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“An Innovative Vocational Education Training Perspective on Agriculture for Climate Change Adaptation”

Smart AgroVETs Project

Training course on agricultural water management

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CHAPTER 6

SUSTAINABLE AGROPRODUCTION UNDER CLIMATE CHANGE: CLIMATE SMART AGRICULTURE (CSA)

6.1 WEATHER, CLIMATE AND CLIMATE CHANGE

Weather refers to atmospheric conditions that occur locally over short periods of time—from minutes to hours or days. Familiar examples include rain, snow, clouds, winds, floods or thunderstorms. Climate, on the other hand, refers to the long-term regional or even global average of temperature, humidity and rainfall patterns over seasons, years or decades.

Climate change is a long-term change in the average weather patterns that have come to define Earth's local, regional and global climates. These changes have a broad range of observed effects that are synonymous with the term.

Greenhouse gases (GHGs) control the Earth's climate system by making the atmosphere warmer. Without greenhouse gases, the earth would be in an eternal ice age, about 30°C lower than the present average temperature of the world. These GHGs form a blanket over the Earth, they retain heat that comes from the Earth's surface. This heat originally comes from the sun in the form of visible light and is re-radiated from the Earth's surface in the form of infrared radiation. Otherwise, this heat would pass through the atmosphere and be lost to space. GHGs, ordered from most impactful to least impactful, are carbon dioxide (CO_2), methane (CH_4), ozone (O_3), water vapor.

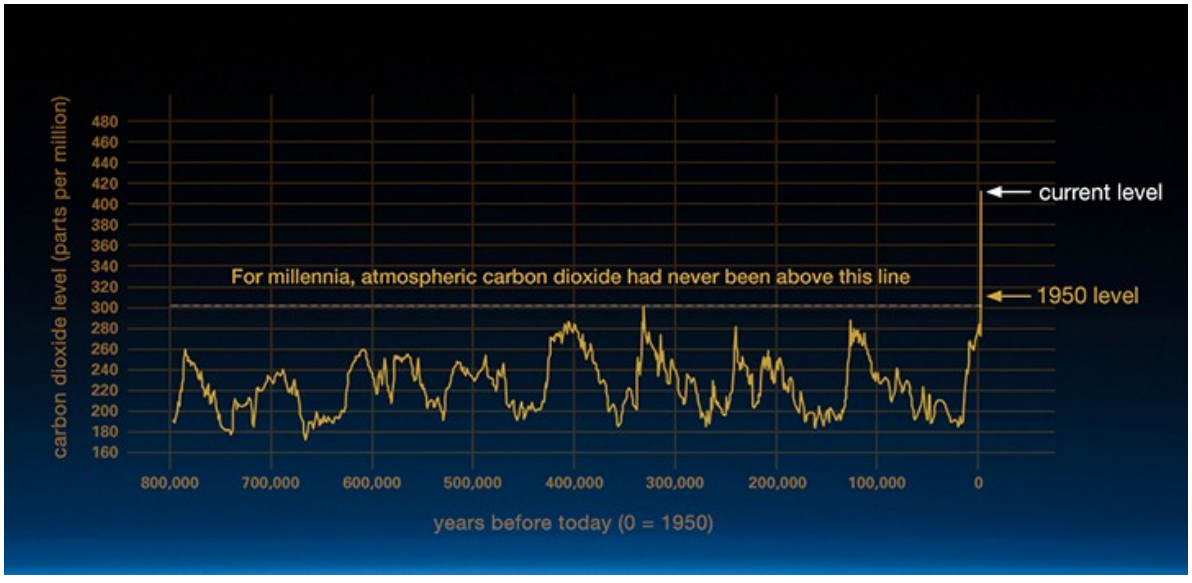


Figure 6.1. The relentless rise of carbon dioxide during the past few decades (Source: https://climate.nasa.gov)

Changes observed in Earth's climate since the early 20th century are primarily driven by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere, raising Earth's average surface temperature. These human-produced temperature increases are commonly referred to as global warming. Natural processes can also contribute to climate change, including internal variability (e.g., cyclical ocean patterns like El Niño, La Niña and the Pacific Decadal Oscillation) and external forcing (e.g., volcanic activity, changes in the Sun's energy output, variations in Earth's orbit) (Source: https://climate.nasa.gov).

Since the pre-industrial period, human activities are estimated to have increased Earth's global average temperature by about 1 degree Celsius, a number that is currently increasing by 0.2 degrees Celsius per decade. It is unequivocal that human influence has warmed the atmosphere, ocean, and land (Source: https://climate.nasa.gov).

Scientists use observations from the ground, air and space, along with theoretical models, to monitor and study past, present and future climate change. Climate data records provide evidence of climate change key indicators, such as global land and ocean temperature increases; rising sea levels; ice loss at Earth's poles and in mountain glaciers; frequency and severity changes in extreme weather such as hurricanes, heatwaves, wildfires, droughts, floods and precipitation; and cloud and vegetation cover changes, to name but a few.

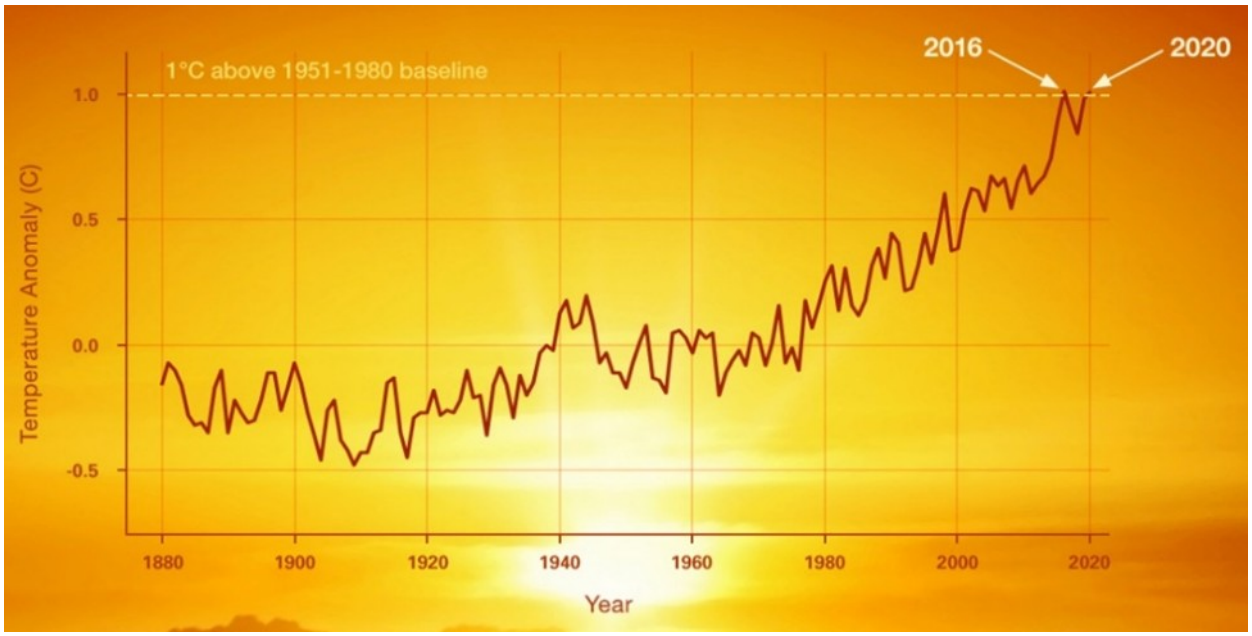


Figure 6.2: The change in global surface temperature relative to 1951-1980 average temperatures, with the year 2020 tying with 2016 for warmest on record (Source: NASA's Goddard Institute for Space Studies, https://climate.nasa.gov)

6.2. IMPACT OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTION

Decrease in suitability for agricultural production: In Turkey, excluding the Black Sea cost line, decreases in spring and summer precipitation coupling with the increase in temperature and evapotranspiration will lead to decreases in yield/cultivated area of summer crops like sunflower, corn, rice, bean, chickpea, lentil, sugar beet, cotton, vegetables and fruits beside alfalfa and pastures. In Turkey, it is predicted that climate change will cause decreases in the yield of some strategically important crops for Turkey, by 8.18% in wheat, 2.24% in barley, 9.11% in corn, 4.53% in in cotton and 12.89% in sunflower by the year 2050. Shortage of forage crops, oilseed crops and legumes will increase with climate change and become more problematic in the medium and long term (Kadıoglu et al. 2017; Dellal et al. 2011).

Water resources will decrease, irrigation water demand and water stress will increase: Due to the climate change the amount of irrigation water needed could be doubled compared to today. Even with irrigation, it is expected that there will be a decrease in the yield of summer plants, as the plants will be exposed to higher and extreme temperatures during the flowering and grain filling period. Beside increases in temperature and decreases in precipitation, prolongation of the crop growing season, decreases in the number of frozen days, soil water deficit in the crop growing season, increases in the frequency and severity of the flood events particularly in the Black Sea coastline will adversely affect the crop production and biodiversity (Kadıoglu et al. 2017; Konukcu 2019).

Damages due to seasonal shifts: If the temperatures are higher than expected at the beginning of winter or in early spring, it will cause early flowering of plants, especially fruits, and a loss of yield and quality with the frost event to be experienced afterwards. If the cold winters can no longer control them, some diseases and pests can survive or even multiply more and more every year, causing epidemics. As temperatures and humidity conditions change, new diseases and pests can cause damage in areas previously unseen. Even in today's somewhat severe weather conditions (hale, heatwave, heavy rainfall, frost), it is seen that the yield and quality of agricultural production decrease, prices rise excessively and exports decrease. With the changing climate, weed populations that are more competitive than

cultivated plants will increase, there will be an obligation to use more chemical pesticides as a result of morphological changes in the plants, which negatively affects the product quality. This will affect human and environmental health negatively (Amare 2016).

Increased risk as a result of extreme climatic events: prolonged droughts will prolong the fire season and increase the risk of fire. Unexpected heavy rains and increased humidity will cause product quality to decline, sometimes even to a complete loss, grain stagnation and soil erosion. While extreme temperatures will cause a decrease in product quality and yield, hail may lead to a big economic lost.

6.3. CLIMATE CHANGE, FOOD SECURITY AND CHALLENGES

To feed an expanding population, the annual world food production will need to increase by 60 percent over the next three decades (Bruinsma 2009). However, the impacts of climate change, which include increasing temperatures, shifting precipitation patterns, more severe and frequent extreme weather events and the loss of ecosystem services and biodiversity, will undermine agricultural production systems and food systems, especially in agricultural communities in developing countries where poverty, hunger and malnutrition are the most prevalent (FAO 2013). The agricultural sectors, which include crop and livestock production, forestry, fisheries and aquaculture, are also a major contributor to global greenhouse gas emissions. According to FAO estimates, in 2010, emissions from the agriculture, forestry and other land use (AFOLU) sector directly accounted for 22 percent of total global emission (FAO 2013). Therefore, agriculture and food systems must improve and ensure food security, and to do so they need to adapt to climate change and natural resource pressures, and contribute to mitigating climate change. These challenges, being interconnected, have to be addressed simultaneously

Therefore, the agriculture sectors need to overcome three intertwined challenges (FAO 2010):

- sustainably increase agricultural productivity to meet global demand;
- adapt to the impacts of climate change; and
- contribute to reducing the accumulation of greenhouse gases in the atmosphere.

To meet these challenges, FAO has developed and promoted the concept of Climate-Smart Agriculture (CSA).

6.4. DEFINITION OF CLIMATE SMART AGRICULTURE (CSA)

Climate-smart agriculture (CSA), as defined and presented by FAO at the Hague Conference on Agriculture, Food Security and Climate Change in 2010, contributes to the achievement of sustainable development goals. It integrates the three dimensions of sustainable development (economic, social an environmental) by jointly addressing food security and climate challenges. CSA is based on 3 objectives or pillars (FAO 2010):

- **Productivity/sustainability/food security**: CSA aims to sustainably increase agricultural productivity and incomes from crops, livestock and fish, without having a negative impact on the environment. This, in turn, will raise food and nutritional security. A key concept related to raising productivity is sustainable intensification.
- **Adaptation:** CSA aims to reduce the exposure of farmers to short-term risks, while also strengthening their resilience by building their capacity to adapt and prosper in the face of shocks and longer-term stresses. Particular attention is given to protecting the ecosystem services which ecosystems provide to farmers and others. These services are essential for maintaining productivity and our ability to adapt to climate changes.
- **Mitigation:** Wherever and whenever possible, CSA should help to reduce and/or remove greenhouse gas (GHG) emissions. This implies that we reduce emissions for each calorie or kilo of food, fiber and fuel that we produce. That we avoid deforestation from agriculture. And that we manage soils and trees in ways that maximizes their potential to acts as carbon sinks and absorb CO_2 from the atmosphere.

Climate-smart agriculture is an approach for transforming and reorienting agricultural production systems and food value chains so that they support sustainable development and can ensure food security under climate change. This does not imply that every practice applied in every location should produce 'triple wins' that deliver positive results for each of these three objectives. Rather the climate-smart agriculture approach seeks to reduce trade-offs and promote synergies by taking these objectives into consideration when agricultural producers, policy makers and researchers make decisions at the local, subnational, national and global levels about short- and long-term strategies to address climate change.

CSA builds on sustainable agriculture approaches, using principles of ecosystem and sustainable land and water management and landscape analysis, and assessments of the use of resources and energy in agricultural production systems and food systems. This is particularly important in developing countries, where agricultural growth is generally a top priority.

6.5. SUSTAINABLE PRODUCTION UNDER CSA

For each crop system, there are countless climate change adaptation and mitigation options that can sustainably improve yields and minimize the harmful environmental impacts of production. They will differ for each farming household, depending on its coping and adaptive mechanisms. Management practices and technologies for climate change adaptation and mitigation include practices with an explicit focus on adaptation and practices with a broader scope on reducing production risks and reducing emissions. Specific climate-smart approaches to crop production include:

- **increasing diversity** and complexity within the agricultural ecosystem, which can be done in many ways (e.g. expanding the diversity of crops or crop varieties), at many spatial scales (e.g. landscape level, within farms, and/or within the same crop) and over different timeframes;
- **improving sustainable soil and land management** (e.g. carefully channelling the expansion of crop and grazing land to mitigate the loss of carbon storage that results from land-use change);
- **increasing energy use efficiency**; promoting sustainable mechanization (e.g. increasing the availability of suitable machinery in combination with proper agronomic management to reduce greenhouse gas emissions from various farm and processing operations); and
- **developing simple and robust scientific tools** to guide the decision-making of farmers on a seasonal and long-term basis.

