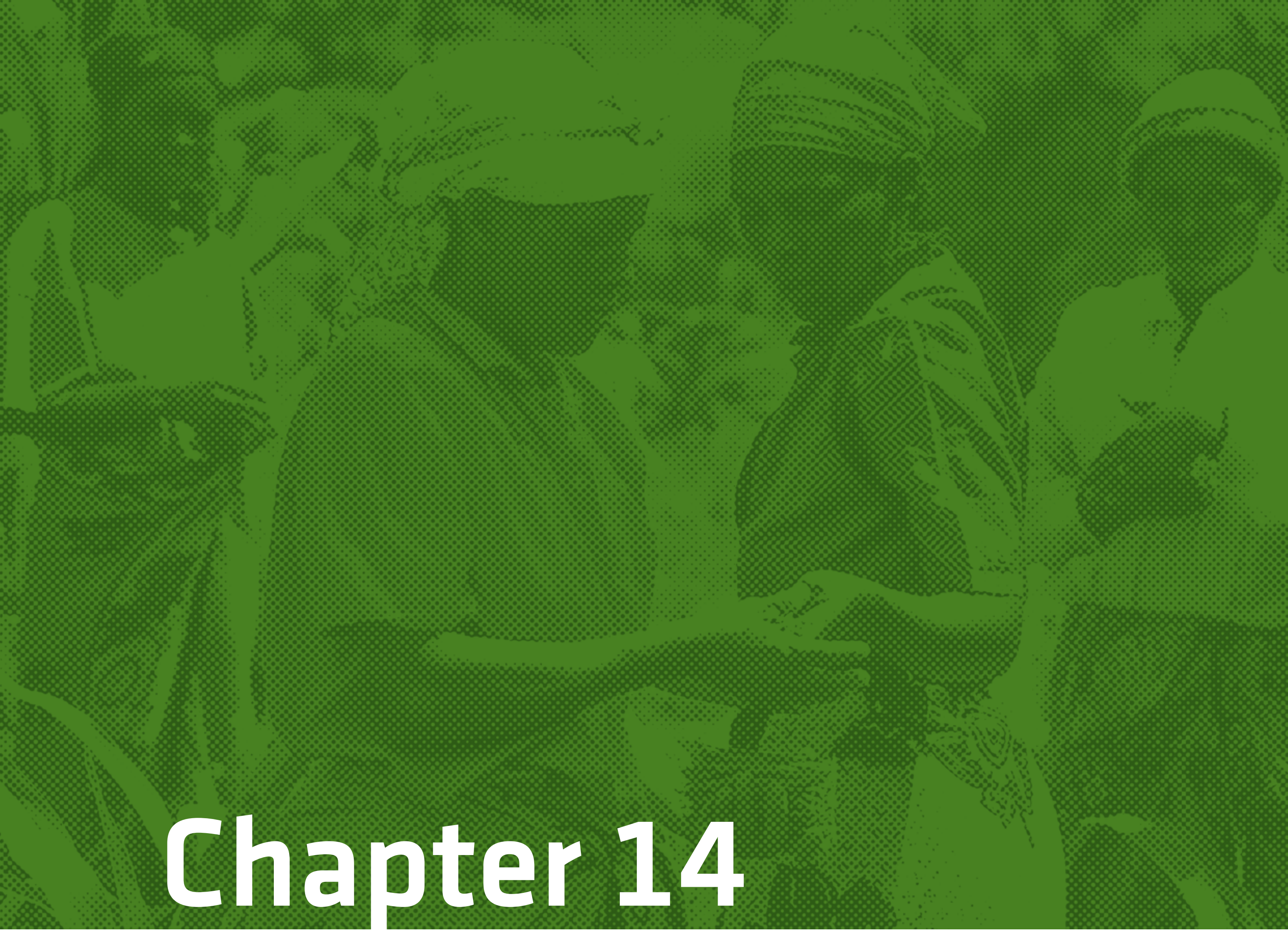
Susan realizes that, apart from the risk assessment, she needs to have a water management plan; this will be a major must (compulsory) for GLOBALG.A.P. certification, from July 2017 onwards. She is now at a critical moment for her business, when exports are highly important, and there is a lot of competition from other companies trying to get their produce into overseas markets. It is a business opportunity not to be missed. She is anxious to ensure that her GLOBALG.A.P. audit goes smoothly, and wants to ensure all 'musts' are met in advance, especially those related to water management.

She has now collected a lot of information including maps and photographs, and her water sources are well identified.

Susan goes through the steps (1 to 13) given in the training course for developing a basic water management plan. As she does so, she finds that she has done a lot of the work on all these points already; she just needs to structure the information into the framework and write it down. Her action plan includes measures at the farm level, and at the watershed/river basin level. These include:

- **At the farm level:** using drip irrigation for her French beans; calculating crop water requirements; monitoring soil moisture content with a tensiometer; completing a water balance for the farm with in-and outflows; amending the soil with organic matter, especially in those patches identified as critical (Example 11). Also, it is clear for her that one crucial action needed is the monitoring of water quality in her waste water effluent. This is priority.
- **At the river basin level:** She needs to engage with other stakeholders additional to the irrigation scheme members. She knows there is a water platform that meets twice per year, and will enquire for membership. She also heard that the district government is preparing a management plan for Galana River basin, so she definitely needs to get their reports and any other information in order to be able to better evaluate her own water risks. She will find out about this from the local administration.

PERSONAL NOTES



Chapter 14

Record keeping

14.1. WHY KEEP RECORDS?

14.1.1. Scope

Record keeping refers to the collection and storage of data relevant to the management of a horticultural farm and business. On the production side, records are kept on soil, climate, crops, fertilizer, crop protection products, hygiene measures, crop yield, outgrowers suppliers, and water, among others. On the business side, data is recorded on employees, input costs, sales, social elements, legal compliance, markets, environmental records, membership of farmer groups or schemes, etc. Record keeping is about the systematically collecting, recording and storage of key data. Records can be kept in paper or electronic form but, with either method, there needs to be a system that allows the data to be accessed easily and rapidly.

In many countries, the national authorities (e.g. Ministry of Agriculture, Ministry of Environment) require certain records to be collected and kept for a specified length of time. A farm or company that is certified to a private standard (e.g. GLOBALG.A.P., BRC, Organic, Fairtrade) will also be required to maintain a series of records that are examined during the audit.

Even where there is no specific legal or commercial requirement to keep records, it should still be an integral part of the running of a successful horticultural business. Keeping and monitoring records provides an understanding of how key factors affect the productivity and profitability of the business. Management decisions that are based on guesswork rather than a real understanding of the situation are risky, and not likely to ensure competitivity and sustainability over the long-term.

> Record keeping is the foundation of any internal control and management system, including traceability.

This Chapter is devoted to water-related record keeping. A farm needs to be aware that keeping records is fundamental to assess and drive performance. Records are vital to manage water efficiently, and are an integral part of water management, including water risk assessment. Water records are kept and used at different levels: internal (to orientate farm operations); supply chain partners (to monitor suppliers and inform buyers); and external (to inform authorities and engage with watershed stakeholders).

14.1.2. Benefits

Some of the benefits of record keeping are as follows:

- An organized record keeping system provides the basic water information needed to assess business **water risks,** and to prepare the **irrigation and water management plans**.
- It allows the **monitoring of progress** in the implementation of water management activities, and an evaluation of **their impact**.
- It provides crucial information for **communication** with suppliers and consumers.
- Information on the water situation in the watershed/river basin allows a company to spot **changes and trends in water availability and quality**, and to have accurate information to make decisions and take action.
- It provides solid data to prove **compliance with legal requirements**; for example, water abstraction permits, water discharges, and quality of effluents. Record keeping also gives the farmer an opportunity to make any necessary amendments prior to a legal inspection.
- It provides evidence of responsible water use to buyers, and is used to assess compliance with private standards such as GLOBALG.A.P. Examination of farm records, including water records, is a fundamental part of a certification audit. Record keeping is a Major Must for GLOBALG.A.P. certification.

14.2. WHAT RECORDS TO KEEP

Previous Chapters have explained in detail the water records that are needed for irrigation planning, for water risk assessments, and for preparation of the water management plan. This section summarizes all water-related data that should be collected at the farm level.

14.2.1. Summary of water-related records

- **Volumes of water abstracted and used (by source):** to monitor basic water consumption over time. This is the most fundamental data to collect. It is essential in order to monitor and demonstrate the impact of improved water management practices. It drives internal water management planning, as well as being used show external stakeholders (e.g. local communities, buyers) that they are responsible water users, and working to reduce consumption.
- **Volumes of water harvested, and storage capacity:** to assess the ability of the farm to be resilient during water scarcity periods, and to calculate potential cost savings on water abstraction.
- **Volumes of water recycled:** to manage supply, report on water stewardship activities, and to calculate cost savings on water abstraction.

- **Quality of intake water,** based on the analysis of key compounds: to monitor trends, address any quality issues with relevant organizations, and to orientate any necessary mitigation or treatment measures.
- **Quality of discharge (waste) water,** based on analysis of key compounds: to report to the relevant authorities, to show water stewardship activities and outcomes, and to orientate any necessary mitigation or treatment measures.
- **Production data** including yield/ha and price/ton: to calculate the agricultural and economic productivity of the water consumed, to monitor trends, and to calculate the financial benefits of improved water management practices.
- **Crop evapotranspiration:** to calculate the blue and green water footprint, productivity, and thus efficiency.
- **Irrigation volumes and scheduling:** to calculate blue water footprint and water productivity.
- **Records of water challenges/extremes:** to better understand and plan for water risks, for example due to water scarcity or flooding.
- **Spillages and pollution incidents** both affecting and caused by the farm: for internal and external reporting to the authorities and other stakeholders, particularly in the event of a risk to drinking water supplies or environmentally sensitive areas. It should be accompanied by information on measures taken to address the problem, and any adaptations to management (mitigation measures) to prevent future incidents.
- **On-farm climate data:** detailed measurements of temperature, precipitation (rainfall) and evaporation, for better management of irrigation, crops and water.
- **Key soil data** (in particular soil texture, structure, nutrient levels, and carbon content)**:** to better understand and improve soils, soil management, and water use.
- Real time soil moisture tension data, field capacity: to improve quantity and scheduling of irrigation.
- **Watershed information** on water scarcity, levels of pollution, biodiversity and ecosystems, and legal frameworks: for the integrated analysis and management of water risks.
- **Supply chain information** particularly concerning smallholder suppliers, as well as buyer requirements.