6.6. ADAPTATION STRATEGIES TO CLIMATE CHANGE IMPACTS

Adaptation to climate change requires taking the right measures to reduce the negative effects of climate change (or take advantage of the positive ones) by making appropriate adjustments and changes. The Intergovernmental Panel on Climate Change (IPCC, 2007) defines adaptation as adjustments to natural or human systems in response to actual or anticipated climatic stimuli or effects that reduce harm or take advantage of beneficial opportunities. It also refers to the actions taken by people, countries and societies to adapt to the occurring climate change. Adaptation has three possible goals: to reduce exposure to the risk of harm; develop the capacity to cope with inevitable harm; and to take advantage of new opportunities (Akinnagbe and Irohibe 2014).

The measures that can be taken for adaptation to climate change impact can be listed as follows.

- Plant variety/species selection or breeding
- Crop diversification
- Change in cropping pattern
- Change in calendar of planting
- Mixed cropping
- Improvement in water and irrigation management
- Adapting soil, soil water and energy conservation measures

Plant variety/species selection or breeding: The easiest way is to select crop varieties of any species resistant to unfavourable climatic condition (heat wave, drought), to diseases and pests. Lodging as a result of excessive precipitation, rust under humid condition and heat stress under heat wave are common problem decreasing wheat yield and quality as a result of climate change. Among the existing cereal varieties, varieties with shorter stems (against lodging) and resistant to heat wave and diseases can be selected. However, the selected resistant new varieties may not always guarantee the high yields as the previous ones. As for the sunflower, another strategic crop, selection of drought and high heat resistant or early varieties may be considered.

Another alternative is to prefer plant species that are resistant to drought. For example, wheat requires significantly less (irrigation) water compared to dry season rice or corn. Against the shortage in summer precipitation and increasing heat waves, winter plants might be preferred instead of summer plants: wheat to corn, canola to sunflower etc.

In addition to extreme climatic conditions (high temperature, drought, frost, etc.), disease and pest resistant varieties should be improved using local genetic resources and developing technologies in this area. Special duties and required support should be given to Agricultural Research Institutes and Universities. Public-private sector cooperation should be ensured.

Crop diversification: Crop diversification could be an effective adaptation option under extreme temperature, frequent and intensive flood, cyclone and other natural disasters due to climate change became acute and expecting to be severe in future as it protects natural biodiversity, strengthening the ability of the agroecosystem to respond to these stresses, minimizing environmental pollution, reducing the risk of total crop failure, reducing incidence of insect pests, diseases and weed problems and secure food supply opportunities and also

providing producers with alternative means of generating income. It provides better conditions for food security and enables farmers to grow surplus products for sale at market and thus obtain increased income to meet other needs related to household well-being. Farmers needs to gain knowledge and skills in affected areas about crop-production techniques, integrated farming systems (including crop rotation and intercropping), and climate resilient production techniques. It can be implemented in a variety of forms and at a variety of scales, allowing farmers to choose a strategy that both increases resilience and provides economic benefits.

Crop diversification can improve resilience in a variety of ways: by engendering a greater ability to suppress pest outbreaks and dampen pathogen transmission, which may worsen under future climate scenarios, as well as by buffering crop production from the effects of greater climate variability and extreme events. Such benefits point toward the obvious value of adopting crop diversification to improve resilience, yet adoption has been slow (Lakhran et al. 2017).

Diversification towards high value crops is feasible in the medium to long term. Crop diversity is a high priority adaptation measure in both irrigated and non-irrigated areas. Considering the climate change projection, drought and heat resistant alternative legumes, forage crops and oil crops should be included in the rotation.

Change in cropping pattern: Cropping systems are increasingly simplified, with fewer and fewer crop species grown in rotation from year to year. But diverse rotations provide higher crop yields compared with continuous monoculture, in particular in years with low precipitation and high temperatures. Swedish, Polish and Italian researchers found this by analysing cereal yield data collected for decades from long-term agricultural field experiments from southern to northern Europe. Diversifying crop rotations emerges as an adaptation to a forthcoming warmer and drier climate. Crop rotation or diversification has been suggested as a general strategy to sustain yields and reduce risks of yield losses from adverse climatic conditions, through improved soil fertility, enhanced beneficial soil biota and suppressed build-up of weeds, pests and diseases. “But the trend in major cropping systems worldwide is that we grow cereals in shorter and shorter rotations, and in some places even in continuous monoculture” Growing multiple crop species in a year-to-year rotation always gave higher yields compared with a continuous monoculture. The average yield gain with rotation was 860 and 390 kg/ha in autumn- and spring-sown cereals, respectively. In spring cereals the benefit of a diverse rotation increased without plateauing over time since the beginning of the

experiments, reaching a gain of 500 kg/ha after 50-60 years. The benefit of a diverse rotation was stronger in hot and dry years, a condition that is predicted to become more frequent with climate change (https://www.slu.se/en/ew-news/2020/11/crop-rotation-a-promising-way-to-improve-food-security-under-a-changing-climate/).

In irrigated area, forage crops (such as sainfoin, vetch) can be used as a ground cover plant in the rotation, and the organic matter content can be enriched by mixing with the soil before planting sunflowers, or if it is harvested for feed, then the second crop corn can be put into the rotation as is practiced in the Thrace Region of Turkey.

Change in calendar of planting: Planting dates should be carefully adjusted to take advantage of precipitation effectively and to get rid of drought and diseases/pests. Shifting the planting time to November in order to prevent yellow dwarf disease in Thrace/Turkey and adjusting the planting time of sunflower in early spring in order to benefit from the rainfall at the highest level are good examples for this measure.

Mixed cropping: Mixed cropping involves growing two or more crops in proximity in the same field. Mixed cropping, typically a mixture of legumes and cereals or tuber crops, is a common practice in marginal agroecological environments, which fulfils a variety of functions, including complementary use of growth factors, such as soil nutrients, light, and water; reduced pest and disease incidence, reduced soil erosion, more total biomass production, more yield stability, and more household food security. Furthermore, the mixtures can be flexibly adjusted to conditions such as late or early onset of the rainy season or status of soil fertility in different fields. Annual crops may be planted between the orchard trees when they are young.

Improved water and irrigation management: More than 70% of renewable fresh water resources are used for irrigation purposes. About 15% savings in irrigation water is equivalent to the household water requirements. The average water usage efficiency in the world is very low 40% and 35%.in Turkey. In any case efficiency can be increased by 10-50% by Selection of plants with high water use efficiency and economic value, focusing on drought and salinity stress studies, preference of piped systems in water transmission, preference of high efficiency (drip if possible) irrigation systems and application of deficit irrigation technique.

Deficit irrigation is when the irrigation water applied to a crop is less than required to meet full crop water requirements resulting in evapotranspiration (ET) less than the maximum crop ET. For a few crops and conditions, irrigation is intentionally reduced to attain a desired plant

response or product characteristic or quality, for example, to reduce vegetative growth, increase fruit quality and value, induce maturity, or facilitate harvest. However, in most cases, deficit irrigation results in reduced yield and gross income. Deficit irrigation may occur due to water delivery or application constraints or errors in scheduling irrigations, or it may be an intentional management practice to maximize net income under conditions of an inadequate or expensive water supply (Trout and Martin 2020).

Limited or expensive water may motivate changing the production goal from maximum yields and gross income per unit area to managing for acceptable yields that maximize economic returns within the water supply constraints.

Water supply limitations may be long-term and predictable or short-term and unanticipated. The planning horizon for deficit irrigation management determines the available options. Awareness of long-term limitations allows the producer to make land and infrastructure investments appropriate to the water supply. When seasonal limitations are known before annual investments are made for preparing and planting fields, operating costs can be adjusted for the anticipated water supply. Unexpected water supply limitations may occur during the season due to lack of precipitation, overestimate of the water supply, or failure of water delivery systems. Unanticipated in-season supply shortages limit the ability to adjust production costs but still allow water supply redistribution among crops and areas, such as abandoning planted fields or portions of fields to concentrate irrigation water on remaining land (Trout and Martin 2020).

Knowledge of a crop's response to water is required to make rational deficit irrigation management decisions. The crop water production function describes the relationship between crop yield or value and the amount of water used. The basic water production function relates biomass produced to plant transpiration. Previous studies found that plant biomass increased nearly proportionally with the amount of water transpired relative to evaporative demand. The water production function varies with the crop and variety, climate, soil, and management practices. Crop water productivity and return after variable cost for the major crops (or alternative crops) grown may be evaluated based on simulated yield using the Decision Support System-Cropping System Model. The most profitable crops should be determined under deficit and full irrigation condition. Water production functions are used with economic parameters to maximize net income with deficit irrigation. Deficit irrigation may maximize net income when irrigation water supplies are limited or expensive (Trout and Martin 2020).

Most of the irrigation water losses, up to 15%, are due to seepage and evaporation losses from open canals with low transmission capacity. These canals must be soon converted to a tubular system that minimizes water transmission losses. The saved water can be used in other sectors or it will be possible to irrigate extra agricultural land. Otherwise, water losses will continue to cause salinization and groundwater problems, reduce the productivity of soils, and pollute ground and surface waters.

On the other hand, the irrigation method applied has a significant effect on the amount of water lost. Water losses according to different irrigation methods are as follows (%): surface irrigation is 20-70, sprinkler irrigation is 20-35, central pivot irrigation is 10-20 and drip irrigation is 5-15. In Turkey, 82% of the existing irrigation systems are surface irrigation, 16% are sprinkler irrigation and only 2% are drip irrigation.

While traditional surface irrigation systems are replaced with the high efficiency pressurized irrigation (drip and sprinkler) systems, energy requirements of these systems must also be accounted, and the sustainable energy sources, wind and solar, should be preferred.

Adapting soil, soil water and energy conservation measures: Better residue management and mulching techniques, no or minimum tillage farming and increased soil organic matter may be considered among the soil, soil water and energy conservation measures.

Crop residue is defined as the portions of crops remaining such as stems, leaves and roots, some fallen grain, and often some weeds in the field after the grain has been harvested. Crop residues may have a direct monetary value to the farmer for livestock feed as well as a value for soil and yield improvement that varies widely according to the environment. Additionally, crop residue retention is one of the components of conservation agriculture (CA), along with zero or minimum mechanical disturbance and crop rotation (Anderson and Siddique, 2015) and is assumed to have value in erosion control, in building soil organic carbon (SOC) (Anderson and Siddique 2015) and in improving or maintaining soil fertility (Lal 2010) which presumably increase or sustain crop yield in the longer term.

In theory, under a better residue management conditions, increased water infiltration and reduced soil evaporation will lead to increased crop yield which, in the absence of other limiting factors, will lead to increased return of organic matter (Anderson and Siddique, 2015). Storage of limited rainfall in the soil during the fallow period after the harvest may be crucial for the soil moisture annealing, germination and emergence of the seed in the early stages of the next cropping season. Crop residues can help this in the ways of increased water

infiltration (Schwilch et al. 2013) and reduced soil surface evaporation, i.e. mulching effect of residue (Sommer et al. 2012).

There are scientific evidences (Loss et al. 2015) that no-till systems with stubble retention increase soil organic matter in comparison to the conventional tillage. The increase of organic matter in the soil improves the physical properties of the soil and accelerates the infiltration of rainwater into the soil. In addition, by increasing the water holding capacity of the soils, it prevents the infiltration of water below the root zone and therefore crops benefited from the limited rainwater effectively. Climate change forecast in Turkey suggest that rainfall characteristic will change, i.e., the number of consecutive dry days will increase and very heavy rainfall will occur at one time. Under these conditions, the increase of soil organic matter provides maximum benefit from this irregular rainfall and prevents soil erosion to a significant extent.

Although there are research results showing that residue affects the plant yield negatively (Scott et al. 2010), it is stated that it generally increases (Schwilch et al. 2013). Farooq et al. (2011) found that the impact of conservation agriculture (including both zero tillage and residue retention) on crop yields was mostly positive, especially at lower rainfall, but suggested that where the yield of conservation agriculture crops did not exceed those of conventional systems, factors such as weeds and diseases may have been responsible.

Minimum tillage and direct seeding practices contribute significantly to energy saving therefore to the environmental protection and climate change mitigation.

Minimum tillage and direct seeding is practiced in summer corn as second crop for silage after harvesting wheat, barley, vetch or pea in about 3.000 ha area in Trakya region of Turkey for the last 10 years to keep soil water, increase organic matter, decrease cost of seeding and use time effectively. The local companies have started to manufacture pneumatic direct sowing machine. While the direct sowing of maize is increasing day by day, direct sowing of sunflower is expected to be widespread in the near future (Figure 13).

6.7. APPROACHES TO INCREASE COMPETITIVENESS IN AGRICULTURAL SECTOR, ENSURE SUSTAINABILITY AND MITIGATE CLIMATE CHANGE UNDER CSA

Previous research on agriculture has focused only on economic impacts, but today agricultural system performance is considered multidimensional, taking into account the economic, environmental and social dimensions and the interaction between these dimensions.

Technological developments, environmental sustainability and competition have led to the emergence of CSA, Organic Farming (OF) and Good Agricultural Practices (GAP), precision agriculture, digital agriculture, vertical agricultural practices and smart greenhouses besides traditional agriculture.

Figure 1. 3: Direct sowing of summer corn as second crop for silage after wheat harvest in Trakya region (Photos were obtained from Ekmen Farming Inc.'s owner, Agricultural Engineer Irfan Ekmen)

OF and GAP practices: OF is expressed as a production system that protects human health and ensures the continuity of the ecosystem. This system is based on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Although there are chemical input applications in GAP, these applications are applied in a way that does not harm human health and the environment. The development of sustainable agricultural systems is seen as a priority target in the prevention of environmental problems in the world. OF and GAP contribute to preventing climate change as well as environmental sustainability. GAP can be made very common in a short time.

Precision agriculture: Precision agriculture *is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.* By using different technologies such as drone, GPS and IoT, it can continue the planning, planting, irrigation and harvesting processes with minimum manpower and minimum resource usage, thus creating maximum product efficiency. In order for precision agriculture to be widely used, it is necessary to transform agricultural enterprises into medium and large enterprises and to increase the education level of farmers.

Vertical farming: It is the practice of growing crops in vertical layers. It combines hydroponic farming techniques such as hydroponics, aquaponics and aeroponics, and controlled-environment farming aimed at optimizing plant cultivation. Vertical agriculture can produce more products with less unit land requirement. Also, since products are indoors, they suffer less losses in extreme or unexpected weather events. Vertical farming technologies have large initial costs compared to conventional farms. The energy requirement is high. If solar or wind energy is not used, it harms the environment more than conventional agriculture and can cause climate change.

Smart greenhouses: Using solar, wind and geothermal energy or hot water released in industrial production can be used to heat fully automated hydroponic smart greenhouses. In this way, there is an opportunity to make long-term agricultural production without being dependent on climatic conditions.

The prevalence of CSA, OF and GAP, precision agriculture, digital agriculture, and vertical agricultural practices will ensure competitiveness in agricultural production, protection of the environment, adaptation to the negative effects of climate change and prevention of climate change. In addition, they can contribute to the development of new industries related to these systems, to increase employment, to ensure sustainable socioeconomic development and food security.

6.8. INSTITUTIONAL ASPECT OF CLIMATE SMART AGRICULTURE IMPLEMENTATION

How can institutions support CSA?: Institutions can support farmers, particularly smallholder, in the implementation of CSA in three vital areas (FAO 2013):

- **Producing and sharing technical knowledge:** For relatively resource-poor smallholder farmers, putting CSA into practice requires knowledge and support. Farmers need easier and more affordable access to the information that underpins innovative CSA practices. Institutions that produce and share information and help people translate this information into knowledge and action are essential.
- **Providing financial services, credit and access to markets:** The benefits gained by adopting CSA usually take time to realize. In the meantime, the farmers must bear the costs in terms of labour, land and cash. As a result, poor farmers lacking access to credit and markets are unable to adopt these techniques. This is why strengthening institutions to support agricultural markets, financing mechanisms and insurance schemes are critical for the CSA's success.
- **Supporting the coordination of collaborative action:** Collective action is critical for managing communal forests and pastures and lowering transactions costs. Many CSA activities are only feasible and affordable if people work together (e.g. improved water or rangeland management). Institutional arrangements that make groups function efficiently and effectively are essential. On a larger scale, institutional arrangements are also needed to facilitate coordination across organizations and sectors (e.g. through networks and knowledge-sharing platforms).

Key institutions for CSA initiatives: Successful changes in agricultural practices, technologies or policies are possible when dialogue and cooperation is encouraged among all the stakeholders who possess, produce, or use different kinds of knowledge. The most effective initiatives allow researchers, community members, private sector actors and policy-makers to jointly define the problems they aim to solve (FAO 2013).

Under changing climate, two types of advice are needed: firstly, information about available options (e.g. technology and market) to help adapt farming and livelihood systems; and secondly, information about the climate itself, in the form of weather forecasts, seasonal forecasts and longer-term climate trends. Preference should be given to early warning and early action initiatives rather than find out solution during the disaster such as drought, flood and etc. (FAO 2013).

Roles and responsibilities, as services provider or as stakeholders, of public sector institutions, civil society, non-governmental organizations, universities and research institutions, the media, private sector institutions, individual farmers, producer cooperatives, national and

international agribusinesses, commercial consultancies, banks, credit and savings institutions, purchasers of carbon credits should be defined.

For the synergy to facilitate interaction and communication between many individual institutional actors, a conducive environment needs to be created. This ‘institutional interplay’ should not only be ‘horizontal’, taking place on the same organizational level, but also integrate institutions ‘vertically’, incorporating perspectives across traditional levels and hierarchies (FAO 2013).

Because of the many institutional interactions involved, CSA initiatives requires reliable networks to support information exchange and partnership-building. Equity issues and cultural considerations should also be tackled with.

CHAPTER 7

SUSTAINABLE WATER RESOURCES MANAGEMENT UNDER CLIMATE CHANGE

7.1. RENEWABLE FRESH WATER RESOURCES AND WATER SCARCITY AROUND THE WORLD AND IN THE PARTNERING COUNTRIES

Water is the fundamental ingredient for life on Earth. Seventy percent of the earth's surface is water. You can find it in the atmosphere above us, in the ocean, rivers and lakes around us, and in the rocks below us. Despite its importance for life, though, fresh water is an extremely rare resource on Earth. Less than 3% of the water found on Earth is fresh water, and the remaining 97% is salt water, such as what is found in the ocean. Most of the world's fresh water is not easily accessible to humans. Approximately 69 percent of Earth's fresh water is locked away in the form of ice in glaciers and polar ice caps, and another 30% of Earth's fresh water is under the surface in the form of groundwater. That leaves only about 1% of Earth's fresh water as readily available for human use (Gleick and Coley 2021).

Numerous studies have been conducted of major natural flows between these stocks of water in the form of precipitation, evapotranspiration, and river runoff, including combinations of observations and model estimates (Gosling and Arnel 2016, Wisser et al. 2010). Water-balance components vary from year to year and there are uncertainties associated with the difficulty of measurement, but the current estimate of total precipitation over land is approximately 110 000 cubic kilometers per year (km^3/year), natural evapotranspiration is approximately 68 000 km^3/year, and river discharge into the oceans and inland sinks is approximately 26 000 km^3/year. The remainder 16 000 km^3/year is net human consumption of water, which corresponds 2 000 m^3/year/per capita in average (Gleick and Coley 2021).

However, the available surface fresh water is not equally distributed in space and time throughout the world (See Figure 7. 1). Brazil, Russia, Canada, Indonesia, China, Colombia, and the United States have most of the world's surface freshwater resources. As a result, approximately one-fifth of the world's population lives in water-scarce areas where, on average, each person receives less than 1,000 cubic meters of water a year. This lack of water affects people's access to clean, usable water, as well as the economic development and geopolitics of different areas (Gleick and Coley 2021).

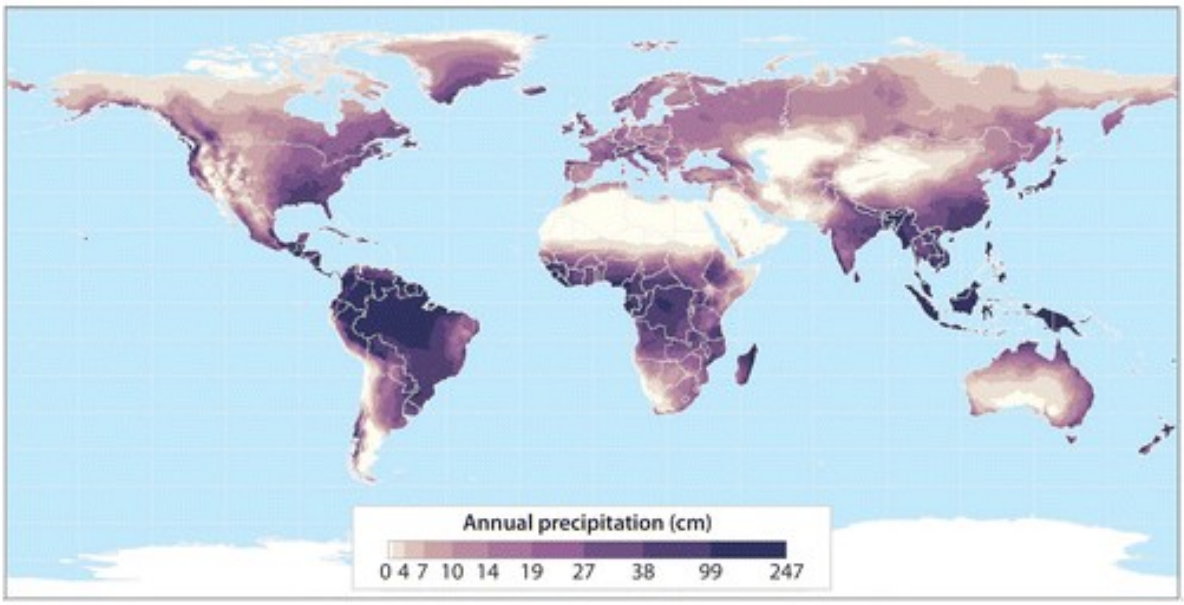


Figure 7. 1. The uneven distribution of precipitation around the world (Gleick and Coley 2021. Annual Review of Environment and Resources. Vol. 46:319-348 https://doi.org/10.1146/annurev-environ-012220-101319).

The 2018 edition of the United Nations (UN) World Water Development Report (WWDR 2018) has provided an update on the present trends of clean water availability and future expectations. Water security, the capacity of a population to safeguard sustainable access to adequate quantities of water of acceptable quality, is already at risk for many, and the situation will become worse in the next few decades (Burek et al.2016, Boretti and Rosa 2019). Clean water scarcity is a major issue in today's' world of 7.7 billion people. The strain on the water system will grow by 2050 when the world population will reach between 9.4 and 10.2 billion, a 22 to 34% increase. The strain will be aggravated by unequal population growth in different areas unrelated to local resources. Most of this population growth is expected in developing countries, first in Africa, and then in Asia, where scarcity of clean water is already a major issue (Boretti and Rosa 2019).

At present, slightly less than one half of the global population, 3.6 billion people or 47%, live in areas that suffer water scarcity at least 1 month each year (WWDR 2018, Boretti and Rosa 2019). Instead, they had access only to contaminated water, which can carry pollution and infectious diseases; populations drinking dirty water are at increased risk of diarrhea, cholera, dysentery, and other diseases. Lack of access to clean drinking water leads to more than 3 million deaths every year. According to Mekonnen and Hoekstra (2016) the number is even larger, 4.0 billion people, or 52% of the global population. By 2050, more than half of the

global population (57%) will live in areas that suffer water scarcity at least one month each year (WWDR 2018, Boretti and Rosa 2019). This estimate by WWDR may be an underestimation. The water demand, water resources, and water quality forecast by WWDR depends on many geopolitical factors that are difficult to predict. The decline of water resources and water quality only partially discussed in WWDR may be much harder to control (Boretti and Rosa 2019).

Access to fresh water is also important for economic development. For example, freshwater sources enable the development of fisheries. People around the world harvest fish from these habitats, providing enough animal protein to feed 158 million people worldwide. These fisheries are both a source of subsistence for local fishermen and a source of income for traders (https://education.nationalgeographic.org/resource/freshwater-resources/).

Beyond the use of fresh water as a habitat, fresh water is also an important resource in other economic activities, such as agriculture. According to one estimate, about 70% of the world's fresh water is used for agriculture. Farmers around the world use irrigation to transport water from surface and ground water sources to their fields. These agricultural activities involve over 1 billion people worldwide and generate over $2.4 trillion in economic value every year. In the future, demand for agricultural fresh water will only increase as global populations grow. According to one estimate, demand will increase by 50 percent by 2050. This increase in water use will put further strain on Earth's limited freshwater supplies and make access to fresh water even more important (https://education.nationalgeographic.org/resource/freshwater-resources/).

7.1.1. Global and regional water withdrawals

Data on water withdrawals by regions and different economic sectors are among the most sought information. The FAO maintains the AQUASTAT database, which has tried to standardize estimates of water withdrawals by country. Despite their limitations, they remain among the most comprehensive datasets available. Within the AQUASTAT database, water withdrawals are divided into three major categories: agriculture, industry, and municipal/domestic, although water-accounting systems are inconsistent.

Agricultural water withdrawals consist of water used for irrigation, livestock watering and cleaning, and aquaculture. Water for processing agricultural products is included under industrial or municipal water withdrawals. In rural areas, agricultural water withdrawals frequently include water for domestic purposes.

Industrial water withdrawals consist of water used by self-supplied industries not connected to a public distribution network for such purposes as fabricating, processing, washing, diluting, cooling, or transporting a product; water incorporated into a product; or water used for sanitation needs within the manufacturing facility.

Municipal withdrawals are a broad category that includes water for domestic uses, as well as water provided by a municipality or other public supplier for commercial, industrial, and institutional purposes.

Around 2010, the most recent year for which data are available, agriculture accounted for 69% of global water withdrawals, followed by self-supplied industry (19%) and municipalities (12%). These ratios, however, are subject to significant regional variability. In Africa and Asia, for example, agriculture accounts for more than 80% of water withdrawals, compared to 65% in Oceania, 48% in the Americas, and 25% in Europe. By contrast, industrial water withdrawals are relatively high in Europe (54%) and the Americas (37%), compared to 15% in Oceania, 10% in Asia, and only 4% in Africa. Regional variability in municipal withdrawals ranges from 9% in Asia to approximately 20% in Oceania and Europe (Gleick and Coley 2021, FAO 2020). Global water withdrawals (km^3/year) by sector from 1900 to 2010 is presented in Figure 7.2.