14.2.2. GLOBALG.A.P. as an example of record keeping requirements

Adequate record keeping is compulsory for GLOBALG.A.P. certification. The records that must be kept are specified, and are checked in detail during the audit.

In the All-Farm CPCCs. Water-related records include:

- Site history and site management. Farm maps to locate key infrastructure, water sources, landscape features, and production areas, among others.
- Information on soils, climatic conditions, water availability, water quality, and water rights.

- A written risk assessment to identify potential physical, chemical and biological hazards, records of previous land use, and key features of the physical and social environment. Develop a plan and put procedures in place to mitigate and control hazards, and to implement long-and short terms solutions. Regularly check, update and record implementation of the plan.
- Hygiene procedures involving water.
- The identification and listing of waste products (e.g. paper, oils, empty containers and bags, water pipes, wood, waste water) and potential sources of pollution (e.g. pesticides, fertilizers, biocides, sanitation products). Record how they are disposed of to protect worker health, food safety, and the environment.
- Have a conservation plan to avoid negative impacts, and to enhance the surrounding environment and biodiversity.
- Any measures put in place to harvest and recycle water, taking into account food safety risks.

Water related records specific to the Crops Base CPCCs include:

- Information on chemical characteristics of purchased material or seeds.
- Soil management plan including soil maps, crop rotation information, erosion control, seed rate and planting dates.
- Pesticides and fertilizer information (sources, types, dates, application rates and methods, storage).
- Tools used to predict irrigation requirements.
- Water management plan identifying water sources and measurements, to ensure water efficiency.
- Identification and location of water infrastructure including wells, valves or gates as well as written maintenance records.
- Volumes used of water, fertilizers and pesticides.
- Water quality (requiring laboratory analysis).
- Water extraction permits and licenses.
- Water storage facilities used, as well as their licenses, condition and characteristics.

14.3. RECORD KEEPING SYSTEMS

14.3.1. Methods available

Depending on the resources, technology, and capacity available on the farm/business, different methods can be used to make and keep farm records. Whatever system is used, it is very important that at least one person is in charge of coordinating data collection in each key area (irrigation, production, packhouse).

Electronic systems greatly facilitate the storage, organisation and analysis of data, particularly in larger farms and businesses. However, in rural areas, access to electricity and the internet can be a limitation. If necessary, data can be recorded on paper and later transferred to a laptop or PC. Record keeping systems using tablets and smartphones are also increasingly available.

14.3.1.1. Paper records

Taking records, making calculations, and drawing farm maps can all be done by hand. Howeber, given that over time this is likely to generate a large quantity of paper, it crucial to have a system in place to organize and store the material so that it is safe, and easy to access when needed. For small farms or businesses, particularly in rural areas, paper records may be the most practical and affordable solution.

14.3.1.2. Checklists and excel spreadsheets

Computer-based systems can be used, with or without internet connection, if the necessary resources and infrastructure are available. Simple checklists or Excel spreadsheets can be used to record the data, and store it in digital form, so that it is easy to access, correct, add to, and analyse at any time. A basic spreadsheet to record the different activities can be downloaded from www.nebeginningfarmers.org/2012/04/15/15-record-keeping.

Checklists from certification schemes can also be downloaded and adapted to create a framework for a record keeping system. An example is the GLOBALG.A.P. checklist.

Also the LEAF checklist, which can be downloaded at www.leafuk.org/leaf/global/search.eb?terms=checklist. LEAF (Linking Environment and Farming) is a UK NGO working with farmers to produce food sustainably. The LEAF checklist has a particular focus on environmental criteria, including water.

14.3.1.3. Web/Smartphone applications and hi-tech record keeping software

Many options now exist in the market to record all types of farm data, enabling the farmer to record, keep and analyze records in real time using different devices including computers, tablets or smartphones. In this case, more advanced equipment, IT capacity, an Internet connection, and possibly IT training or support, are needed. An example of this technology can be found at farmlogs.com.

Are your current records and record keeping system good enough?

- Do you already have to keep farm records and make them available to an external agency (e.g. local authority, client, certification scheme)?
- If so, which agency? What records? Does this include water-related data?
- Do you systematically collect and keep water-related records for your own internal farm/business use? If so, which records?
- Do you analyze and use this information to help you make management decisions (e.g. cropping, irrigation volumes and scheduling, investment in water infrastructure)?
- Is this information sufficient for you to have a full picture of your water situation and the effectiveness of your water management activities?
- Is the information enough for you to conduct a water risk assessment, and develop a water management plan?
- What key information do you feel is missing?

14.4. EXAMPLE

14.4.1. Suzan and Kioko

Kioko thinks about all the changes he has made to his farm in search of more efficient water use. This includes calculating crop water needs, measuring irrigation, changing the irrigation systems, managing soils and fertilizer applications, knowing the water risks... However, while thinking about and planning next seasons cropping, he can't remember the volume of water he needed to irrigate his tomatoes last year; he has also forgotten to write down some rainfall measurements from the rain gauge, and so doesn't have a complete picture. He realizes that he will have to try and get rainfall data from somewhere else, as well as having to do the calculations again, and he feels annoyed.

When he attended the water training course, he drew a map with his farm and water sources; this was quite useful, and helped him to see how water and climate change are affecting his crops. He also drew a rough soil map, blocking out different soil types according to their textures, but since then he hasn't really looked at it. He realizes that he is wasting an opportunity to use all this information, and decides to take further action and follow it up. Next day he goes to Taveta town and buys notebooks, paper, pens, and folders to record all the data he has, and to start organizing it.

While he is in town, he comes across an old friend who tells him about new stricter regulations on water pollution control. He also hears about a supermarket chain that is looking for local growers to supply high quality produce for a new store in Nairobi. This really motivates Kioko to think about taking more control over his farm activities. He really wants to avoid any problems with the authorities (and possible fines), and is keen to explore the possibility of making more money with the new market. He knows that he has already done a lot of the work, but just needs to be better at organizing the information, and using it.

With the help of his wife, they recalculate the water needed to irrigate last year, and start to record daily data on water. This includes rainfall, water harvested from the roof, irrigation water, pesticides and fertilizer used, dates of planting and other production-related activities, and the volume of all water used. It makes him much more aware of the value of water, especially as water abstraction permits are becoming very limited, and rainfall patterns are becoming quite unpredictable (perhaps because of climate change).

After that, he wonders about the best method to organize these records, as well as the measures he needs to take something goes wrong. With all of this, he feel that he is in a better position to look into the possibility of accessing the new market he heard about.

Now that he is taking more control and care of the farm, is being more systematic and businesslike, the farm looks cleaner, crops seem to be growing well, he is less dependent on purchased water (under the permit), and he knows what he needs to do every day to keep things running smoothly.

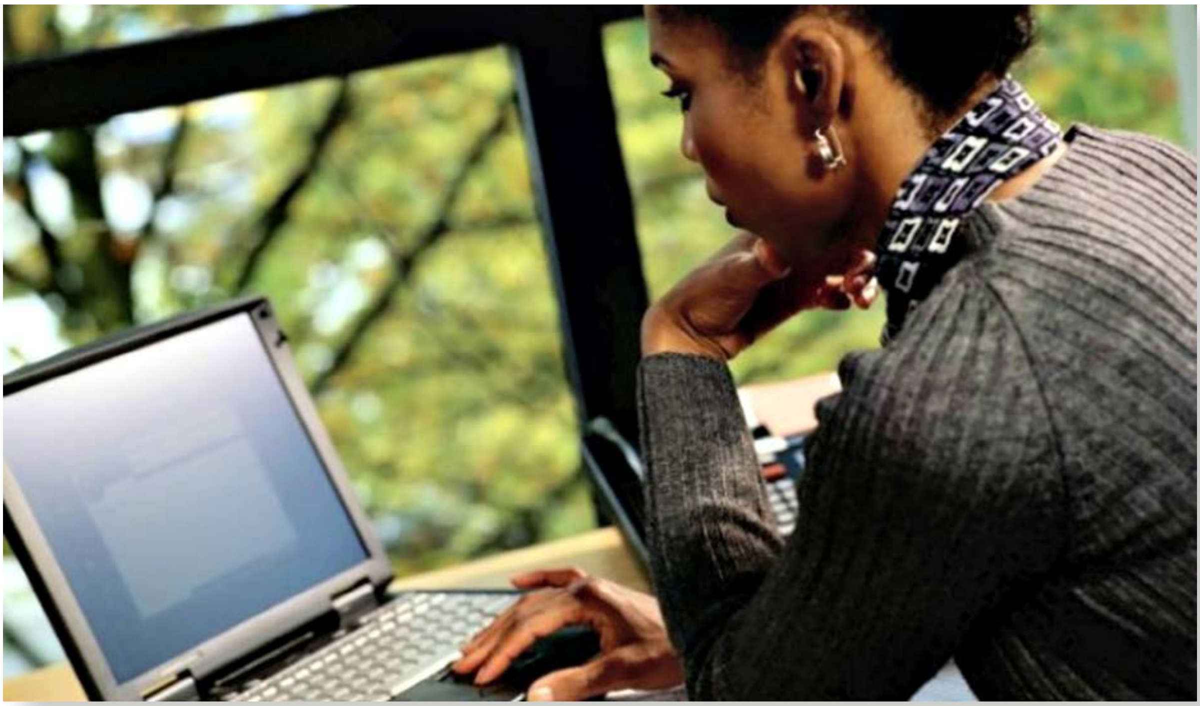
Susan has been taking detailed records of many criteria and farming activities since she received a request from her buyers in the UK to become GLOBALG.A.P. certified.

She has created maps and drawings of water sources; she records volumes of fertilizers and water used; and she has developed a water management plan. However, there are still several more areas that are causing her trouble. This includes the solid wastes she found in the field, and the untreated water that she is still discharging into the river. She also realizes that record keeping is a major must for GLOBALG.A.P. certification, but her records are incomplete and disorganized. She also recalls that one of her workers told her about an issue with salts in the soil, which she has not addressed.

She has come to realize that since the farm started recording all of this data, her workers are much more aware, and are taking more care of the way they use water. The volumes of water abstracted have reduced, and the farm in general looks much better. However, she is afraid that because she has not taken control of the effluent problem, or put in place measures to control incidents that could affect her crops, she may have a problem with the GLOBALG.A.P. audit. She also fears that she may not be complying with new local regulations on pollution control and environmental protection.