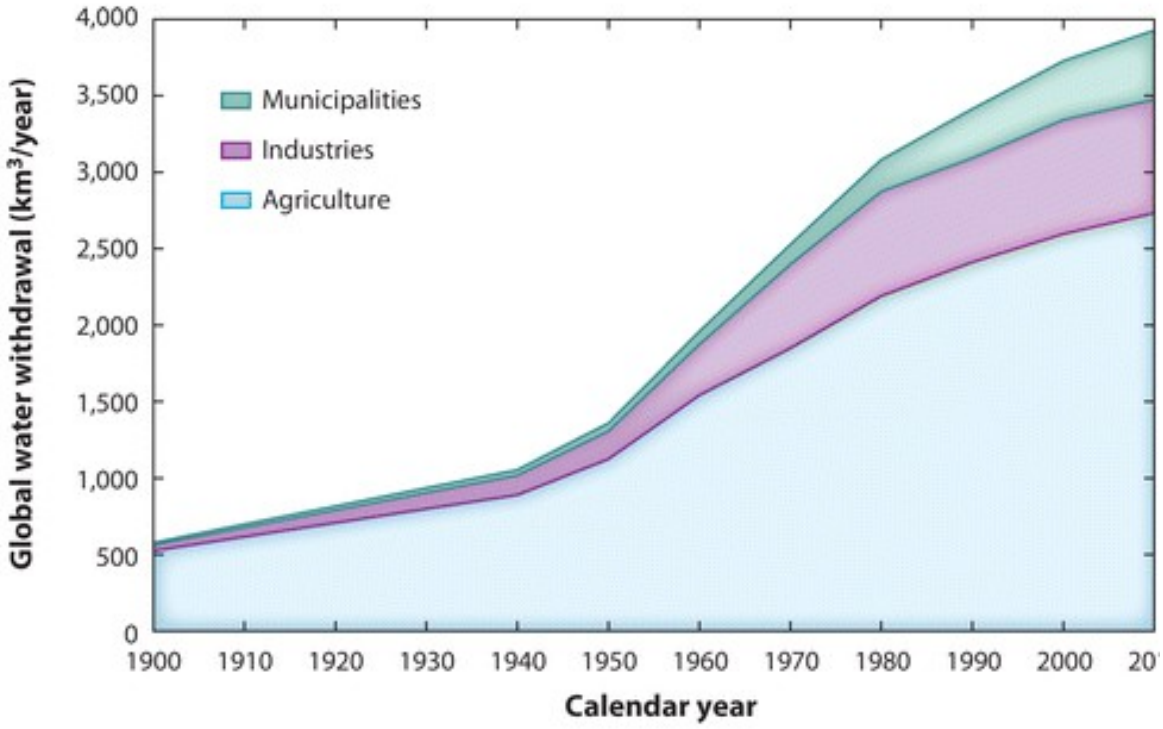


Figure 7.2. Global water withdrawals (km^3/year) by sector from 1900 to 2010. Global water withdrawals are dominated by irrigated agriculture (Gleick and Coley 2021. Annual Review

of Environment and Resources. Vol. 46:319-348 https://doi.org/10.1146/annurev-environ-012220-101319).

Global water withdrawals increased nearly sixfold between 1900 and 2010 (Figure 2.2) (FAO 2020, Gleick and Coley 2021,). This corresponds to an annual increment rate of 1.8%. According to Wada et al. (2016) the present annual growth rate is less, only 1%, but this figure may be optimistic. The period of most rapid growth was between 1950 and 1980, when global water withdrawals increased by a factor of 2.5. There was a similar trend for consumptive use of water, including surface and groundwater use (Wada and Bierkens 2014). The rate of growth began to slow in 1980, and there is some indication that water withdrawals started to slow around the year 2000. Between 2001 and 2010, global water withdrawals increased by only 2.7%, compared to an average increase of 30% in each 10-year period spanning 1951 to 1960, 1961 to 1970, and 1971 to 1980.

7.1.2. Global water demand and supply by 2050

Global water demand will grow significantly over the next two decades in all the three components, industry, domestic and agriculture. Industrial and domestic demand will grow faster than agricultural demand but demand for agriculture will remain the largest. Global water demand for all uses, presently about 4 600 km^3 per year, will increase by 20% to 30% by 2050, up to 5500 to 6000 km^3 per year. By 2050 the global population will increase to between 9.4 to 10.2 billion people, an increment of 22% to 32%. The food demand by 2050 will increase by 60%, and this increment will require more arable land and intensification of production. This will translate into increased use of water (Boretti and Rosa 2019, Gleick and Coley 2021, WWDR 2018).

Water demand cannot exceed water availability. While water demand is increasing, water availability is decreasing because of shrinking resources and pollution. The available surface water resources are forecasted to remain about constant at continental level, although quality will deteriorate, and spatial and temporal distribution will change. More likely, aquifers will shrink, and salt intrusion in coastal areas will be very dramatic. In contrast, the growth of population, gross domestic product (GDP), and water demand will increase globally and unequally. Changes will be much more pronounced at the sub-regional level than at the country level, and the global average (Boretti and Rosa 2019, Gleick and Coley 2021, Wada et al 2016).

7.1.3. Other ecological changes by 2050

Changes in the ecosystems will be affected by changes in the water demand and availability and vice versa. Conservation or restoration of the ecosystems will impact on water availability for human consumption, both resources and quality. About 30% of the global land area is forested, and 65% of this area is already in a degraded state (FAO 2015, Boretti and Rosa 2019). Large areas of forests and wetlands have been converted into grasslands, for livestock grazing or production of crops. The loss of natural wetland area has been 87% since 1700. The rate of wetland loss has been 370% faster during the 20th and early 21st centuries (Davidson 2014, Boretti and Rosa 2019). Soils are also changing. Most of the world's soils are in only fair, poor or very poor condition (FAO 2015, Boretti and Rosa 2019), and the situation is expected to worsen in the future. The major global issues are soil erosion, loss of soil organic carbon and nutrient imbalance. Presently, soil erosion from croplands carries away 25 to 40 billion tons of soil every year. Crop yields and soil's ability to regulate water, carbon, and nutrients are reduced. 23 to 42 million tons of nitrogen and 15 to 26 million tons of phosphorus are presently transported off the land. Soil erosion and nutrient run-off have negative effects on water quality. Sodicity and salinity of the soils are global issues in both irrigated and non-irrigated areas. Sodicity and salinity take out 0.3 to 1.5 million ha of farmland each year (FAO 2015, Boretti and Rosa 2019). The production potential is also reduced by 20 to 46 million ha. Ecosystems, biodiversity, and soil degradation are expected to continue to 2050, at an ever-faster rate. This will have an impact on the availability and quality of water.

As clean water demand is increasing, and clean water availability is reducing, with local situations much worse than global, clean water demand will eventually exceed the availability of clean water at some local levels much earlier than at the global level. These break-points may occur earlier than 2050 in many areas of the world. Considering when a vital resource is in short supply, people will fight for it, provision of water to 2050 will be very likely played against a social background of competition and probably conflict if nothing will be done to prevent a water crisis (Boretti and Rosa 2019).

7.1.4. Water supply and demand of partnering countries

Turkey: The annual average precipitation in Turkey is approximately 574 mm, which equates to about 450 Billion Cubic Metres (BCM) of water. Surface water potential that can be used for various purposes averages 94 BCM/year under today's technical and economic conditions. Turkey's consumable surface and groundwater potential is 112 BCM/year, of which 57 BCM is utilized (Table 7.1).

Table 7.1. Water potentials of Turkey (DSI, 2018: http://www.dsi.gov.tr/)

Mean annual precipitation (mm/year)		574
Area of Turkey (km^2)		783 577
Total volume of water (BCM)		450
Annual runoff (BCM)		186
Usable surface water (BCM)		94
Annual abstracted groundwater (BCM)		18
Total usable water potential (BCM)		112
Current water use	Agriculture (BCM)	44 (%77)
	Domestic and industry (BCM)	13 (%23)
	Total (BCM)	57 (%100)

Turkey has some of the highest levels of water security threat of the countries in Europe. Due to a rapid population increase from 28 million in the 1960's to 84 million in 2023 the availability of water resources decreased from around 4000 m^3 to 1333 m^3 per capita/year today (DSI, 2018). Water demand in Turkey approximately has doubled in the second half of the last century. The overall water demand in Turkey continues to increase, even more in the light of the effects of drought (or climate change). Turkey will suffer from water scarcity in the next years. Water availability is expected to decline to around 1000 m^3 in 2050 as a result of population growth and impact of climate change (SYGM, 2016).

About 77% of the total water supply of Turkey is used for agricultural irrigation, remaining 23% is used for drinking-domestic and industrial purposes (DSI, 2018).

According to both, optimistic and pessimistic, scenarios in Turkey, the amount of precipitation is expected to decrease in in the years 2015-2100. From 2050 onwards, more pronounced reductions up to 250-300 mm are predicted (average 60 mm). Negative rainfall anomalies stand out, especially in the Aegean and Mediterranean coasts, and in the Southeast and East regions. Increases in total precipitation and extreme rainfall events are expected in

the east of the Black Sea. Significant reduction in snow-covered areas and amount of snowfall is predicted (SYGM, 2016).

Estimates of changes in runoff of between -52% and -61%, and reductions of surface waters in the Turkish basins of 20%, 35% and 50% for 2030, 2050 and 2100 have been reported. By 2100 Turkey could experience an expansion of arid areas that could lead to increased water stress around the southern Mediterranean areas (Bozkurt and Sen, 2012)

Austria: Austria is marked by a high volume of water resources. They develop via springs and waterfalls into mountain torrents and rivers, feed lakes, mark the landscape and are invisibly stored in the underground as groundwater (Federal Ministry Republic of Austria - Agriculture, Regions and Tourism, 2021)

The total annual precipitation of 1190 mm, which falls on a long-term average on the federal territory, corresponds to a water volume of about 99.8 BCM. Of this volume a major part flows off on the surface and/or near to the surface via the running waters or evaporates. On Austrian average a share of almost 27 % of the precipitation seeps into the groundwater and is intermediately stored there on a medium- or on a long-term basis.

The total annual water demand in Austria amounts to about 3.1 BCM (see Table 7.2) The potential development until 2050 is represented in Table 7.3.

About 60 % – which are about 1.9 billion m³ – are withdrawn from surface waters. The major part of it is used as cooling water for trade and industry, a smaller part is used by agriculture and services (artificial snow).

About 40 % of the total water demand – which are about 1.2 billion m³ – are covered by groundwater (68 % wells, 32 % springs). The highest share is used for water supply, a smaller share is assigned to trade and industry as well as to agriculture and services.

Table 7.2. Water demand in million cubic meter (MCM) currently Water demand

Water demand (MCM)	Ground-water Total (MCM)	Surface waters (MCM)	Total (MCM)	Share in the total sum (%)
Water supply	753		753	24
Agriculture	118	6	124	4
Trade and industry	353	1857	2210	70
Selected services	7	45	52	2

Total	**1232**	**1908**	**3140**	**100**

The assumptions for 2050 anticipate that the demand for trade and industry will remain approximately the same while the demand for water supply for domestic agricultural sector, selected services is expected to increase and total water demand will be in the range of 3312 – 3359 MCM for the Water Treasure Scenario "favourable" and "unfavourable", respectively.

Table 7.3. Potential development of the water demand in million m³ until 2050

Water demand (MCM)	**Currently (MCM)**	**Scenarios 2050 (MCM)**	**Change of water demand (%)**
Water supply	753	830-850	10.2-12.9
Agriculture	124	182-202	46.8–62.9
Trade and industry	2210	2237	-
Selected services	52	63-70	21.2–34.6
Total	**3140**	**3312 - 3359**	**5.5–7.0**

Czech Republic: Long-term average annual precipitation of Czech Republic is 2017 mm/year, which corresponds 53.4 BCM/year water potential across the country.

Sum of renewable groundwater and renewable surface water resources (both internal and external) is about 13 billion m³/year, 1215 m³/person/year (Table 7.4).

Table 7.4. Water potentials of Czech Republic (https://www.worldometers.info/water/czechia-water/#water-precipitation)

Mean annual precipitation (mm/year)		2017
Area of Czech Republic (km^2)		78.871
Total volume of water (BCM)		53.4
Total renewable water (surface and groundwater, both internal and external) (BCM)		13
Current water use	Agriculture (MCM)	44.5 (%3)
	Industry (MCM)	981.8 (%60)
	Domestic (MCM)	605.6 (%37)
	Total (MCM)	**1.635 (100)**

Central and Northern European countries including Czech Republic show an increase in the average annual water availability (Bisselink et al 2020).

Poland: Long-term average annual precipitation of Poland is 600 mm/year, which corresponds 187.6 BCM/year water potential across the country (Table 7.5).

Sum of renewable groundwater and renewable surface water resources (both internal and external) is about 61 billion m^3/year, 1585 m^3/person/year.

Table 7.5. Water potentials of Poland (https://www.worldometers.info/water/poland-water/#water-resources)

Mean annual precipitation (mm/yr)		600
Area of Czech Republic (km^2)		312.696
Total volume of water (BCM)		187.6
Total renewable water (surface and groundwater, both internal and externall) (BCM)		61
Current water use	Agriculture (BCM)	1.053 (%10)
	Industry (BCM)	7.483 (%71)
	Domestic (BCM)	2.046 (%19)
	Total (BCM, %)	**10.58 (100)**

Central and Northern European countries including Poland show an increase in the average annual water availability (Bisselink et al. 2020).

7.1.5. Water Scarcity

Water stress can be qualitatively defined as the lack of sufficient fresh water for domestic, agricultural, and/or industrial needs. Water stress may result from overuse of water supplies due to population increase, industrialization, and/or lack of conservation practices, as well as from decreased rainfall due to changes in climate and/or lack of storage capacity in areas that receive variable amounts of water throughout the year. Building on work by Falkenmark (Falkenmark 1986), world relief agencies commonly define conditions of "water stress" as less than 1700 m^3 of available water per person per year and "severe water stress" as less than 1000 m^3 per person per year.

The three key aspects of water scarcity, water demand, water resources, water pollution, are strongly related to population growth and economic growth. They are strongly interconnected, and dramatically variable in space and time, with local conditions that will be much worse than the global conditions. Many factors drive water scarcity, including the basic hydrology of a region, demographics and economics, the level and type of water infrastructure and institutions built to satisfy human demands, and the nature of those demands themselves (Gleick and Cooley 2021).

Hydrology: Temporary regional moisture imbalance is called drought. It is basically a climate phenomenon defined as water scarcity. There are many different types of drought, including hydrological, meteorological, agricultural, and economic. Hydrological and meteorological drought, for example, may be defined as a shortfall of runoff, groundwater, precipitation, or another water-related metric compared to the amount of water expected on average. Agricultural drought may be a shortage of water during a particularly critical time required for the successful production of a crop. A social or economic drought can be defined in the context of a specific social or economic demand for water when that demand cannot be fully met. Ecological drought is a deficit in naturally available water supplies that create stresses across ecosystems (Mann and Gleick 2015; Wilhite and Glantz 1985).