Based on the experience she has gained over the past year, she decides to get training for herself and perhaps some of her workers on using excel spreadsheets. In addition, she needs to make or find templates she could use to help her organize her records, and to make sure that she covers all the points included in the audit (checklist). She also knows that she needs to put in place a system for more effective internal auditing so that she is fully prepared for certification.

She realizes that she could really do with some more help and advice. She contacts the national horticultural association to get information on any technical assistance programmes operating in the horticulture sector, who could provide her with the support she needs.



Most used abbreviations and acronyms

MOST USED ABBREVIATIONS AND ACRONYMS

ACP	African, Caribbean and Pacific (Group of ACP States that have signed a series of agreements with the EU, called the 'Cotonou Agreements')
AWS	Alliance for water standardship
BOD	Biochemical oxygen demand
C	Chemical symbol for carbon
Ca	Chemical symbol for calcium
CCP	Critical control point (under the HACCP method)
CDP	Carbon Disclosure Project
CEC	Cation Exchange Capacity
Cl	Chemical symbol for Chlorine
CO_2	Chemical symbol for Carbon dioxide
CPCC	Control points and compliance criteria
CR	Capillary Rise
CSA	Climate-smart agriculture
DP	Deep percolation
Dr	Root zone depletion
dS/m	Deci-Siemens per meter
ea	Application efficiency
ec	Conveyance efficiency
EC	Electrical conductivity
EEA	European Environmental Agency
EPA	Environmental Protection Agency (USA)
ET	Evapotranspiration
ET_c	Evapotranspiration for a specific crop
EU	European Union
FAO	Food and Agriculture Organisation: UN organisation that addresses food security problems in the world

FC	Field capacity
GIS	Geographic Information Systems
GMO	Genetically modified organism
GSI	Good Stuff International
GRAS	Generally Recognised As Safe
H	Chemical symbol for hydrogen
H_2O	Chemical symbol for water
HCO_3	Chemical symbol for bicarbonate
HGCA	Home Grown Cereals Authority
I	Irrigation
IFA	Integrated Farm Assurance
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
IR	Irrigation requirements
IT	Information Technology
IWRM	Integrated Water Resource Management
K	Chemical symbol for potassium
K_c,	Equilibrium constant, the equilibrium of a chemical reaction
KCl	Chemical symbol for potassium chloride
kPa	Kilopascal
K_s	Stress coefficient
K_{sat}	Average permeability
ky	Yield response factor
LEAF	Linking Environment and Farming
LLL	Laser Land Levellers
m.a.s.l.	Meters above sea level
Mg	Chemical symbol for magnesium

MIR	Maximum infiltration rate of the soil
N	Chemical symbol for nitrogen
NaCl	Chemical symbol for sodium chloride
O	Chemical symbol for oxygen
OECD	Organisation for Economic Cooperation and Development
OM	Organic matter
P	Chemical symbol for phosphorus
PAN	Pesticide Action Network
pH	Potential for hydrogen
PIC	Prior Informed Consent
PWP	Permanent Wilting Point
RAW	Readily Available Water
RO	Runoff
S	Chemical symbol for sulphur
SAR	Sodium Adsorption Ratio
SO_4^{2-}	Chemical symbol for sulphate
SOM	Soil organic matter
SWC	Soil Water content
TAW	Total Available Water
TDS	Total Dissolved Solids
UN	United Nations Organisation
UNEP	United Nations Environment Programme
UNESA	University of New England Student Association
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFPA	United Nations Population Fund
WBCSD	World Business Council for Sustainable Development
WFD	European Water Framework Directive

WFN	Water Footprint Network
WFP	World Food Programme
WHO	World Health Organization
WP	Wilting Point
WRI	World Resources Institute
WRMA	Water Resources Management Authority
WRUA	Water resource user associations
WUE	Water use efficiency of productivity
WWF	World Water Forum

Glossary

GLOSSARY

Action limit/ level	Value set for a parameter in a given matrix. Threshold established to launch an 'action' such as: notification, product recall, counter-analysis, destruction. Thresholds are based on regulatory admissible value limits (e.g.: MRL). In the absence of a reference standard, the threshold is proposed by the industry and validated by an authority.
Action threshold	Threshold at which the source of pollution must be determined and measures taken to reduce or exterminate it. See 'Action limit/level'.
Additional declaration	A statement required by an import country to be entered on a phytosanitary certificate and which provides specific additional information on a consignment regarding regulated pests.
Aggregate sample	The combined total of all the incremental samples taken from the lot or sub-lot.
Approval	Procedure by which a local or regional authority officially recognises that a body (e.g.: ICB), a laboratory (e.g.: laboratory accredited for microbiological analyses) or an individual (e.g.: self-evaluation system inspector) is competent to undertake specific tasks.
Approved/ Accredited laboratory	Laboratory officially authorised, on the basis of its performance, to examine samples (which may be official samples). It can also be an 'accredited' laboratory under ISO 17025.
Attribute sampling plan (n, c, m, M)	A 3-class attribute sampling plan is determined by the number of samples that must be tested (n), the level (or number of germs) authorised (m), the maximum level authorised (M) and the number of samples showing a result between m and M (c).
Audit	A systematic and independent examination to determine whether activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve objectives (source: Regulation No 882/2004 of the European Parliament and of the Council of 29 April 2004 on official controls performed to ensure the verification of compliance with feed and food law, animal health and animal welfare rules). The term 'audit' is used in the internal validation of self-evaluation systems.
Authority (or Competent Authority)	Central authority of a State (e.g.: food agency, ministry, etc.) competent to organise official controls and to validate self-evaluation systems.

Cause	An activity, factor or situation responsible for introducing a hazard or increasing it to an unacceptable level.
Checklist	Tool comprising a complete inventory of the points to be checked, which is completed by inspectors on the basis of what they observe.
Clean water	Water that does not compromise food safety in the circumstances of its use.
Cleaning	The removal of soil, food residue, dirt, grease or other objectionable matter.
Codex Alimentarius	Set of internationally recognised laws and standards applicable to processes, directives and recommendations on food, food production and food safety. The name is Latin for 'food book'. The texts that make up this system of laws and standards are drawn up by the *Codex Alimentarius* Commission (CAC), an institution set up by the Food and Agriculture Organisation (FAO) and the World Health Organization (WHO).
Commodity	A type of plant, plant product or other article being moved for trade or other purpose.
Commodity pest list	A list of pests occurring in an area which may be associated with a specific commodity.
Compliance procedure (of a consignment)	Official procedure used to verify that a consignment complies with phytosanitary import requirements or phytosanitary measures related to transit.
Contaminant	Any biological or chemical agent, foreign matter, or other substances not intentionally added to food which may compromise food safety or suitability.
Contamination	Introduction or occurrence in a food product, storage area, means of transport or container of pests or other regulated contaminants, without there being infestation (see infestation).
Contamination (or alteration)	Occurrence or introduction in a food product of biological, chemical or physical substances, in a quantity sufficient to endanger health or to render this food product unfit for human consumption.
Control (noun)	The state wherein correct procedures are being followed and criteria are being met.
Control (verb)	To take all necessary actions to ensure and maintain compliance with criteria established in the HACCP plan.

Control measure	Any action and activity that can be used to prevent or eliminate a food safety hazard or reduce it to an acceptable level. Any measure that can be used to prevent, limit or eliminate an identified hazard.
Control point	A step in a system where specific procedures can be applied to achieve a defined effect and can be measured, monitored, controlled and corrected.
Corrective action	Any action to be taken when the results of monitoring at the CCP indicate a loss of control.
Critical Control Point (CCP)	A step at which control can be applied and is essential to prevent or eliminate a food safety hazard or to reduce it to an acceptable level.
Critical limit	A criterion which separates acceptability from unacceptability. Deviation: Failure to meet a critical limit.
Cultivation	Any agricultural action or practise used by growers to preserve and improve the conditions for growing fresh fruits or vegetables in the field.
Disinfection	The reduction, by means of chemical agents and/or physical methods, of the number of micro-organisms in the environment, to a level that does not compromise food safety or suitability.
Distribution	Placing of a product on the market without any major changes to the nature of the product.
Dose-response	Determining the relationship between the amount of exposure (dose) to a chemical, biological or physical agent, and to severity and/or frequency of the resulting effects on health (response).
Efficacy (treatment)	A defined, measurable, and reproducible effect of a prescribed treatment.
Establishment	Any building or area in which food is handled, as well as the surroundings under the control of the same management.
Export	Sending plants, vegetables or other materials to another country.
FAO (Food and Agriculture Organisation)	The United Nations Food and Agriculture Organisation is an organisation that fights hunger in the world.
Flow diagram	A systematic representation of the sequence of steps or operations used in the production or manufacture of a particular food item.

Food handler Any person who directly handles packaged or unpackaged food, food equipment and utensils, or food contact surfaces and is therefore expected to comply with food hygiene requirements.

Food hygiene Comprises conditions and measures necessary to ensure safe and suitable food at all steps of the food chain (guaranteeing fitness for human consumption).

Food or foodstuff Any substance or product, whether processed, partially processed or unprocessed, intended to be, or reasonably expected to be ingested by humans.

Food safety Assurance that food will not cause harm to the consumer when it is prepared and/or eaten according to its intended use.

Food suitability Assurance that food is acceptable for human consumption according to its intended use.

Fresh Living; not dried, deep-frozen or otherwise conserved.

Fruits and vegetables Category of commodity corresponding to the fresh parts of plants intended for consumption or processing, not for planting (FAO, 1990; revised ICPM, 2001).

HACCP A system which identifies, evaluates, and controls hazards which are significant for food safety.

HACCP Plan A document prepared in accordance with the principles of HACCP to ensure control of hazards which are significant for food safety in the segment of the food chain under consideration.

Hazard A biological, chemical or physical agent in, or condition of, food with the potential to cause an adverse effect to human, animal or vegetable health.

Hazard analysis Approach that consists of collecting and evaluating data on risks and the factors that lead to these risks, in order to decide which pose a threat to food safety and should thus be taken into account in the HACCP plan.

Host pest list List of pests that that infest a plant species, globally or in an area.

Incidence The number of *new* cases of a disease per population for a given time unit. Incidence should not be confused with prevalence, which indicates how many people/animals in a given population suffer from a disease at a given time.

Incremental sample A quantity of material taken from a single place in the lot or sub-lot.