Demographic and Economic Factors: As populations increase, the amount of water available per capita declines. The simple metric—per capita water availability (water per unit population)—is a common way to measure water scarcity. With population and economic growth, the demand for water has traditionally increased as well, creating measurable and significant new contributors to scarcity and supply/demand imbalances. Economic factors can also drive perceived scarcity when for reasons of poverty people are unable to pay for the water services they need and are deprived of access to those services (Molle and Mollinga 2003).

Infrastructure and Institutions: Even when physical or economic availability of water is not a problem, water scarcity can still occur if inadequate infrastructure exists or problems with institutions and water management systems keep desired water services from reaching the point of demand. Another aspect of institutional scarcity is when water policy limits the amounts of water that can be used, for example, when efforts to protect and restore ecosystems lead to commitments of water for the environment that might previously have been used by humans (Fischhendlen and Zilberman 2005)

Climate Change: Human-induced climate changes are accelerating. Water and climate change are inextricably linked. Extreme weather events are making water more scarce, more unpredictable, more polluted or all three. These impacts throughout the water cycle threaten sustainable development, biodiversity, and people's access to water and sanitation.

Among the now unavoidable consequences are fundamental changes in the hydrologic cycle, including increases in evapotranspiration rates as temperatures rise, regional shifts in stocks and flows of water and ice, alterations in the intensity and severity of extreme events such as droughts and floods, shifts in the freshwater balances of coastal aquifers and estuaries as sea levels rise, and more (Field et al. 2014.). Climate changes will also have direct and indirect impacts on water scarcity by changing both the supply and demand of fresh water. Although climate models continue to improve, uncertainties about the detailed long-term implications of climate change for regional and local hydrology remain. As climate changes worsen, the risks of water scarcity for hundreds of millions of people are expected to increase, barring major efforts to reduce scarcity risks (Gampe et al. 2016).

7.2. IMPACT OF CLIMATE CHANGE ON AGRICULTURAL WATER MANAGEMENT

Agriculture is the sector that may be most seriously affected by climate change as crop and livestock systems depend critically on climatic variables such as precipitation and temperature. In particular, climate change affects agricultural water requirement, water availability, and water quality (Kundzewicz et al. 2007, Cai et al. 2015). The impacts of climate change on water management have been assessed in several recent special reports from international agencies, such as the Food and Agriculture Organization of the United Nations (Turral et al. 2011), the International Food Policy Research Institute (IFPRI) (Nelson et al. 2009) and IPCC (2013, 2014). More recently Cai et al. (2015) published a review on impacts of climate change on agricultural water management. These studies all share a common conclusion: Climate change will likely affect agriculture negatively, thereby threatening global food security (Cai et al. 2015).

Climate change may alter both water availability and crop water requirement significantly as a result of changing temperatures and precipitation at the local and regional levels. Crop water requirement is usually measured by water evapotranspiration (ET), the sum of evaporation, and plant transpiration from the Earth's land surface to atmosphere. Water availability,

including both precipitation and irrigation, can satisfy crop water requirements is a major factor determining crop production (Cai et al. 2015).

7.2.1. Crop water requirements (ET) under climate change

Crop ET can be fully or partially satisfied by precipitation that can be effectively used by crop (i.e., effective precipitation) for rainfed crops and by both precipitation and irrigation for irrigated crops. The water deficit of rainfed crops (i.e., the difference between ET and effective precipitation) is sensitive to climate projection scenarios (Zhang and Cai 2013).

Zhang and Cai explained their findings by showing the trend of crop ET. It is usually believed that rising temperatures will lead to increasing evaporative demand; however, a warmer atmosphere does not necessarily cause higher evaporation (Zhang and Cai 2013, Ohmura and Wild 2002). This is probably because of the observed decrease in ET under warmer climate is the decline of the diurnal temperature range (DRT, defined as the difference between daily maximum temperature and daily minimum temperature); Recent IPCC reports (2014 Part A and Part B) have shown that declined DTR is a primary factor leading to the decline of ET.

Regional heterogeneity of climate change impacts on crop water requirements is significant. Some patterns in irrigation requirements and water deficit on rainfed crops can be identified. Lower water requirements can be expected in Africa, Australia, and China, while other regions—Europe, North India, the eastern portion of South America, and the eastern United States—may be adversely impacted by climate change (Zhang and Cai 2013).

The requirements and deficits will decrease in Western Europe but increase in the Eastern Europe; Southern Europe has a higher probability to experience greater water gaps than the north due to the altered precipitation Water stress is likely to intensify in the Mediterranean countries (Portugal, Spain and Turkiye) and some parts of Central and Eastern Europe (Bates et al. 2008).

According to the results of a research conducted in the Thrace Region of Turkey (Deveci 2015), the average ETo values in 2012 were calculated as 3.0 mm/day according to the Penman Monteih method (Allen et al. 1998). Considering climate change projections, ET0 is expected to increase to 3.2 mm (7%) between 2016 and 2025; to 3.6 mm (20%) between 2046-2055 and 4.0 mm (33%) between 2076 and 2085.

The change of the timing of the growing season for specific crops also complicates the estimate of irrigation requirements under climate change (Mínguez et al. 2007). Rising temperature would extend the length of the growth period, allowing both earlier planting and

later harvesting, in the northern temperate zones, but reduce the length almost everywhere else (Turral et al. 2011). Longer growth periods will likely increase crop water requirements. Furthermore, one crop may become unsuitable to plant in a particular region as the climate changes. Such agricultural alteration makes the estimates of crop water requirement more complicated. Adaptation measures such as adjusted crop calendars, increased crop water use efficiency, and advanced irrigation technologies can further reduce crop water requirement (Cai et al. 2015).

7.2.2. Water availability under climate change

In agriculture, water available for rainfed crops is called green water, i.e., water stored in soil that can be used for crop growth; while water available for irrigated crops includes both green water and blue water (i.e., water in rivers, lakes, and aquifers) (Falkenmark and Rockström 2006). The change of precipitation, including the total amount and seasonal distribution, will be a determining factor for rainfed crops. Irrigation is a measure to mitigate the impact of water shortage within the crop growth season by withdrawing blue water from surface or ground water sources. Local and regional changes in precipitation and temperature affect water available for irrigation (Schewe et al. 2014, Rosegrant 2002).

Surface water: The impacts of climate change on surface water resources in rivers, lakes and reservoirs, and wetlands are primarily determined by the timing, the location, the quantity and the form (snow or rain) of precipitation (Bates et al. 2008). Local patterns are more variant and important for precipitation than temperature.

Changes in precipitation and temperature lead to changes in runoff and water availability (Figure 7.3). Runoff is projected with high confidence to increase by 10 to 40% by mid-century at higher latitudes and in some wet tropical areas, including populous areas in East and South-East Asia, and decrease by 10 to 30% over some dry regions at mid-latitudes and dry tropics, due to decreases in rainfall and higher rates of evapotranspiration. There is also high confidence that many semi-arid areas (e.g. the Mediterranean Basin, western United States, southern Africa and north-eastern Brazil) will suffer a decrease in water resources due to climate change (IPCC 2007).

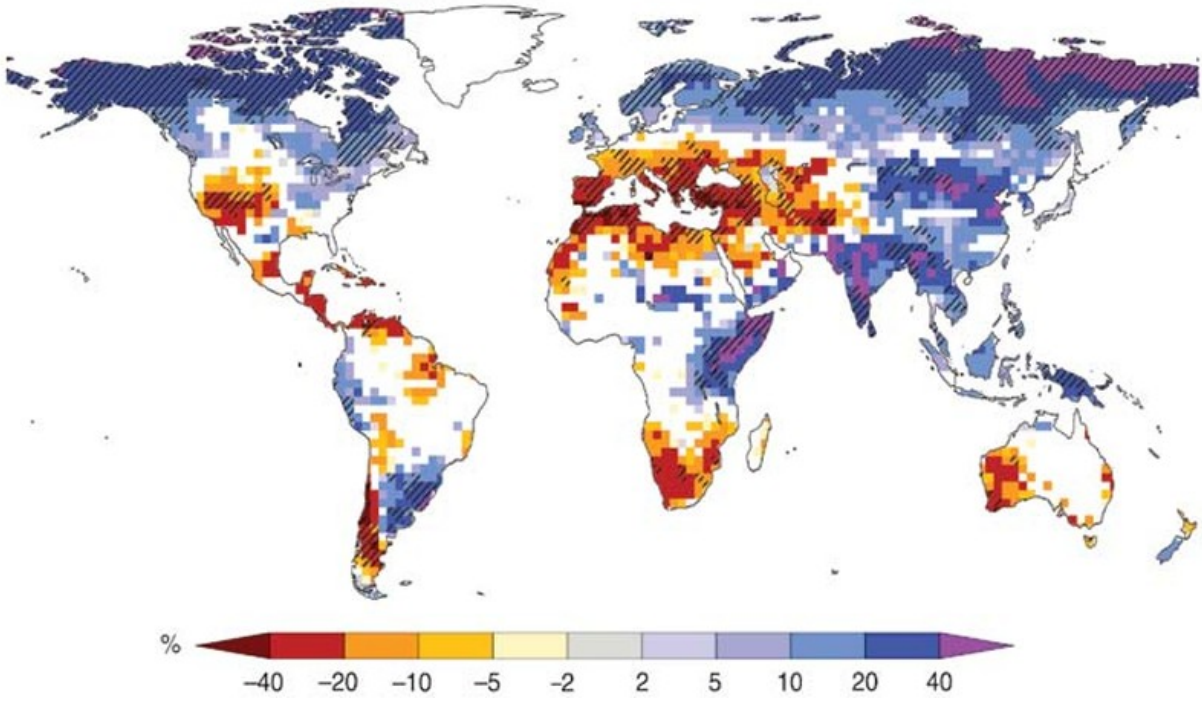


Figure 7.3. Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999 (Source: IPCC 2007, SYR Fig.3.5).

Many large-scale irrigation systems in the world depend on surface water, and the impact of climate change can be complicated with the upstream–downstream water allocation issues at the river basin scale and international water sharing in many regions (Cai et al. 2015, Turral et al. 2011).

Snow and Glaciers: Glacial ice is recognized as the largest reservoir of freshwater on Earth, 'storing' about 70% of global freshwater. Water stored as glacial ice/snow is considered as hydrologic insurance for a region specifically for agriculture. Many irrigation systems in the world depend on water flow from snow melting in the upstream glacial areas in the crop season. Increased temperature in the winter or early spring increases water flow prior and/or post the crop season but decreases flows within the crop season (Cai et al. 2015).

Warming effects are likely to alter the hydrological cycle in snow-dominated regions significantly. It was concluded with high confidence that the rising temperature would alter seasonality of river flow regimes at places where the form of winter precipitation shifts from snow to rain. This will change the timing of the peak stream flows originating from snowmelt in many continental and mountainous regions. As a consequence, winter flow increases due to earlier snowmelt while summer flow decreases. Places of lower elevations with marginal amounts of snowfall are more sensitive to this effect, and peak flow could occur at least

month earlier in many cases. As the reservoir storage capacity is insufficient to handle this shift in maximum runoff, most of the 'early water' will be wasted and end in the ocean (Kundzewicz et al. 2007, Barnett et al. 2005, IPCC 22013, Cai et al. 2015).

For example, according to climate change projections, decreases in snow-covered areas and snowfall amounts are predicted in Turkey. The decrease in snow cover thickness in winter and spring in eastern Turkey indicates a change in the character of precipitation. The decrease in snow in the Eastern Anatolia region may cause serious decreases in the flow rates of streams in the spring and summer months, when melting occurs today. This will cause economic losses in Turkey's agricultural sector and energy sector. Increasing evapotranspiration, especially due to the increase in temperatures, will increase the need for irrigation in the agricultural sector (SYGM 2016, Konukcu et al. 2019).

Groundwater Sources: Groundwater is of vital importance to the water security of many communities as it serves as a buffer during an extreme climate event. Irrigation is the primary user of groundwater in many regions. However, extensive groundwater pumping for irrigation has already caused groundwater depletion and the situation can be aggravated in the future because of climate change, threatening groundwater sustainability (Taylor et al. 2013).

Climate variability and change influence groundwater systems directly through groundwater recharge and indirectly through altering groundwater withdrawal for human water supply (Taylor et al. 2013). Warming effects on glacier melting, which may increase runoff in spring and decrease it in summer, can further increase the demand for groundwater. Such situations might be exacerbated due to the rising occurrence of droughts and other extreme climate events (Hagg et al. 2007). Moreover, climate change will enforce a great threat on groundwater resources in islands and coastal areas because of sea-level rise and salt water intrusion of aquifers (Bates et al. 2008).

Thus, additional surface water storage capacity, as well as artificial recharge to groundwater before and after the crop growth season especially in wet years, can be effective measures to enhance hydrologic insurance in some regions.

Soil moisture: Rainfed crops depend on soil moisture which is an important variable of the climate system. Soil moisture is affected by other climate variables, such as precipitation, temperature, and wind speed, as well as soil physical conditions. Therefore, projected climate change can have considerable impact on soil moisture at the local and regional scale (Seneviratne et al. 2010, Cai et al. 2015). Such change can have either positive or negative

impact on rainfed crops directly. Small-scale rainfall harvest projects are a key to mitigate the effect of precipitation change in both amount and temporal distribution (Turral et al. 2011, IPCC 2013).

7.2.3. Water Quality

Water availability for human society and the environment critically depends not only on water quantity but also on water quality because water quality and quantity are connected and affect each other. However, the impact of climate change on water quality has not been sufficiently studied compared to water quantity (Kundzewicz et al. 2007, Bates et al. 2008). Climate change directly affects water quality through the change of water temperatures in water bodies. On the other hand, human activities in agriculture and other sectors are primarily responsible for water quality degradation indirectly due to disposal of waste water.

There are many reasons for water quality degradation due to agricultural activities under climate change: i) soil erosion in agricultural land, ii) water salinization in coastal regions due to excessive water withdrawals from aquifers causing saltwater intrusion which can be exacerbated by sea-level rise caused by global warming, iii) land use and management, including soil cultivation and fertilization, and pesticide applications, iv) irrigation by water from sewage treatment plants during drought, v) irrigation return flow in areas with increased irrigation water uses especially through traditional irrigation systems such as flooding systems (Cai et al. 2015).