Inspection	Controlling the performance of the self-evaluation system, either by an authorised ICB or by an official control service.
Inspector	Person authorised, by a public or private, national or international, organisation to carry out this task. Synonym of 'controller'.
IPPC (International Plant Protection Convention)	The IPPC is an international plant health agreement that aims to undertake actions to prevent the introduction and spread of pests and to promote adequate pest control measures.
Iteration	Process that is repeated, making it possible to perform calculations.
JECFA (Joint FAO/ WHO Expert Committee on Food Additives)	The JECFA is an international scientific expert committee administered jointly by the FAO and the WHO. Initially set up to evaluate the safety of food additives, its work now also includes the evaluation of contaminants and naturally occurring toxicants.
Laboratory sample	The sample sent to, or received by, the laboratory. A representative quantity of material removed from the bulk sample.
Latent infection	Infection for which no clinical signs of infection can be detected.
Legislation	The set of laws, decrees, regulations, directives or other administrative measures adopted by a government. Phytosanitary legislation refers to the phytosanitary regulations of the FAO.
Limit of detection (LOD)	The lowest quantity of a substance that can be distinguished, by analytical testing, from the absence of that substance within a pre-determined acceptable statistical certainty. For substances that have no admissible values, the detection capacity is the smallest concentration at which an analysis method can demonstrate that a sample is in fact polluted.
Lot (for animals)	A group of animals living together.

Lot (plants) Set of units (plants or plant products): (1) belonging to the same plot of land or same section of this plot, which was planted at approximately the same time, received the same treatments, and which has not yet been harvested; (2) single commodity, identifiable by its homogeneity of composition, origin, etc., forming part of a consignment.

According to the standard ISPM No 31, a lot to be sampled (to control the consignment) should be a number of units of a single commodity identifiable by its homogeneity in factors such as:

- origin;
- grower;
- packing facility;
- species, variety, or degree of maturity;
- exporter;
- area of production;
- regulated pests and their characteristics;
- treatment at origin;
- type of processing.

Manure Animal excrement which may be mixed with litter or other material.

Mark An official stamp or brand, internationally recognised, applied to a regulated article to attest its phytosanitary state.

Maximum authorised levels Maximum residue levels of plant protection products and nitrates, established respectively in Regulation (EC) No. 396/2005 and Regulation (EC) No. 1881/2006 on maximum residue levels of certain contaminants in food.

Maximum residue level (MRL) Upper legal level of a concentration for a pesticide residue in or on food or feed set on the basis of good agricultural practice and the lowest consumer exposure necessary to protect vulnerable consumers.

Mesophile (flora or germ) Mesophilic micro-organisms are those that multiply between 20 and 45 °C, with optimum growth at 37 °C. They can be found in foods kept at room temperature. The main species of germs and bacteria can be classified as mesophiles, in particular pathogens, but also spoilage bacteria.

Microbiological criterion	A microbiological criterion for food defines the acceptability of a product or a food lot based on the absence, presence or number of micro-organisms including parasites, and/or the quantity of their toxins/metabolites per unit(s) of mass, volume, area or lot.
Micro-organisms	Includes yeasts, moulds, bacteria, viruses and parasites or any other live organism not observable to the naked eye. Occasionally, the term 'microbe' is used.
Monitor	The act of conducting a planned sequence of observations or measurements of control parameters to assess whether a CCP is under control.
NOAEL (No Observed Adverse Effect Level)	Level of exposure, expressed, for example, in µg/kg bw/day, for which no negative effect on health has been found. This level is determined through testing on animals.
Notification level	Limit value from which an operator/laboratory/certification or inspection body is obliged to notify authorities about a given parameter/matrix.
OIE (World Organisation for Animal Health)	Intergovernmental organisation responsible for promoting animal health at global level.
Operator	Natural or legal person responsible for respecting the rules established in regulations on self-evaluation, mandatory notification and traceability in the food chain under its management.
Organism	Any biological entity that can reproduce and multiply in its natural state (ISPM No. 3, 2005). A quarantine pest is a pest of potential economic importance to the endangered area and either not yet present there or present but not widely distributed and being officially controlled.
Oro-faecal route	Transmission route of a pathogen found in the faeces (excrement), which is involuntarily ingested through contact between the mouth and soiled hands or when this agent has been transmitted to food by unwashed hands or soiled objects. Many parasites are transmitted in this way.
Packaging	Placing a product in a container or recipient in direct contact with the product concerned. Also the actual container or recipient.
Pathogen	Micro-organism capable of causing injury or illness.

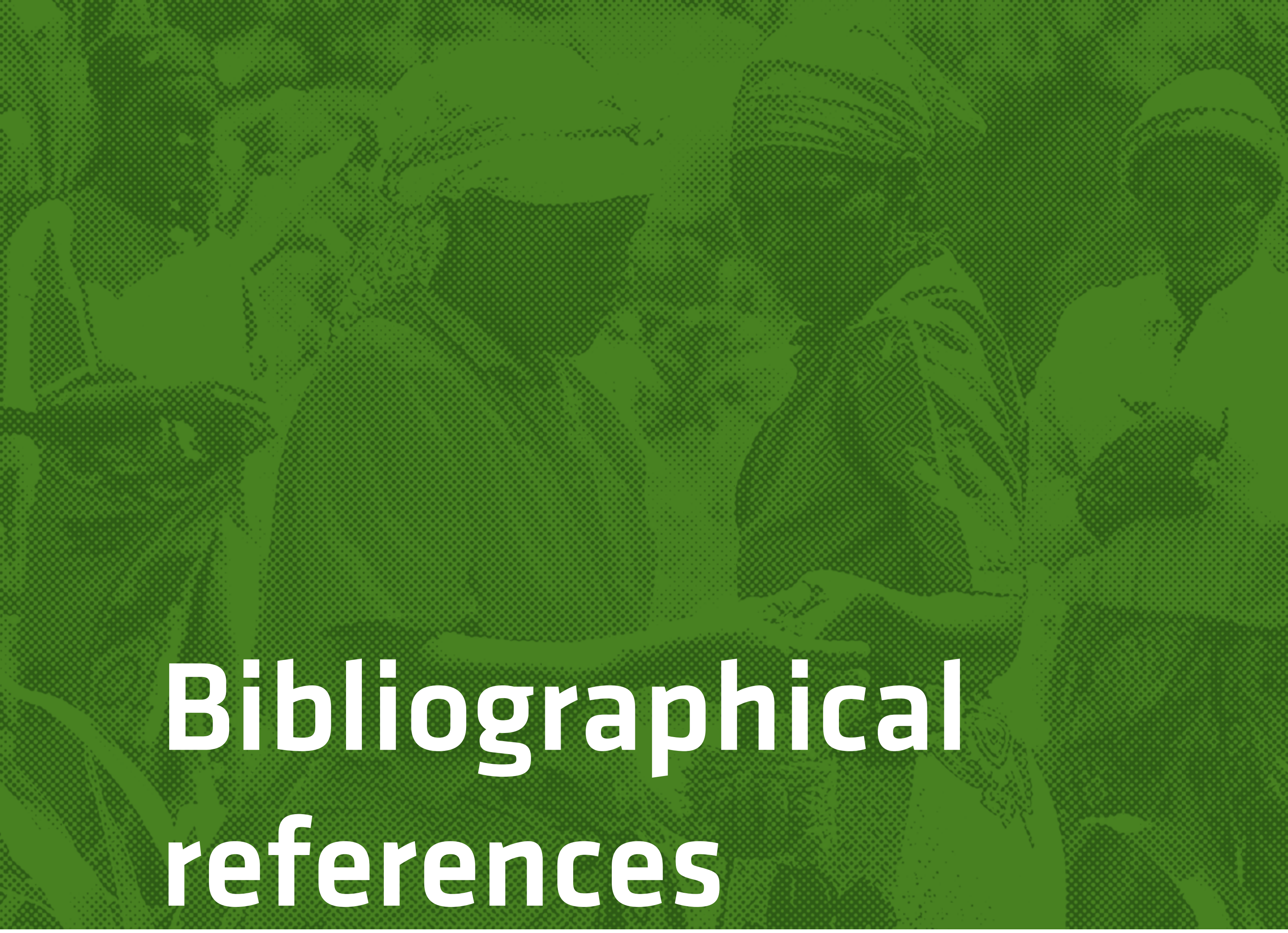
Percentile	A percentile of a set of data is one of the 99 points along the orderly set of data divided into 100 parts of equal size. The 95th percentile, for example, is a number that is higher than or equal to 95% of the data and less than or equal to 5%.
Performance criteria	Result required by one or more control measures that have been implemented, at one or more production stages, to guarantee food safety. If performance criteria are established, they must account for the foodstuff's initial degree of contamination by the microbiological hazard and any changes that occur in this degree of contamination during production, processing, distribution, storage, preparation and consumption of this foodstuff.
Performance objective (PO)	The maximum frequency and/or concentration of a hazard in a food at a specified step in the food chain before the time of consumption that provides or contributes to a Food Safety Objective (FSO).
Pest	Any animal or insect of public health importance including, but not limited to, cockroaches, rodents, etc. that may carry pathogens that can contaminate food.
Pesticide residues	Remnants, including active substances, metabolites and/or products generated by the degradation or reaction of the active substances used, presently or in the past, as contaminants on or in a food.
Phytosanitary Certificate	Certificate patterned after the model certificates of the IPPC.
Phytosanitary inspection	Official visual examination of plants, plant products or other regulated articles to determine whether pests are present and/or to determine compliance with phytosanitary regulations (FAO, 1990; revised CEPM, 1999).
Place of production	Any premises or collection of fields operated as a single production or farming unit. This may include production sites which are separately managed for phytosanitary purposes.
Plant products	Unmanufactured material of plant origin (including grain) and those manufactured products that, by their nature or that of their processing, may create a risk for the introduction and spread of pests.
Potable water	Water which meets the quality standards of drinking water as described in the WHO Guidelines for Drinking Water Quality.

Precautionary principle	Regulation (EC) No 178/2002 describes the precautionary principle as follows: In specific circumstances where, following an assessment of available information, the possibility of harmful effects on health is identified but scientific uncertainty persists, provisional risk management measures necessary to ensure the high level of health protection chosen in the Community may be adopted, pending further scientific information for a more comprehensive risk assessment.
Pre-harvest control	Control of certain fruit and vegetable species made before harvest by an approved producers' organisation or other approved body. This control consists in sampling the lot and analysing it in an accredited laboratory (for example, to detect certain residues and, if one or more maximum levels are exceeded, to monitor the batch concerned).
Prevalence	How many people/animals in a given population suffer from a disease at a given time.
Primary production	Those steps in the food chain up to and including, for example, harvest, slaughter, milking and fishing. The set of steps taken in the growing and harvesting of fresh fruits and vegetables such as planting, irrigation, application of fertilizers, application of agricultural chemicals, etc.
Primary production - plants	The production of plants, fruits and vegetables intended for trade and processing, or as fresh food or feed. Primary production: production and growing of primary products, including harvest.
Producers' organisation	Organisation as defined in article 11 of Council Regulation (EC) 2200/96 of 28 October 1996 on the common organization of the market in fruit and vegetables.
Product inspection	Controlling whether the quality and quantity of a lot corresponds to the conditions contained in the order form
PS	Private, or voluntary, standard: industry-defined production standard compiled in reference systems or technical specifications.
Quality	All characteristics relating to the nature, state, composition, nutritional aspects, packaging and labelling.
Quarantine	Official confinement of products for observation and research or for further inspection, testing and/or treatment.
Recall	Any measure applied after distribution that aims to prevent consumption or use of a product and/or to inform about the danger involved if the product has already been consumed.

Registration	(1) Document in a quality system; (2) Data; (3) Identification of a product or an operator and his establishment.
Regression analysis	Statistical technique for analysing data which focuses on a (possible) specific relation (called a *regression function*) between variables.
Risk	Probability that a hazard will cause an effect considered to be 'harmful' to consumer health (health risk) or to that of plants (phytosanitary risk). When hazards can be identified and the risks analysed their impact on health can generally be predicted. Food risk is that to which the consumer is exposed on eating.
Risk assessment -deterministic	The deterministic method, for each variable of the model, uses a single point estimate (such as the average) to determine the result of the model.
Risk assessment -probabilistic	In the probabilistic method, the model variables are considered as distribution values.
Sampling	Controlling a product based on analysis of a sample taken for this purpose. The act of taking a sample.
Sampling plan	The steps, collection method and number of samples that must be taken and tested to ensure the control and monitoring of a process.
Saprophyte (flora or germ)	Micro-organisms that develop from food products or non-living organic matter (milk, excrement, humus, etc.) which they decompose and putrefy. Many fungi and bacteria are saprophytes. Although they are not often directly pathogens, they can produce toxins that can lead to poisoning.
Scenario analysis	In a scenario analysis, various risk management measures ('scenarios') are compared in order to study which is more apt to limit the risk. Scenario analysis can also be used when the current state of knowledge precludes a single evaluation of risks, i.e. if information is missing or insufficient to attribute a probability to different scenarios.
Self-assessment	Set of measures taken by operators to ensure that the products they manage at all production, processing and distribution stages meet food safety legal requirements and product quality and traceability requirements; and that there is effective control of these requirements. The term 'self-assessment system' means the application of rules regarding hygiene and record-keeping.

Sensitivity analysis	Method used to examine which variables, in a hazard analysis model, have the greatest impact on the results of this model.
Spreading	The transfer of contamination to the healthy (parts of) plants through contact with the diseased (parts of) plants. Spreading is often associated with the presence of exudate on the (parts of the) plants infected by the bacteria. Large quantities of bacteria accumulate in an oozing substance (exudate) formed in specific conditions. The exudate also protects bacteria against unfavourable external conditions such as drying, sunlight or heat. Bacteria can thus survive several months in this exudate.
Standard	(1) Limit established by regulation (2) Document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context.
Step	A point, procedure, operation or stage in the food chain including raw materials, from primary production to final consumption.
Storage area(s)	The place or set of places where foodstuffs are stored
Stored Product	Unmanufactured plant product intended for consumption or processing, stored in a dried form (this includes in particular grain and dry fruits and vegetables).
Surveillance/ Monitoring	Careful observation of events that have a risk or significant impact on health. National monitoring/surveillance plans are an essential tool for food safety and for added value in exported products: • effective and complete plans provide a guarantee of product quality; • regular publication of their results provides information on the stringent controls conducted by a State's inspection and phytosanitary services in order to protect consumer health.
Third party	See ICB. Party that has no vested interest in its action.
Tolerance level (for a pest)	Incidence of a pest. Specifies a threshold for action to control that pest or to prevent its spread or introduction.
Traceability	The ability to follow the movement of a food through all the stages of production, distribution and processing.

TRV (Toxicological reference value)	A general expression to designate toxicological parameters such as ADI (acceptable daily intake), AOEL (acceptable operator exposure level), etc.
Uncertainty	Also called epistemic uncertainty, this is a lack of perfect knowledge. When uncertainty is associated with variability, it becomes impossible to predict what will happen in the future.
Validation	Obtaining evidence that the elements of the HACCP plan are effective.
Variability	Variability means heterogeneity or diversity in a pre-defined population. It can also mean the consequence of incomplete knowledge and thus, when associated with uncertainty, makes it impossible to predict what will happen in the future.
Variability - interspecies	Variability among different species.
Variability - intraspecies	Variability within the same species.
Verification	The application of methods, procedures, tests and other evaluations, in addition to monitoring to determine compliance with the HACCP plan.
WHO	The World Health Organization (WHO) is a United Nations organisation established to provide an overview of global public health aspects, coordinate public health activities and improve the health of the global population.
Withdrawal	Any measure aiming to prevent the distribution and display for sale of a product, as well as its availability to consumers.
Wood packaging material	Wood or wood products (excluding paper products) used to support, protect or carry a commodity (includes dunnage) (ISPM No. 15, 2002).



Bibliographical references

BIBLIOGRAPHICAL REFERENCES

Abbott, C.L. and Hasnip, N.J., *The safe use of marginal quality water in agriculture. A guide for the water resource planner*, HR Wallingford, Report OD 140, 1997, eprints.hrwallingford.co.uk/101/1/od140.pdf.

Agrofair Sur, ''Factores que predisponen el crecimiento y desarrollo del cultivo de banano orgánico en 'Savanna grown'", TASTE, ApecoInca, Master SRL, 2011.

Agrofair Sur, ''Introducción de bananos 'Savanna grown' y 'Mountain grown': hacia nuevos conceptos para una fruta tropical más sostenible. Estudio territorial ambiental y estudios de caso socioeconómicos y ambientales de fincas bananeras en Perú'', TASTE, ApecoInca, Master SRL, 2011.

Alberta Water Council, "Water conservation", 2015, www.waterforlife.alberta.ca/01549.html.

Aldaya, M., García-Novo, F. and Llamas M.R., "Incorporating the water Footprint and environmental Water requirements into Policy: reflections from the Doñana region (Spain)", Papeles Agua Virtual, Madrid, Observatorio del agua, Fundacion Marcelo Botin, 2010, www.huellahidrica.org/Reports/Aldaya-et-al-2010-Donana.pdf.

Aldaya, M.M., Garrido, A., Llamas, M.R., Varelo-Ortega, C., Novo, P. and Casado, R.R., "Water footprint and virtual water trade in Spain", in *Water policy in Spain* (A. Garrido and M.R. Llamas eds.), Leiden, CRC Press, 2010, pp. 49-59.

Allen R.G., Pereira, L.S., Raes, D. and Smith, M., "Crop evapotranspiration - Guidelines for computing crop water requirements", FAO Irrigation and drainage paper 56, Rome, FAO, 1998.

Bachman, J. and Earles, R., "Postharvest handling of fruits and vegetables", ATTRA, 2000.

BBC news, "Kenya aquifers discovered in dry Turkana region", 2013, www.bbc.com/news/science-environment-24049800.

Bifani, P., *Medio ambiente y desarrollo sostenible*, 4th ed., Madrid, Instituto de Estudios Políticos para América Latina y África (IEPALA), 1999.

Bihn, E.A., Schermann, M.A., Wszelaki, A.L, Wall, G.L. and Amundson, S.K., "Sanitation and Postharvest Handling Overview", 2014, gaps.cornell.edu/sites/gaps.cornell.edu/files/shared/documents/sanitation/Sanitation%20and%20Postharvest%20Handling-COMPLETE-FINAL.pdf.

BPIA, "History of biopesticides", 2015. www.biopesticideindustryalliance.org/history-of-biopesticides.

Broner, I., “Irrigation Scheduling”, Colorado State U. Extension, 2005, www.ext.colostate.edu/pubs/crops/04708.html.

Brouwer, C. and Heibloem, M., *Irrigation water management: Irrigation water needs*, Rome, FAO, 1986.

California SWRCB, “Regulation of Agricultural Drainage to the San Joaquin River: Executive Summary”, California State Water Resources Control Board, Doc. No. WQ-85-1, 1987.

CDP, “Water disclosure project”, 2015, www.cdp.net/water.

Chandler, D., Bailey, A., Tatchell, G., Davidson, G., Greaves, J. and Grant, W., “The development, regulation and use of biopesticides for integrated pest management”, Philosophical Transactions B of The Royal Society of London, vol. 366, iss. 1573, 2011, rstb.royalsocietypublishing.org/content/366/1573/1987.

Chaplin, M., “Water phase diagram. Water structure and science”, 2015, www1.lsbu.ac.uk/water/water_phase_diagram.html.

Chen, L., “Development of a Continuous Water Recycling Unit for Application in Postharvest Washing of Leafy Greens”, Guelph U., 2013, atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/7618/Liang_Chen_201311_MSc.pdf?sequence=1.

Chun E. Kan, “Improving Irrigation Management Systems for Rice Farming”, Department of Bioenvironmental Systems Engineering, National Taiwan University, 2004, www.fftc.agnet.org/library.php?func=view&style=type&id=20110808164432.

Clayton, R., “A Review of Current Knowledge Desalination for Water Supply”, Bucks, Foundation for Water Research, 2011, www.fwr.org/desal.pdf

COLEACP, *Integrated management of bioagressors*, Training Manual, Brussels, COLEACP, 2017, coleacp.org

COLEACP, *Principles of hygiene and food safety management*, Training Manual, Brussels, COLEACP, 2017, coleacp.org

COLEACP, *Sustainable production*, Training manual, Brussels, COLEACP, 2017, coleacp.org

Colorado geological society, “What is an Aquifer?”, 2015, www.douglas.co.us/water/water-supply/what-is-an-aquifer.

Conservation Gateway, "Nature's value: water conservation through agricultural practices", 2015, www.conservationgateway.org/ConservationPractices/EcosystemServices/NaturesValues/NaturesValuesWaterConservationThroughAgriculturalPractices/Pages/nature's-values-water-con.aspx#.