Agricultural activities will have to adapt to longer growing seasons combined with reduced water availability, with new crops suited to drier, warmer conditions implying lower volumes of effluent discharges with higher concentrations. Plans to address undesirable water quality impacts, especially those related to agriculture, will require the integration of interventions ranging from water resources protection, agricultural adaptations, and operational procedures in other sectors such as water supply, urban drainage and treatment systems, which may change due to climate change (Murdoch et al. 2000, Cai et al. 2015).

7.2.4. Extreme climate events

Climate change affects not only long-term trends and shifts of climatic variables such as temperature and precipitation, but also the frequency, intensity, and duration of extreme events. An extreme climate event can be defined as the occurrence of a value of a climate variable above (or below) an upper (or lower) threshold. Extreme climate events include flood, drought, heat wave, hurricane, cyclone, typhoon, and tornado. More than 70% of the

'billion-dollar events' in the second half of the past century were related to extreme climatic events (Cai et al. 2015).

Agriculture has been substantially affected by extreme climate events all around the world (Nelson et al. 2009, Turral et al. 2011, IPCC 2012). The frequency and intensity of these extreme events are likely to be amplified by climate change in the future (IPCC 2012). In fact, observations show that there has already been an increasing trend of the various climate extremes over the past 60 years, such as an increase in the number of unusually warm days and nights at the global scale, an increase of the number of heavy precipitation events in some regions, a pole-ward shift in extra-tropical cyclones, and earlier occurrence of spring peak river flows in snowmelt and glacier-fed rivers (IPCC 2012, Cai et al. 2015). Here, among the many extreme climate events, the two most important for agriculture, floods and drought, will be discussed.

Floods: Floods have been the most reported natural disaster events in many regions, affecting 140 million people per year on average (WDR, 2003, 2004). The observed increase in precipitation intensity and other observed climate floods indicate that climate change might already have had an impact on the intensity and frequency of floods (Kron and Berz, 2007, Bates et al. 2008).

The flood-producing processes include intense and/or long-lasting precipitation, snowmelt, dam break, reduced conveyance due to ice jams or landslides, or by storm. Floods depend on precipitation intensity, volume, timing, phase (rain or snow), antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice), soil character and status (frozen or not, saturated or unsaturated), wetness, rate and timing of snow/ice melt, urbanisation, existence of dykes, dams and reservoirs.

Flooding often has a great impact on rural areas in terms of losses and damages because agricultural lands have a high vulnerability to flooding due to their location in or nearby flood expansion areas and floodplains. In addition, heavy rainfalls cause excess soil moisture which affects agriculture production considerably. Excess precipitation also causes agricultural losses due to pests and plant diseases, delayed field work, soil erosion, as well as environmental problems such as epidemics, prevalence of leaf fungal pathogens, and dissemination of soil-borne pathogens to noninfected areas (Rosenzweig et al. 2001, Cai et al. 2015).

Hurricanes, cyclones, and typhoons, which often cause severe flooding, are perhaps the most destructive extreme climate events. They combine very strong winds and very high precipitation, and are often associated with sea-level rise. Under climate change, it is likely that the frequency and intensity of hurricanes will change in the future, but the uncertainty on the trends remains high, and the impact is complex (Knutson and Tuleya 2004, Cai et al. 2015).

Droughts: Drought is a form of climate extreme that is mainly associated with dry (i.e., precipitation deficit) and hot (i.e., high temperature) weather conditions and is accompanied by heat waves in some extreme cases (Mishra and Singh 2010).

Droughts expand from meteorological systems to agricultural systems and can greatly impair water quantity, water quality, agricultural production (Calanca et al.2007, Mishra and Singh 2010) food security, (Schmidhuber and Tubiello 2007) and economy (Wang et al. 2011) at local, regional, and national scales. 'Agricultural drought' relates to moisture deficits in the topmost one metre or so of soil (the root zone) that impacts crops (Trenberth et al 2007).

Droughts cause losses in agriculture through multiple factors including heat stress, insects, as well as water deficit. For example, in Central and Eastern Europe, crop productivity usually drops due to spreading of insects during droughts (Eitzinger et al. 2013).

Droughts are expected to intensify in the future in some areas such as southern and central Europe, Alpine region, central North America, the Mediterranean region, Australia, southern Africa, Mexico, and northeast Brazil although there is no definitive evidence that droughts have increased or decreased with climate change in recent years (Calanca et al.2007, Wang et al. 2011, IPCC 2012, Sheffield et al. 2012, Eitzinger et al. 2013, Cai et al. 2015).

Heat waves are usually accompanied by drought events and refer to persistent elevated temperatures, which eventually pose stress on crop and livestock production (Lobell et al. 2013). Economic losses due to heat waves are considerable (Beniston 2009, García-Herrera et al 2003). For example, the 2003 heat wave in Europe, which caused the warmest summer since the year of 1540, caused 30% reduction of the gross primary productivity in Europe (Ciais et al 2005). Heat waves are expected to occur more frequently in the future based on the many projections for the end of the 21st century (Meehl and Tebaldi 2004).

7.3. SUSTAINABLE WATER MANAGEMENT STRATEGIES/POLICIES UNDER CLIMATE CHANGE

Options for adaptation to climate change will necessarily combine investments, improved or adaptive management, and modifications in or development of policies, institutions and capacity development. Such options will need to be applied at different scales: on fields and farms; in irrigation schemes (particularly in large schemes); in watersheds or aquifers; in river basins (including transboundary river basins); and at the national level (Table 2.6) (FAO 2013, Turral et al. 2011). McGray et al (2007) and OECD (2009) reported that adaptation activities that span the continuum from development to climate change can be organized in four categories. These categories are:

Fostering human development: These activities focus on reducing poverty and addressing factors that make people vulnerable to harm, regardless of the cause.

Building response capacity: Mostly of a capacity-building nature, these activities tend to involve institution-building and technological approaches adapted from development efforts.

Managing climate risk: Activities in this category focus specifically on hazards and impacts and follow the concept of climate risk management.

Confronting climate change: They focus almost exclusively on addressing climate change impacts. Activities in this category tend to target climate change-related risks that are beyond historic climate variability.

7.3.1. Coping with water scarcity

Water scarcity is already the main challenge facing agriculture in many river basins around the world. In areas where water is scarce, climate change is expected to exacerbate tensions and increase competition for water. If agriculture is to continue meeting the demand for food and other commodities, efforts will be needed both on the supply side and on the demand side (FAO 2013).

Enhancing supply includes:

- increased access to and improved management of conventional water resources;
- habitat rehabilitation;
- dam operations;
- re-use of drainage water and wastewater;
- transfer of water between river basins;
- desalination;
- and pollution control.

Table 7.6. Options for climate change adaptation in water at different scales (Source: FAO 2013, Turral et al. 2011)

Options	Field/farm	Irrigation scheme	Watershed/ aquifer	River basin	National
1.Investments					
On-farm water storage: water harvesting	+				
Groundwater development	+				
Modernisation of irrigation infrastructure		+			
Breeding for resistance to droughts and floods	+				
Dam construction/enhancement		+	+	+	
Drainage	+		+	+	
Introduction of appropriate fish species	+		+	+	
2. Land, water and crop management					
Enhancing soil moisture retention capacity	+				
Changing cropping pattern and diversification	+				
Adapting cropping (and fish harvesting) calendar	+				
Supplementary irrigation x	+	+			
Deficit irrigation		+			
Alternate wet and dry rice production system	+	+			
Drainage and flood management		+	+	+	
Irrigation scheme operation improvement		+			

Integrated water resources management				+	
Adaptation of dam operation rules				+	
Riparian habitat restoration or creation in rivers				+	
3. Policies, institutions and capacity building					
Climate proofing of I&D infrastructure		+	+	+	
Reallocation of water (between or within sectors)	+	+	+	+	+
Strengthening land/water right access	+	+	+	+	+
Crop insurances	+		+	+	
Improved weather forecasting capacity	+	+	+	+	+
Improved hydrological monitoring				+	
Development of flood/droughts					+
Review of food storage strategies					+

Demand management is defined as a set of actions that control water demand:

- either by raising the overall economic efficiency of its use as a natural resource,
- or operating intra- and intersectoral reallocation of water resources.

A combination of **technical**, **managerial**, **legal** and **investment** options are needed to help farmers produce more with less water. These options need to be backed with a policy and incentive framework that alerts farmers to water scarcity and rewards more productive use of water at the farm level (FAO 2013).

7.3.2. Building resilience

Building resilience involves reducing farmers' exposure or sensitivity to shocks, or increasing their capacity to respond. The ability to increase the buffering capacity of agricultural systems in the face of more variable rainwater resources is of primary importance. **This necessitates an increased capacity to store water in the soil, in surface reservoirs or in underground reservoirs.** Any action that increases the capacity to access water when needed will increase resilience to climate variability (FAO 2013).

These actions include (FAO 2013):

- on-farm water harvesting;
- the enhancement the soil's capacity to hold moisture;
- on-farm water retention and enhanced infiltration; and,
- where possible, more systematic access to groundwater.

Supplementary irrigation at critical periods of the cropping season can reduce losses and boost productivity.

7.3.3. Adaptation at field and farm level

Adaptation at field and farm level includes (FAO 2013):

More efficient irrigation technologies that reduce evaporation losses: These actions can be combined with deficit irrigation approaches to maximize productivity per volume of water applied rather than per area of land.

Crop selection and changes in crop calendars: This will help farmers adapt to new temperatures and rainfall patterns. The use of crops or varieties with better resilience to dry spells will be preferred.

Increased agricultural diversification: Agricultural diversification including better integration of trees, crops, fish and livestock will reduce risk and increase the resilience of farming systems. In particular, the farming and fishing of aquatic species that do not require extensive migrations and that have wide environmental tolerances will help aquaculture and capture fisheries adapt to new climatic conditions.

Adopt more systematically measures to respond to increased frequency of floods and more intensive rainfalls: Farmers will also need to adopt more systematically measures to respond to increased frequency of floods and more intensive rainfalls. A combination of erosion control actions and better drainage capacities will be needed.

7.3.4. Adaptation at irrigation scheme level

Adaptation at irrigation scheme level focuses on (FAO 2007, FAO 2013):

Modernisation of irrigation systems: Actions for adapting to climate change in irrigation schemes need to be considered in the overall context of irrigation modernization. Modern irrigation systems require better water allocation mechanisms, the clear transmission of alerts about water scarcity to farmers, and the adaptation of both infrastructure and management for more flexible and reliable delivery of water (FAO, 2007).

Intermediate storage within the irrigation scheme and, where possible, access to groundwater: These are part of the options for building the resilience and reliability of water supply and must be considered in adaptation plans for irrigation schemes.

Water pricing and the establishment of water markets: They are often advocated as demand management tools for promoting better water use and reducing water wastage. While these options have proven effective in some places, they are often difficult to apply for a combination of technical, institutional and policy reasons. There are other options, such as limiting seasonal allocations to users or to groups of users, that may be simpler and more effective for inducing more productive water use behaviour.

7.3.5. Adaptation at watershed, river basin and national levels

Climate change adaptation at higher levels will involve a combination of policy adjustments and investments in infrastructure and management. In river basins, increased frequency and intensity of extreme weather events will require adjustments in the storage capacity and management of dams and river protection works (FAO 2013).

Flood management plans: Flood management plans will need to combine infrastructure upgrades with nonstructural, information-rich approaches that can better mitigate the impact of floods through a combination of **land planning**, **early warning** and **insurance schemes** (FAO 2013).

Drought management plans: Similarly, there will be a need to shift from drought emergency response to drought management plans that include **prevention**, **preparedness**, **relief and rehabilitation** and **long-term measures to mitigate the impacts** of droughts (FAO and NDMC, 2008, FAO 2013).

Cultivated crop varieties for adaptation to floods and droughts: Crop In all these cases, adaptation approaches to floods and droughts used by water managers and farming communities should be considered systematically. To reduce the severity of flood impacts and

provide erosion control, nutrients, shade and oxygen, habitat engineering and rehabilitation will also be needed. This will also create suitable environments for fish production (FAO 2013).

Integrated water resources management in river basins: Integrated water resources management in river basins will become more and more important as the combination of increased water use and the occurrence of extreme events will increase the interdependency of people and communities living in river basins, and as actions in one part of a basin will have repercussions for people further downstream. In places where climate change contributes to increased water scarcity, the whole package of supply enhancement and demand management options will need to be considered (FAO, 2012). Improved governance of land and water use will be required to accommodate the multiple uses of water, including for livestock and fish (FAO 2013).

Improved weather forecasting and hydrological monitoring: Improved weather forecasting and hydrological monitoring will become a critical element of modern adaptation strategies (Faurès et al., 2010). However, progressive improvements in the timing and reliability of seasonal forecasts offer new opportunities for farming communities. As efforts focus on improving the accuracy of these forecasts, more emphasis should now be given to improving the way information is conveyed to farmers and building their capacity to make best use of climate information (Gommes et al. 2010). Monitoring and early warning during the cropping season remain a priority to help farmers make informed decisions (FAO 2013).

Insurances: Insurances represent a potential solution that should also be systematically considered as part of adaptation strategies. National crop insurance schemes should critically be reconsidered for the disasters caused by extreme climate events such as flood, drought, hail damage etc. The role of national governments in promoting crop insurances must reflect national interests and at the same time ensure the smooth operation of private insurance companies. This must be based on the concept of shared risk between producers, insurance companies and governments (FAO 2013).

7.3.6. Conditions for successful adaptation

Climate change adaptation must be mainstreamed in both rural development and water scarcity programmes and not carried out on a separate track. Water, land and food policies must be more aligned and viewed through the perspective of climate change. In particular, agriculture and rural development goals must be brought into water planning and take into

consideration other water use sectors. Links must also be made with disaster risk management strategies, which are in a large part directly related to water management (FAO 2013).

7.3.7. Water management for climate change mitigation

Irrigated agriculture accounts for only 20 percent of the area of global agriculture, but is more intensively managed. On average, irrigated agriculture uses greater amounts of inorganic fertilizer and other agrochemicals than most rainfed systems. Consequently, efforts to reduce greenhouse gases through improved crop management practices are likely to have more impact in irrigated lands than in rainfed areas (FAO 2013).