Convention on Biological Diversity, "Aichi Biodiversity Targets", 2011, www.cbd.int/sp/targets/default.shtml.

Dahal, S., *Post-harvest handling of cut-flower rose*, Rampur, IAAS, 2013, www.academia.edu/3276681/POST_HARVEST_HANDLING_OF_CUT-FLOWER_ROSE.

Dingman, S.L., *Physical Hydrology*, Prentice Hall, Upper Savage, 1992.

Dudley, T. and Fulton, A., "Conjunctive Water Management. What is it? Why consider it? What are the Challenges?", Red Bluff, U. Ca., 2005.

EC, Regulation (EC) 852/2004 of the European parliament and of the Council on the hygiene of foodstuffs, *OJEU*, 2004, eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:139:0001:0054:en:PDF.

EC, "Urban Wastewater Treatment", Directive 91/271/EEC, 1991, eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271.

EC, "Water Framework Directive objectives", 2015, ec.europa.eu/environment/water/water-framework/index_en.html.

EC, Water Framework Directive, Brussels, 1999.

EC, "Water protection and management", Water Framework Directive 2000/60/EC, 2000, eur-lex.europa.eu/legal-content/EN/TXT/?uri=URISERV:l28002b.

EEA, *The European environment – state and outlook 2015 – synthesis report*, Copenhagen, EEA, 2015, www.eea.europa.eu/soer-2015/synthesis/report, retrieved 23 September 2015.

EEA, "Water pollution – overview", 2008, www.eea.europa.eu/themes/water/water-pollution.

EPA, "About Pesticides", 2015, www.epa.gov/pesticides/about.

EPA, "A Citizen's Guide to phytoremediation", 2012, clu-in.org/download/Citizens/a_citizens_guide_to_phytoremediation.pdf.

EPA, "Nonpoint source: agriculture", Washington D.C, 2003, water.epa.gov/polwaste/nps/agriculture/upload/2003_09_24_NPS_agmm_chap4f.pdf.

EPA, "Nutrient Management", 2015, www.epa.gov/oecaagct/ag101/cropnutrientmgt.html.

EPA, "Parameters of water quality. Interpretation and Standards", 2001, www.epa.ie/pubs/advice/water/quality/Water_Quality.pdf.

EPA, "The origins of EPA", 1985, www.epa.gov/history/origins-epa.

EPA, "Water Quality Standards Handbook", 2015, water.epa.gov/scitech/swguidance/standards/handbook.

ESCAP, "Guidelines for the Preparation of National Master Water Plans", UN Water Resources Series No. 65, 1989.

Falkenmark, M. and Rockström, J., "The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management", 2006, ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9496(2006)132%3A3(129).

FAO, "Agricultural drainage water management in arid and semi-arid areas", FAO irrigation and drainage paper 61, Rome, FAO, 2002, www.fao.org/docrep/005/y4263e/y4263e00.htm#Contents.

FAO, *Agriculture and water quality interactions: a global overview*, Thematic Report 08, Rome/London, Earthscan, 2011.

FAO, "Aquamaps", 2015, www.fao.org/nr/water/infores_databases_aquamaps.html.

FAO, *Canals*, Training Manual No. 7, Rome, FAO, 1992, ftp.fao.org/agl/aglw/fwm/Manual7.pdf.

FAO, "Climate-smart agriculture source-book", Rome, FAO, 2013, www.fao.org/docrep/018/i3325e/i3325e.pdf.

FAO, "CLIMWAT model", Rome, FAO, 2010, www.fao.org/nr/water/infores_databases_climwat.html.

FAO, "Control of water pollution from agriculture", FAO irrigation and drainage paper 55, Rome, FAO, 1996, www.fao.org/docrep/w2598e/w2598e00.htm#Contents.

FAO, "CROPWAT model", Rome, FAO, 2010, www.fao.org/nr/water/infores_databases_cropwat.html.

FAO, *Deficit irrigation practices*, Water reports 22, Rome, FAO, 2000, www.fao.org/docrep/004/y3655e/y3655e00.htm#TopOfPage.

FAO, "Economic and social development department. Water and people. Whose right is it?", Rome, FAO, 2015, www.fao.org/docrep/005/y4555e/y4555e00.htm.

FAO, "Fertigation", *Pressurized irrigation techniques*, 2007, ftp.fao.org/docrep/fao/010/a1336e/a1336e16.pdf.

FAO, *Fish production in irrigation canals. A review*, Rome, FAO, 1991.

FAO, *Grape: Post-harvest Operations. InPho Post-harvest compendium*, Rome, FAO, 2005.

FAO, *Guidelines to control water pollution from agriculture in China. Decoupling water pollution from agricultural production*, FAO Water reports 40, Rome, FAO, 2013.

FAO, *Handling and Preservation of Fruits and Vegetables by Combined Methods for Rural Areas*, Rome, FAO, 2003, www.fao.org/docrep/005/y4358e/y4358e00.htm#Contents.

FAO, "Integrated Plant Nutrient Management", Rome, FAO, 2015, www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-plant-nutrient-management/ipnm-what/en/#b.

FAO, *Introduction to Irrigation*, Training Manual No. 1, Rome, FAO, 1985, www.fao.org/docrep/r4082e/r4082e00.htm#Contents.

FAO, *Irrigation Methods*, Training Manual No. 5, Rome, FAO, 1989.

FAO, *Irrigation Scheduling*, Training Manual No. 4, Rome, FAO, 1989.

FAO, *Management of agricultural drainage water quality*, Water reports 13, Rome, FAO, 1997, www.fao.org/docrep/w7224e/w7224e00.htm#Contents.

FAO, *Mango: Post-harvest Operations. InPho Post-harvest compendium*, Rome, FAO, 2002.

FAO, "Modern water rights. Theory and practice", FAO legislative study 92, Rome, FAO, 2006, ftp.fao.org/docrep/fao/010/a0864e/a0864e00.pdf.

FAO, "New LocClim: local climate estimator", 2014, www.fao.org/nr/climpag/pub/en3_051002_en.asp.

FAO, "Plant nutrition for food security. A guide for integrated nutrient management", Rome, FAO, 2006, ftp.fao.org/docrep/fao/009/a0443e/a0443e.pdf.

FAO, Policy brief on Food Security, iss. 2, Rome, FAO, June 2006, www.fao.org/forestry/13128-0e6f36f27e0091055bec28ebe830f46b3.pdf.

FAO, "Save and Grow toolkit. A policymaker's guide to the sustainable intensification of small-holder crop production", Rome, FAO, 2011, www.fao.org/ag/save-and-grow.

FAO, *Scheme Irrigation Water Needs and Supply*, Training Manual No. 6, Rome, FAO, 1992, www.fao.org/docrep/u5835e/u5835e00.htm#Contents.

FAO, "Simple methods for Aquaculture", FAO training series, Rome, FAO, 1998, ftp.fao.org/fi/CDrom/FAO_Training/FAO_Training/ENG_MENU.htm.

FAO, "Soils portal, physical properties", 2015, www.fao.org/soils-portal/soil-survey/soil-properties/physical-properties/en.

FAO, *The role of post-harvest management in assuring the quality and safety of horticultural produce*, Rome, FAO, 2004, www.fao.org/3/a-y5431e/y5431e00.htm#Contents.

FAO, "Water Quality for Agriculture", Irrigation and Drainage Paper No. 26, Rome, FAO, 1994, www.fao.org/DOCReP/003/T0234e/T0234E06.htm, retrieved 3 December 2015.

FAO, "Watershed Management Field Manual. Gully Control", Rome, FAO, 1986, www.fao.org/docrep/006/ad082e/AD082e00.htm#cont.

FAO, IFAD and WFP, "The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress", Rome, FAO, 2015, www.fao.org/3/a-i4646e.pdf.

FloraCulture, "New post-harvest water recycling technology for the flower industry", 2015, www.floraculture.eu/?p=21172.

French, A.N., Schmugge, T.J., Kustas, W.P. and Prueger, J.H., "Evapotranspiration Estimation Using Multispectral Thermal Infrared Data from ASTER and MODIS", American Geophysical Union, Fall Meeting 2009, abstract #U32A-08.

FSA Ireland, *Code of Practice for food safety in the fresh produce supply chain in Ireland*, Dublin, FSA, 2001.

GlobalG.A.P., "Integrated Farm Assurance – All Farm Base – Crops Base – Fruit and Vegetables – IFA V5.0_July15", English Version Control Points and Compliance Criteria, Cologne, 2015.

Government of Kenya, Water Act, Chapter 372, revised edition 2012, National Council for Law Reporting within the Authority of the Attorney General, Nairobi, 2012, faolex.fao.org/docs/pdf/ken37553.pdf retrieved 23 September 2015.

Government of South Africa, National Water Act No. 36 of 1998, www.acts.co.za/national-water-act-1998, retrieved 16 September 2015.

Greene, B., "How did Water come to earth?", *Smithsonian magazine*, 2013, www.smithsonianmag.com/science-nature/how-did-water-come-to-earth-72037248/?no-ist.

Green Farming, "Green Farming's hydroponic system in Kenyan flower farm to save 60% irrigation water and to produce 10% more roses", 2012, www.dutchwatersector.com/news-events/news/4017-green-farming-s-hydroponic-system-in-kenyan-flower-farm-to-save-60-irrigation-water-and-to-produce-10-more-roses.html.

Groenfeldt, D. and Sun, P., "The concept of participatory irrigation management", *Medit*, No. 2, 1997, www.iamb.it/share/img_new_medit_articoli/765_45groenfeldt.pdf.

Gustavsson, J. *et al.*, "Global food losses and food waste. Extent, causes and prevention", Rome, FAO, 2011, www.fao.org/docrep/014/mb060e/mb060e.pdf.

Hansen, R., "Water and wastewater systems in imperial Rome", *Waterhistory*, 2015, www.waterhistory.org/histories/rome/rome.pdf.

Hanson, B., "A simple way to estimate the distribution uniformity in furrow irrigation systems", U. Ca., 2011, cetulare.ucanr.edu/files/82038.pdf, retrieved 8 December 2015.

Hatum, T. and Worm, J., "Rainwater Harvesting for Domestic USE", Wageningen, Agrosima and CTA, 2006, www.sswm.info/sites/default/files/reference_attachments/HATUM%20and%20WORM%202006%20Rainwater%20Harvesting%20for%20Domestic%20USE.pdf.