Groundwater is used for irrigation on 38 percent of all irrigated land. The use of groundwater is expanding (Siebert et al. 2010), and this is increasing the use of fossil fuels and raising the energy costs of water supply (FAO 2013).

Agricultural methane (CH4) emissions account for more than 50 percent of CH_4 emissions from human activities. One-third of these emissions come from flooded rice production. If the area of irrigated rice is grown relatively quickly, future increases in CH_4 emissions from rice fields are expected to be small (HLPE, 2012).

Emissions during the growing season can be reduced by using various water management practices, such as cultivating aerobic rice and, where conditions allow, alternate wetting and drying. Avoiding water saturation when rice is not grown and shortening the duration of continuous flooding during the rice growing season are effective options for mitigating CH_4 emissions from rice fields. Currently, true aerobic rice yields tend to be poor (less than 2 tonnes per hectare), and this is a strong disincentive for adoption even when natural drainage conditions are favourable (Comprehensive Assessment 2007). Aerobic rice saves water and may possibly reduce nitrous oxide emissions (HLPE 2012).

One of the most effective methods of reducing carbon emissions in irrigated areas may be to use sustainable energy resources such as solar or wind instead of fossil fuels for pumping energy requirements.

CHAPTER 8

SUSTAINABLE IRRIGATION MANAGEMENT UNDER CLIMATE CHANGE

8.1. INTRODUCTION TO IRRIGATION

In parallel with the rapid increase in the world population, people's nutritional needs are also increasing. It is estimated that agricultural production will need to increase by approximately 60% by 2050, with the population expected to be over 10 billion. Therefore, in order to increase crop production, unit area yields must be increased. However, in arid and semi-arid regions where rainfall is insufficient, many cultivated plants either do not grow or very few of them grow. This limits the amount of crop production. This problem can only be overcome with irrigation practices (FAO 2010).

Irrigation: In general, it is the application of water to the soil by some methods when the water required for ideal plant development cannot be met by rainfall.

Water is a critical input for agricultural production and plays an important role in food security. Irrigated agriculture accounts for 20 percent of the total cultivated area in the world. Additionally, irrigated agriculture contributes to 40 percent of the total food produced in the world. Irrigated agriculture is at least twice as productive per unit land as non-irrigated agriculture. Thus, it is possible to provide more production and product diversity.

In plant production, if the moisture deficit in the soil is eliminated with correct planning, there will be a significant increase in the productivity of the plants. This increases the welfare of the regional producers. In addition to this increase in productivity, the washing of excess salts in the soil and softening of the base stone is also possible thanks to irrigation.

It is predicted that agricultural production will decrease in the coming years due to climate change. Therefore, food must be safe. Food security means that every person has access to sufficient, quality food at all times. Sustainable food production is one of the most important elements of food security. One of the most important principles of sustainable agriculture is management of soil and water wisely.

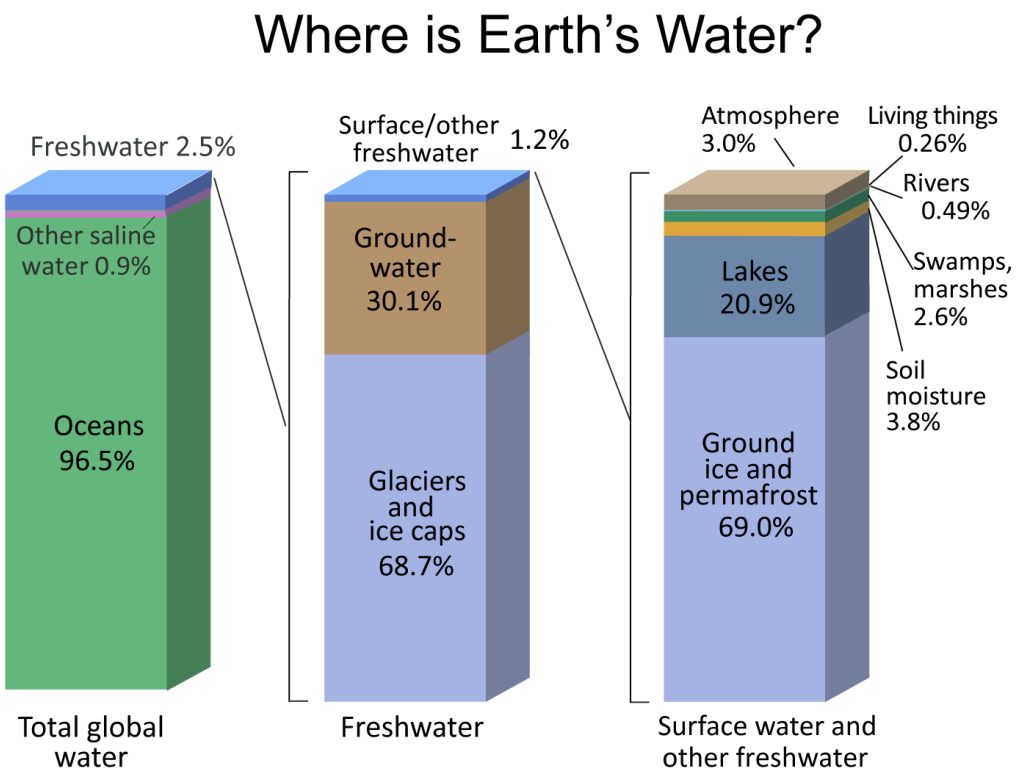
At the World Food Summit in 1996, the Food and Agriculture Organization (FAO) predicted that 60 percent of the extra food needed in the future should come from irrigated agriculture. The International Commission on Irrigation and Drainage (ICID) estimates that current food production will need to double over the next 25 years. ICID's strategy for implementing the

Water for Food Vision refers to the same FAO estimate of the role of irrigated agriculture in sustaining the future world food supply (FAO 2003).

Increasing food production through irrigation is very important. It is necessary to expand irrigated areas and water resources and increase the efficiency of use of existing water resources. However, failure to meet food production needs through efficient expansion and intensification of irrigated agriculture will increase the pressure on land resources and accelerate the process of environmental degradation (Carruthers, 1997).

8.1.1. Irrigation in the World, Europe and Turkey

Approximately 97.5% of the amount of water in the world consists of salt water. The remaining 2.5% is fresh water. Approximately 68.7% of fresh water is found in glaciers, 30.1% underground and 1.2% on the surface (Figure 3. 1). Surface water meets almost all the water needs of life.



Credit: U.S. Geological Survey, Water Science School. https://www.usgs.gov/special-topic/water-science-school
Data source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Figure 8. 1. World water potential (Sorce:https://www.usgs.gov/media/images/distribution-water-and-above-earth#:~:text=About%2071%20percent%20of%20the,in%20you%20and%20your%20dog).

Today, agriculture uses (on average) 70 percent of all freshwater withdrawals globally. In other sectors, domestic use is 11% and industrial use is 19%. According to FAO's 2021 data, the total land area suitable for irrigation worldwide has reached 22% of the world's total cultivated area, with 352 million hectares, an increase of approximately 20% in the last 20 years (FAO 2023a). When we look at the distribution of these 352 million hectares of irrigable land across the continents, Asia ranks first with 248.2 million hectares. North and Central America ranks 2nd with 36.3 million ha, Europe ranks 3rd with 27.2 million ha, South America ranks 4th with 19.3 million ha, Africa ranks 5th with 17 million ha and finally Oceania ranks 6th 3.3 with million ha, (FAO 2023a).

The European continent, where Turkey country is located, has 273 million hectares of arable land. Approximately 10% of this amount, i.e. 27.2 million ha, constitutes irrigable land (FAO 2023a). When we look at EU-28 countries, they have 166 million hectares of arable land. 11.3% of this area, i.e. 18.6 million hectares, is irrigable area. 10.2 million ha of land has been opened for irrigation. When we look at the countries that open their irrigable areas to irrigation, Greece comes first with 77%. Italy, which has important agricultural areas, has irrigated 72%, France 51%, and Spain 43% of its irrigable areas (EUROSTAT 2016). Considering the countries that are important producers of tree fruit in these irrigated areas, the irrigation rate of fruit trees is around 80% and the irrigation rate of vineyards is around 30%. While this value is around 10% in wheat, it is over 50% in corn.

Turkey's surface area is 78 million hectares, and 24 million hectares of this area is agricultural land. According to the studies carried out; the amount of agricultural land that can be irrigated with the current water potential is calculated as 8.5 million hectares. By the end of 2019, 6.65 million hectares of land were opened to irrigation and the rate of currently irrigated land in the potentially total irrigable land reached 78%. Work is currently ongoing for 1.85 million hectares of land (DSI 2023).

8.2. SOIL AND WATER

An adequate air-moisture balance in the soil is essential for good root development. If this balance is established well, the production amount increases; if the balance is disrupted, serious losses in productivity occur.

Soil is a structure consisting of three phases. These are solid, liquid and gas. The solid phase consists of inorganic and organic particles. The liquid phase represents soil water, and the

gaseous phase represents soil air. The liquid phase and gas phase constitute the void volume between the solid grains (Figure 8. 2a-2b).

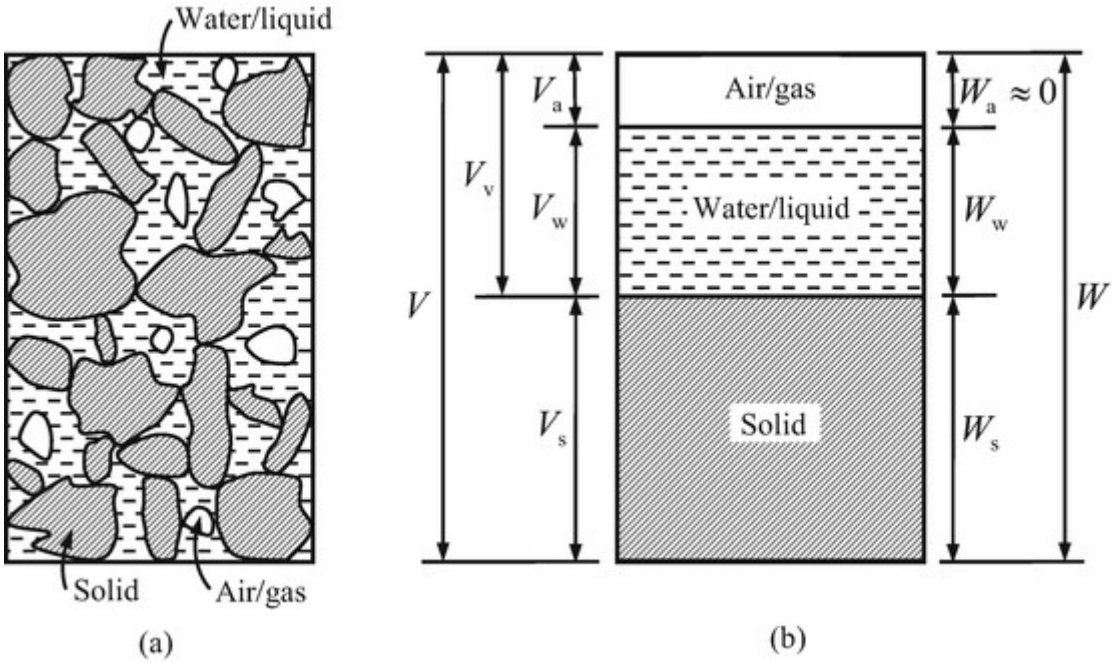


Figure 8. 2. a) Form of three phases in soil b) soil phase diagram (source: Shukla 2017).

Soil texture: It is the proportional amount of soil groups of different sizes such as clay, silt and sand, which make up the inorganic part of the soil. The diameters of these groups are less than 2 mm. The size of clays is smaller than 0.002 mm. The size of the silt grains is between 0.002-0.05 mm. The size of sand grains is between 0.05-2 mm. Clayey soils are called heavy textured soils, sandy soils are called light textured soils, and loamy soils are called medium textured soils.

Soil structure: It is the clustering, arrangement and grouping of soil grains that form the solid phase of the soil. Hydraulic conductivity and permeability properties of the soil, water retention capacity, aeration, ease of tillage, suitability of plant nutrients, microorganism activities, plant root development and therefore soil productivity are closely related to structure.

The solid, liquid and gas phases of a soil sample are schematized in Figure 4.2b. Volumes are shown with the symbol V and weights with the symbol W. In order to better define the physical conditions and properties of the soil, it is necessary to approach the three phases as if they were separate from each other and to explain some basic physical properties and the relationships between them.

Solid particle density (specific gravity of the soil): It is the ratio of the weight of soil solid parts in a certain volume to the weight of an equal volume of pure water. It is a measure that expresses the density of the soil. Specific gravity can vary depending on factors such as the mineral composition of the soil and the presence of capillary water.

Soil volume weight (Bulk density): It is the ratio of the dried (oven dried) soil sample weight to the sample volume. Bulk density varies depending on factors such as soil compaction, moisture content and mineral composition. Low bulk weight represents light, friable soils; high volume weight indicates compacted, dense soils.

Porosity: Porosity refers to the proportion of voids in the soil and measures the amount of space between soil particles. It is usually expressed in percentage (%). Porosity is important for the storage and movement of soil water. High porosity indicates a looser soil structure where more water and air movement is possible.

Pore ratio: pore ratio is the ratio of the pore volume (water + air) in a certain soil mass to the solid part volume of the mass.

Saturation degree: Saturation refers to how much the soil porosity is filled with water. It is usually expressed in percentage (%). When the saturation is 100 percent, the soil is completely filled with water.

Measuring and quantifying soil moisture is very important in planning irrigation time and determining the amount of water to be applied. Soil moisture can be explained in different ways in terms of irrigation.

Gravimetric moisture: It is the mass of water in a certain soil mass.

Volume moisture: It is the ratio of the volume of water in a certain soil mass to the total volume of the sample.

Moisture in depth: It refers to the depth of water per unit soil depth.

Soil moisture tension: It is the power of holding soil water by soil particles. As moisture in the soil decreases, the soil's ability to retain water increases.