Helling, C.S., Chesters, G. and Corey, R.B., "Contributions of organic matter and clay to soil cation exchange capacity as affected by the pH of the saturating solution", *Soil Sci. Soc. Am. Proc.*, No. 28, 1964, pp. 517-520.

Helvetas, "Advanced furrow irrigation technologies save water and increase water productivity", 2015, assets.helvetas.org/downloads/factsheet_furrow_irrigation_final_high_en.pdf.

HGCA, *Home-grown cereals authority. Precision farming of cereals. Practical guidelines and crop nutrition*, London, HGCA, 2002.

Hijmans, R.J. *et al.*, "The WorldClim interpolated global terrestrial climate surfaces", vers. 1.3, 2004, www.worldclim.org.

Hoekstra, A., *The Water Footprint of Modern Consumer Society*, London, Routledge, 2013.

Hoekstra, A.Y. and Mekonnen, M.M., "Global water scarcity: monthly blue water footprint compared to blue water availability for the world´s major river basins", *Value of Water Research Report Series*, No. 53, Delft, UNESCO-IHE, 2011.

Hoekstra, A.Y. and Mekonnen, M.M., "Water Footprint of Humanity", *PNAS*, vol. 109, No. 9, 28 February 2012, www.pnas.org/content/109/9/3232.full.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E. and Richter, B.D., "Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability", PLoS ONE, vol. 7, No. 2, art. e32688, 2012, doi:10.1371/journal.pone.0032688, journals.plos.org/plosone/article?id=10.1371/journal.pone.0032688.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M., *The water footprint assessment manual: Setting the global standard*, London, Earthscan, 2011, waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf.

ICID, "Pressurized irrigation", 2014, www.icid.org/press_irri.html.

Indira, V. and Sudheer, K.P., ''Postharvest Technology of Horticultural Crops'', *Horticulture Science Series*, vol. 07, 2007.

Infonet-biovision (ed.), *Water for Irrigation*, Zürich, Biovision, 2010.

Interagency Task Force, *Irrigation Water Use and Management*, Washington, DC, US Gov't Printing Office, 1979.

IPCC, *The Regional Impacts of Climate Change*, Special reports, 2015, www.ipcc.ch/ipccreports/sres/regional/index.php?idp=11.

ISO 14046:2014, "Environmental management, Water footprint, Principles, requirements and guidelines", Geneva, 2014.

Jarvis, A. *et al.*, "Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database", 2008, srtm.csi.cgiar.org.

Jenny, H., *Factors of Soil Formation: A System of Quantitative Pedology*, New York, Dover, 1994, www.soilandhealth.org/01aglibrary/010159.Jenny.pdf.

Kader, A. *et al.*, *The role of post-harvest management in assuring the quality and safety of horticultural produce*, Rome, FAO, 2004.

Kitinoja, L. and Kader, A. *Small-Scale Postharvest Handling Practices: A Manual for Horticultural Crops*, 4th ed., U. Ca., Davis Postharvest Technology Research and Information Center, 2002, ucce.ucdavis.edu/files/datastore/234-1450.pdf.

Landis, T., Pinto, R. and Davis, A., "Fertigation – injecting soluble fertilizers into the irrigation system", *Great lakes Christmas tree journal*, 2010, christmastree.for.msu.edu/pdf/nutrition_manage/Fertigation.PDF.

Library of Congress, Legislation on Use of Water in Agriculture, 2013, blogs.loc.gov/law/2014/04/legislation-on-use-of-water-in-agriculture.

Liu, C., Kroeze, C., Hoekstra, A.Y. and Gerbens-Leenes, W., "Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers", *Ecological Indicators*, No. 18, 2012, pp. 42-49.

Malesu, M.M., Oduor, A.R. and Odhiambo, O.J. (eds), *Green Water Management Handbook. Rainwater Harvesting for Agricultural Production and Ecological Sustainability*, Nairobi, The World Agroforestry Centre, 2007, www.sswm.info/sites/default/files/reference_attachments/MALESU%202007%20Green%20Water%20Management%20Handbook.pdf.

McMahon, T.A. *et al.*, "Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis", *Hydrol. Earth Syst. Sci.*, No. 17, 2013, pp. 1331–1363, www.hydrol-earth-syst-sci.net/17/1331/2013/hess-17-1331-2013.pdf.

MDA, "Conservation practices – Minnesota conservation funding guide", 2014, www.mda.state.mn.us/protecting/conservation/practices/winderosion.aspx.

Mechell, J., "Rainwater Harvesting: Soil Storage and Infiltration Systems", The Texas A&M University System, 2005, www.ctahr.hawaii.edu/hawaiirain/Library/papers/Mechell_Justin.pdf.

Mekonnen, M.M. and Hoekstra, A.Y., "The blue water footprint of electricity from hydropower", Department of Water Engineering and Management, U. Twente, Enschede, 2012.

Mekonnen, M., Hoekstra, A. and Becht, R., "Mitigating the Water Footprint of Export Cut Flowers from the Lake Naivasha Basin, Kenya", *Water Resources Management*, No. 26, 2012, pp. 3725-3742.

Meyer, B., Newenhouse, A., Miquelon, M. *et al.*, "Post Harvest Handling for Best Crop Quality", Wisconsin School for Beginning Market Gardeners, 2001, bse.wisc.edu/HFHP/tipsheets_html/postharvest.htm.

Ministry of Agriculture, Nature and Food Quality, The Netherlands, *IWRM: for sustainable use of water. 50 years of international experience with the concept of integrated water management*, Wageningen, 2004.

Mugira, F., "120 M US Dollars for Lake Victoria Water and Sanitation Programme", *Water Journsalists Africa*, 2011, waterjournalistsafrica.com/2011/04/20/120-m-usd-for-lake-victoria-water-and-sanitation-programme.

National Geographic, "India's Food Security Threatened by Groundwater Depletion", 2015, voices.nationalgeographic.com/2015/02/03/indias-food-security-threatened-by-groundwater-depletion.

NOAA, "Glossary of Hydrologic Terms", 2015, www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm.

Nowak, J. and Rudnicki, R.M., *Postharvest handling and storage of cut flowers, floristgreens and potted plants*, Portland, Timber press, 1990, p. 210.

NSW, Department of Primary Industries, "Postharvest care of cut flowers", 2002, www.dpi.nsw.gov.au/agriculture/horticulture/floriculture/post-harvest/care.

OECD, "Sustainable Management of water resources in agriculture", 2010, www.oecd.org/tad/sustainable-agriculture/49040929.pdf.

Oregon Department of Agriculture, "'Cut-off' Flood Irrigation. A management practice that works for the inland Rogue Basin", Jackson Soil and Water Conservation District, 2008.

PAN, "Environmental effects of pesticides", 2015, www.pan-uk.org/environment/environmental-effects-of-pesticides.

Peña Varón, M., *Waste stabilization ponds*, IRC, Cali/Leeds, 2004, www.bvsde.paho.org/bvsacd/cd27/ponds.pdf.

Perry, C., "Efficient irrigation; inefficient communication; flawed recommendations", *Irrigation and Drainage*, vol. 56, Wiley Interscience, 2007, pp. 367-378.

Pescod, M.B., "Wastewater treatment and use in agriculture", FAO irrigation and drainage paper 47, Rome, FAO, 1992, www.fao.org/docrep/t0551e/t0551e00.htm#Contents.

Peter, K.V., *Basics of Horticulture*, 2nd ed., Delhi, New India publishing Agency, 2015.

Phocaides, A., *Technical Handbook on pressurised irrigation techniques*, Rome, FAO, 2000, ftp.fao.org/agl/aglw/docs/pressirrig.pdf, retrieved 8 December 2015.

Plumer, B., "We've covered the world in pesticides. Is that a problem?", *The Washington Post*, 18 August 2013, www.washingtonpost.com/blogs/wonkblog/wp/2013/08/18/the-world-uses-billions-of-pounds-of-pesticides-each-year-is-that-a-problem.

Porter, D. and Marek, T., "Irrigation management with saline water", *Texas Agricultural Experiment Extension*, 2006, www.k-state.edu/irrigate/oow/p06/Porter06.pdf.

Queensland Government, "Salinity Management Handbook", 2011, publications.qld.gov.au/en/dataset/salinity-management-handbook/resource/529b12b0-8e23-4cd3-a1cd-7659d0b9b3b4, retrieved 3 December 2015.

Rhoades, J., Kandiah, A. and Mashali, A., "The use of saline waters for crop production", FAO irrigation and drainage paper No. 48, Rome, FAO, 1992, www.fao.org/docrep/T0667E/t0667e00.htm#Contents.

SAI, "Water conservation technical briefs – TB-6, Irrigation scheduling", SAI platform, 2010, www.saiplatform.org/uploads/Library/Technical%20Brief%20 6.%20Irrigation%20Scheduling.pdf.

SAI, "Water conservation technical briefs – TB-14, Salinity control", SAI platform, 2012 www.saiplatform.org/uploads/Library/Technical%20Brief%20 6.%20Irrigation%20Scheduling.pdf.

Schemenauer, R. and Cereceda, P., "Fog Collection", *Tiempo*, 1997, www.sswm.info/sites/default/files/reference_attachments/SCHEMENAUER%20 and%20CERECEDA%201997%20Fog%20Collection.pdf.

Scherer, T., "Selecting a Sprinkler Irrigation System", Fargo, NDSU, 2010, www.sswm.info/sites/default/files/reference_attachments/SCHERER%202010%20 Selecting%20a%20Sprinkler%20Irrigation%20System.pdf.

Simply hydroponics and Organics, "What is hydroponics?", 2008, www.simplyhydro.com/whatis.htm.

Standish, S., "How to Irrigate On A Shoestring", Portland, Global Envision, 2009, www.globalenvision.org/2009/11/19/how-irrigate-shoestring.

Stehle, S. and Schulz, R., "Agricultural insecticides threaten surface waters at the global scale", *PNAS*, vol. 112, No. 18, May 2015.

Suslow, T., "Ozone applications for post-harvest disinfection of edible horticultural crops", U. Ca., Division of Agriculture and Natural Resources, Publ. 8133, 2004, anrcatalog.ucanr.edu/pdf/8133.pdf.

Suslow, T., "Postharvest Chlorination. Basic Properties and Key Points for Effective Disinfection", U. Ca., Division of Agriculture and Natural Resources, 1997, ucfoodsafety.ucdavis.edu/files/26414.pdf.

Sytsema, W. and Kalkman, E.C., "Post-harvest studies on Syringa vulgaris", *Acta Horticulturae*, No. 298, 1991, pp. 127-133.

Tacker, P., "Border irrigation good alternative", Delta Farm Press, 2003, deltafarmpress.com/soybeans/border-irrigation-good-alternative.

TNAU Agritech portal, "Fertigation", 2015, agritech.tnau.ac.in/agriculture/agri_nutrientmgt_fertigation.html.

UCCE (ed.) and GWPA, "Irrigation Systems and their Performance", UCCE, 2005, www.sswm.info/sites/default/files/reference_attachments/UCCE%202005%20 Irrigation%20Systems%20and%20their%20Performance.pdf.

UN, DESA, "Food and Agriculture: The future of sustainability", 2012, sustainabledevelopment.un.org/content/documents/1443sd21brief.pdf.

UN, Resolution 64/292, "The human right to water and sanitation", adopted by the UNGA on 28 July 2010, www.un.org/es/comun/docs/?symbol=a/res/64/292&lang=e.

UN, "Water for life decade", 2006, www.un.org/waterforlifedecade/scarcity.shtml.

UN, Status Report on Integrated Approaches to Water Resource Management, Water report 2012, www.unwater.org/fileadmin/user_upload/unwater_new/docs/ UNW_status_report_Rio2012.pdf, retrieved 15 September 2015.

UN, "World Water Day 2010", www.unwater.org/wwd10/faqs.html.

UNEP, "Freshwater use by sector at the beginning of the 2000s", 2008, new.unep.org/dewa/vitalwater/article48.html.

UNEP, "Science in UNEP: about the global water quality challenge", 2015, www.unep.org/science/chief-scientist/Activities/ EcosystemsManagementandAgricultureEfficiency/GlobalWaterQualityChallenge.aspx.

UNFPA, "Water: a critical resource", New York, 2002, lwvlaplata.org/files/unfpa_water_1_.pdf.

UNEP/DEWA, "Groundwater and its susceptibility to degradation", 2003, www.unep.org/DEWA/water/groundwater/pdfs/Groundwater_INC_cover.pdf.

UNESCO, "World Water Assessment Program. Facts and figures", 2015, www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact2-agricultural-use.

University of Montana, "Saline and/or sodic water and soils", 2015, waterquality.montana.edu/energy/cbm/faq-watersoil.html.

USAID, "Rehabilitation of irrigation systems in Afghanistan", 2015, www.usaid.gov/results-data/success-stories/rehabilitation-irrigation-systems-afghanistan.

USDA Salinity Lab, Agricultural Research Service, "Salt Tolerance databases", 2015, www.ars.usda.gov/Services/docs.htm?docid=8908.

USGS, "General facts and concepts about ground water", 2013, pubs.usgs.gov/circ/circ1186/html/gen_facts.html.

USGS, "Summary of the Water Cycle", 2015, water.usgs.gov/edu/watercyclesummary.html.

USGS, "Types and Sources of Water-Quality Benchmarks for Pesticides", 2014, water.usgs.gov/nawqa/pnsp/benchmarks/source.html.

van Koppen, B., Giordano, M. and Butterwort, J., "Community-based Water Law and Water Resource Management Reform in Developing Countries", CAB International, 2007, www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Community_Law/protected/index.htm.

Van der Ent, R. *et al.*, "Land use change influences continental water cycle", Delft University, 2013.

Vos, J., Boelens, R. and Mena, P., "From local to virtual water control: The globalization of water insecurity and water access conflicts", Global Water Forum, 2014, www.globalwaterforum.org/2014/05/13/from-local-to-virtual-water-control-the-globalization-of-water-insecurity-and-water-access-conflicts.

Walker, W.R., "Guidelines for designing and evaluating surface irrigation systems", FAO Irrigation and drainage paper 45, Rome, FAO, 1989, www.fao.org/docrep/t0231e/t0231e00.htm#Contents.

Walker, W.R., *Surface Irrigation Simulation Evaluation and Design*, Logan, Utah State U., 2003, ocw.usu.edu/Biological_and_Irrigation_Engineering/Surface_Irrigation_Design/SIRMOD_III_Manual.pdf.

Water Nexus Solutions, "The perfect storm scenario", 2015, www.waternexussolutions.org/284.

WBCSD, "Facts and Trends of Water", 2006, www.unwater.org/downloads/Water_facts_and_trends.pdf.

WBCSD, "The WBCSD Global Water Tool", 2015, old.wbcsd.org/work-program/sector-projects/water/global-water-tool.aspx.

WFN, "Glossary of terms", 2015,
waterfootprint.org/en/water-footprint/glossary.

WFN, "Water Footprint Assessment Tool", 2015,
waterfootprint.org/en/resources/interactive-tools/#CP.

Whitcher, B., Byers, S., Guttorp, P. and Percival, D., "Testing for Homogeneity of Variance in Time Series: Long Memory, Wavelets and the Nile River", *Water Resources Research*, No. 38, 2002.

WHO, *Guidelines for drinking water quality*, 4th ed., Rome, WHO, 2011,
www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en.

WHO, "Wastewater use in agriculture", vol. 2, *Guidelines for the safe use of wastewater, excreta and greywater*, Rome, WHO, 2006,
www.who.int/water_sanitation_health/wastewater/wwuvol2intro.pdf.

World Bank, Natural Resources Institute and FAO, *Missing food: The case of postharvest grain losses in sub-Saharan Africa*, Report No. 60371-AFR, 2011,
siteresources.worldbank.org/INTARD/Resources/MissingFoods10_web.pdf.

WRI, "AQUEDUCT. Measuring and mapping water risk", 2015,
www.wri.org/our-work/project/aqueduct.

WRI, "Disappearing Food: How Big are Postharvest Losses?", *EarthTrends*, 1998.

WRI, "The global food challenge explained in 18 graphics", 2015,
www.wri.org/blog/2013/12/global-food-challenge-explained-18-graphics.

Wright, K.R., Zegarra, A.V. and Lorah, W.L., "Ancient Machu Picchu Drainage Engineering", *Journal of Irrigation and Drainage Engineering*, November-December 1999.

WWF/DEG, "Water Risk Filter", 2015, waterriskfilter.panda.org.

Zarate, E., "Water Footprint Assessment of bananas produced by small banana farmers in Peru and Ecuador", *Acta Horticulturae*, March 2016.

Zhang, L., Dawes, W.R. and Walker, G.R., "Predicting the effect of vegetation changes on catchment average water balance", 1999,
catalogue.nla.gov.au/Record/408538.

Zomer, R.J. *et al.*, "Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation", *Agric. Ecosystems and Envir.*, No. 126, Rome, FAO, 2008, pp. 67-80.

Useful Websites

USEFUL WEBSITES

African Farming:
africanfarming.net/crops/horticulture/horticulture-faces-many-challenges

AgroFair:
www.Agrofair.nl

Alberta Environment and Parks:
aep.alberta.ca

Alliance for Waterstewardship – AWS:
www.allianceforwaterstewardship.org

aWhere:
www.awhere.com

BBC:
www.bbc.com

CDP:
www.cdp.net

Ceres:
www.ceres.org

CFIA – Canadian Food Inspection Agency:
www.inspection.gc.ca

CGIAR CSI:
www.cgiar-csi.org

COLEACP:
coleacp.org/en

Conservation Gateway:
www.conservationgateway.org

Convention on Biological Diversity:
www.cbd.int

Dutch Water Sector:
www.dutchwatersector.com

Eur-Lex:
eur-lex.europa.eu/homepage.html?locale=en

European Commission:
ec.europa.eu

European Environment Agency:
www.eea.europa.eu

Geographical Open Data Kit:
www.geoodk.com

Global Water Forum:
www.globalwaterforum.org

Good Stuff International:
www.goodstuffinternational.com

FAO:
www.fao.org

H_2O:
All-water.org

Huella Hídrica:
www.huellahidrica.org

IFAD – International Fund for Agricultural Development:
www.ifad.org/english/water/key.htm

Indian Council of Agricultural Research:
www.icar.org.in

INPIM:
www.inpim.org

Intergovernmental Panel on Climate Change:
www.ipcc.ch

Ireland Environmental Agency:
www.epa.ie

Irrigation Association:
www.irrigation.org

Mississippi State University Extension:
extension.msstate.edu

National Geographic:
nationalgeographic.com

National Library of Australia:
catalogue.nla.gov.au

National Weather Service:
nws.noaa.gov

OECD:
www.oecd.org

Pacific Community:
pacificwater.org

Pesticide Action Network UK:
www.pan-uk.org

PLOS One:
journals.plos.org/plosone

Proceedings of the National Academy of Sciences:
www.pnas.org

Smithsonian:
www.smithsonianmag.com

Soil & Health Library:
soilandhealth.org

TASTE:
www.fairtaste.nl

UNESCO:
www.unesco.org

United Nations:
www.un.org

United Nations Environment Programme:
www.unep.org

United Nations Inter-Agency Mechanism on all Freshwater:
www.unwater.org

U.S. Aid:
www.usaid.gov

U.S. Department of Agriculture –USDA:
www.ams.usda.gov

U.S. Environmental Agency:
www.epa.gov

U.S. Geological Survey:
www.usgs.gov

Water4Everyone:
www.water4everyone.org

Water Footprint Network:
waterfootprint.org

Water History:
Waterhistory.org

World Health Organization – WHO:
www.who.int/en

World Mapper:
worldmapper.org

Worldorometers:
www.worldometers.info/water

World Resources Institute:
www.wri.org

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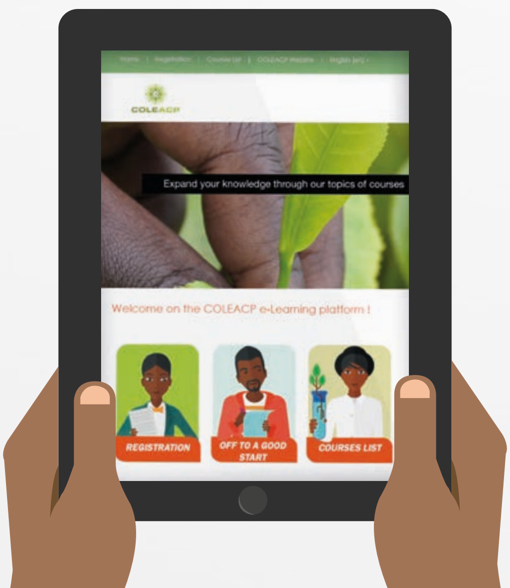

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