In terms of irrigation practices, it is necessary to determine the ability of the soil to retain water at certain points. Moisture is held at different tensions at these scientifically accepted points, called soil moisture constants, which are entirely related to the physical properties of the soil. In this context, it is explained that soil water is kept at 4 different tensions, these are;

1. **Saturation Point:** Saturation point is the upper limit of soil moisture content. It is the point where all the pore spaces in the soil are filled with water and the soil cannot hold it any longer. Water retention by soil is zero.
2. **Field Capacity:** Field capacity is the maximum amount of water that the soil can hold against the gravity. In other words, it is the point where the soil holds moisture under 1/3 atm tension against gravity. Field capacity is an important parameter, it is the highest humidity point for plant water use.
3. **Wilting Point:** Wilting point is the moisture level at which the soil holds water at an average tension of 15 atm and the plants cannot absorb water beyond this point. It represents the lower limit of plant water use. This condition is defined as the point at which plants wilt and physiological deaths occur, even if soil moisture is increased.
4. **Oven-dried:** Oven dried refers to the condition of the soil when it is completely dried by heating in an oven to remove all moisture content. Drying is done at 105 °C for 24 hours to ensure that all water in the soil evaporates. Oven dried soil is used as a reference to calculate various soil moisture properties.

After soil moisture constants, it is necessary to make some definitions related to them.

Excess water: It is the water between field capacity and saturation point that drains freely under the control of gravity.

Plant available water: Plants can benefit from water between field capacity and wilting point. Available water is the difference between the current moisture in the soil and the wilting point.

Available water holding capacity: Available water holding capacity is the moisture gap between field capacity and wilting point.

Hygroscopic water: It is the moisture content of the soil that is held so tightly by the soil that plants cannot absorb it with their roots. Essentially it cannot be used for plant use. Hygroscopic water is the moisture found in the soil in the region between the wilting point and oven dry.

8.2.1. Soil moisture and its measurement

Soil moisture is an important factor for plant development in irrigation works. Accurate determination of humidity will enable planning of irrigation time and accurate determination of the amount of irrigation water. There are various methods and tools to measure soil moisture. Some common techniques for measuring soil moisture include:

1. **Gravimetric Method:** In this method, soil samples are taken every 30 cm with the help of an auger (Figure 8.3), weighed, and dried in an oven to eliminate existing moisture. The oven dried soil is then weighed again to determine the moisture content. This method gives the most accurate results, but the method is time consuming and labour intensive.

Figure 8.3. a) Taking the sample with an auger, b) drying the sample in the oven (Photo: Erhan GOCMEN)

2. **Tensiometers:** Tensiometers are instruments that measure the matric potential of the soil, which is the energy required for a plant to take up water from the soil through its roots. The tip of the tool is permeable. Pure water is filled from the top. It is tightly closed with a leak-proof stopper. Soil matrix potential is measured in centibars (cbar) or kilopascals (KPa) with the monometer located at the top of the transparent tube that forms the body of the instrument. They are suitable for measuring soil moisture in the range where plants can access water. It can measure up to approximately 85 cbar. They are produced at various depths (Figure 8.4).

Figure 8.4. Tansiometer (Photo: Erhan GOCMEN)

3. **Electrical resistance blocks (Watermark):** When operating, soil moisture is constantly absorbed or released and the electrical resistance between the electrodes changes. This resistance is read by a reader and the matrix potential of the soil is determined in cbar or Kpa (Figure 8.5). Its biggest advantage over the tensiometer is that it can measure up to 200 cbar. They can be placed at various depths.

Figure 8.5. Electrical resistance blocks (Watermark) (Photo: Erhan GOCMEN)

4. **Time Domain Reflectometry (TDR):** TDR are devices that send electromagnetic waves from a probe placed in the ground and measure the time it takes for the waves to reflect back (Figure 8.6). The moisture content of the soil is measured by affecting the round-trip speed of these waves. They are placed at the desired depths.

Figure 8.6. TDR soil moisture meter. (Source: Photo by Maja Krzic, University of British Columbia, Vancouver BC. Access: https://labmodules.soilweb.ca/time-domain-reflectometry/ 13.10.2023)

5. **Frequency Domain Reflectometry (FDR):** FDR is similar to TDR but operates at different frequencies. It measures the dielectric constant of the soil. They are placed at the depths to be measured.

6. **Neutron Meter:** These instruments use neutron scattering to estimate soil moisture content. The device consists of a radioactive material and control screen connected to a cable end (Figure 8.7). Holes with a diameter of approximately 6 cm are opened in the soil and aluminium tubes of the desired length with high neutron permeability are placed inside. Thanks to the radioactive substance lowered to the desired depth by means of the cable, it is activated through the control screen and neutron emission is initiated. Neutrons slow down by hitting the hydrogens in the water in the soil. These slowed down neutrons are reflected back and counted by the detector. The device, which is calibrated in a tank full of water without taking any readings, evaluates the incoming data accordingly and gives the humidity amount. It is extremely sensitive and, compared to other moisture

sensors, gives more accurate results because it measures a larger area in the soil. However, due to the use of radiation, they typically require special training and licensing.

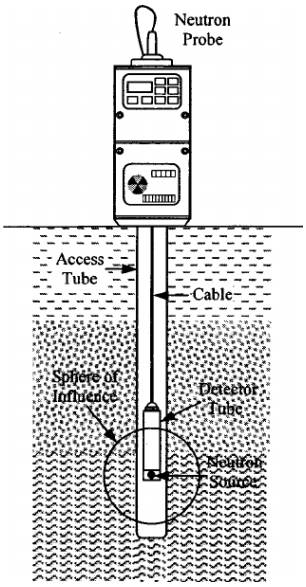


Figure 8.7. Schematic of neutron gauge (Source: Li et al 2003).

7. **Remote Sensing:** Remote sensing technologies such as satellites and aerial imagery can be used to estimate soil moisture over large areas. Humidity in large areas can be obtained in a shorter time and at lower cost.

8.2.2. Movement of Water in Soil

The condition in which the spaces in the soil are completely filled with water is called saturated conditions. However, it is not possible for the soil profile to be completely filled with water. Because some air compression occurs. However, completely saturated conditions are achieved in the topsoil profile. The direction of flow is from a region of higher matrix potential to a region of lower matrix moisture potential.

The condition in which the voids in the soil are not completely filled with water is called the unsaturated condition. In these conditions, the direction of flow is from a region with lower matrix potential to a region with higher matrix moisture potential.

During irrigation, water enters the soil by infiltration and moves downwards by gravity and capillarity. After irrigation is completed, evaporation begins to occur from the upper soil layer. Plants benefit from the water in the area below this upper layer (approximately 15-45 cm) through their roots. In this region, water movement is towards the roots and a very small amount is towards the upper evaporation zone. Most of the moisture in the 45-90 cm area

where the secondary root zone is located is towards the roots and downwards. Very little can leak into the lower layer. The condition that allows water to be taken up by plants is high osmotic tension. If the high osmotic tension is greater than the soil tension, the plant absorbs water through its capillary roots. Conversely, when the soil tension is greater than the osmotic pressure, the plant will begin to wilt.

Infiltration: It is the movement of water from the soil surface into the soil. The amount of water entering the soil per unit time is called infiltration rate.

Factors affecting infiltration rate:

- Soil texture,
- Soil structure,
- Pore size distribution and geometry,
- Organic matter content of the soil,
- Vegetation,
- Swelling degrees of clay and other colloids,
- Initial moisture status of the soil,
- Topographic situation (soil surface shape).

Infiltration rate is high in light-textured soils and low in heavy-textured soils.

Infiltration rate is determined by double cylinder infiltrometer tests. The material to be used in the test is two nested cylinders (Figure 8.8). The outer cylinder is 40 cm in diameter and the inner cylinder is 20-25 cm in diameter. Their height is 40 cm. Cylinders are driven approximately 15-20 cm. It is then filled with water. The amount of water decreasing at a certain time is detected and recorded by a stopwatch from the inner cylinder. As it decreases, water is constantly added to the cylinders and recorded. This measurement takes at least 5 hours. For example, a water uptake rate of 10 mm/h means that it will take one hour to infiltrate a height of 10 mm of water above the soil surface.

Figure 8.8 Performing the infiltration test (Source: https://americangeoservices.com/soil-infiltration-testing.html, Access: 29.09.2023)

8.3. CROP WATER REQUIREMENT

When water requirement of the plant cannot be met by rainfall, the remaining amount is provided by irrigation.

To determine the irrigation water needs of plants;

- Plant water consumption,
- Effective rainfall, and
- Irrigation efficiency needs to be determined.

Plant water consumption (evapotranspiration): It is the sum of evaporation from the soil surface and transpiration from plant leaves, expressed in mm.

The amount of water consumed by the plant varies depending on the soil, plant type and climatic conditions. There is a close relationship between some climate parameters and plant water consumption:

- As the temperature increases, plant water consumption increases.
- As wind speed increases, plant water consumption increases.
- As sunshine duration increases, plant water consumption increases.
- As relative humidity increases, plant water consumption decreases.

When evaluated in terms of soil properties, plant water consumption will increase as evaporation increases, especially at moisture values above the field capacity. Likewise, at humidity values below field capacity values, the amount of evaporation will decrease as the

soil matrix suction increases. Cultivation of the land will increase plant water consumption. Covering the land with vegetation will provide shading and reduce the amount of evaporation.

For example, leaf size and number of pores affect plant water consumption. Plant development stages also play an important role in plant water consumption. As the plant grows, the amount of transpiration from the leaves increases. However, as the plant develops, the amount of evaporation from the soil surface decreases as the shading rate increases. In the early development stages of the plant, evaporation is considerably higher than transpiration. With the development of vegetation, the transpiration rate increases and when it reaches the highest value, transpiration becomes more than evaporation values. The length of the growing period affects plant water consumption, the longer the development period, the longer the evapotranspiration. Evaporation may be determined in various methods.

Direct measurement methods

Although direct measurement methods give better results, they are both quite expensive and time consuming. For this reason, direct measurement of plant water consumption is only done for the purpose of calibrating prediction equations from climate data and finding local plant coefficients (Gungor et al. 2004).

- Tanks and lysimeters
- Field trial plots
- Monitoring of moisture decrease in soil, and
- Measuring flow into and out of the basin.

Prediction methods from climate data

The fact that direct measurement methods are expensive and time consuming has led to the development of estimation methods. While there are methods that estimate plant water consumption by using a few climate data, there are also complex methods that are more accurate and use many climate data.

In estimating plant water consumption, a reference plant water consumption is first determined. Then, the water consumption of the reference plant is corrected by multiplying it with the plant coefficient (kc) values obtained by taking into account the plant characteristics.

$$ET=k_c x ET_0 \qquad 8.1$$

Where,

ET : Plant water consumption, mm/day

k_c = experimentally obtained crop coefficient,

ET_0 = reference plant water consumption, mm/day.

Reference crop water consumption: It refers to the reference plant water consumption that can occur from a well-watered, actively growing reference plant (grass plants).

Although there are many methods and empirical equations in practice, one of the most commonly used ones are the Class A pan evaporation method and the Penman-Monteith method.

Reference plant water consumption can also be determined from evaporation containers placed in the field. It is assumed that all climatic parameters that cause evaporation from the container also affect plant water consumption. The results obtained with the method are quite healthy. The daily evaporation values obtained are corrected with an evaporation cup coefficient obtained according to local conditions and plant water consumption is obtained.

$$ET=k_p x E_p \qquad 8.2$$

Where,

ET : Plant water consumption, mm/day

K_p = Pan coefficient obtained according to local conditions,

E_p=Daily evaporation from pan, mm/day.

Class A evaporation pan consists of an open-top cylinder with a diameter of 121 cm, a height of 25.5 cm, and made of 2 mm galvanized sheet metal. A wire cage is placed on the container to prevent the animals from drinking the water in the pan. Changes in the water level in the container are measured daily with a depth measuring tool. Figure 8.9 shows the Class A evaporation pan in the area.

Figure 8.9. Class A evaporation vessel (Photo: Erhan GOCMEN).

In estimating reference plant water consumption from the climate data, the method defined as FAO-56-PM, obtained by revising the Penman-Monteith method by Allen et al (1998), is used:

8.3

Where;

ET_0: Reference plant water consumption (mm/day),
Rn: Net radiation on the plant surface (MJ/m2/day),
G: Heat flow in the soil (MJ/m2/day),
T: Average temperature (°C),
u_2: Wind speed at 2 meters height (m s^{-1}),
e_a: Saturated vapor pressure (kPa),
e_d: Actual vapor pressure (kPa),
Δ: Slope of the saturated vapor pressure curve (kPa/°C),

γ: the psychometric constant (kPa/°C) values.

Irrigation models and technologies

An example of an irrigation model is the free CROPWAT 8.0 software developed by FAO's Land and Water Development Division. The model is a computer program for calculating plant water and irrigation requirements based on soil, climate and crop data.

All calculation procedures used in CROPWAT are based on two publications of FAO Irrigation and Drainage Series, namely, No. 56 "Plant Evapotranspiration - Guidelines for calculating plant water requirements" and No. 33 "Water yield response".

CROPWAT 8.0 includes plant, soil and meteorological data. If climate data are not available, they can be obtained from CLIMWAT, the corresponding climate database for more than 5 000 stations worldwide. The equation 8.3 is used to calculate plant water consumption. With the program, the results regarding plant water consumption are evaluated very quickly (FAO 2023b).

In addition, smart meteorological stations, monitoring meteorological data such as temperature, radiation, relative humidity, wind speed and precipitation in the study area, instantly calculate the reference plant water consumption through the Penman-Monteith equation and transmit all results instantly over the internet. This data can be easily monitored via computer, tablet or mobile phone. The mentioned meteorological station is shown in Figure 8.10.

Effective precipitation: It is defined as the amount of rainfall that plants use to meet some of their water needs during the growing season. It takes into account the amount of rainfall that can be stored in the soil and used effectively by plants, without infiltration below the root zone and runoff. Effective rainfall is an important factor that should be taken into account in agricultural irrigation planning to determine the amount of applied irrigation water.

Irrigation efficiency: Irrigation efficiency refers to how effectively water is used in agriculture to sustain plant growth. It is a measure of how well an irrigation system delivers water to plants and how efficiently the plants use that water. All efficiencies affecting irrigation performance are explained below. These are:

Transmission and distribution system efficiency: It is related to the condition of the irrigation infrastructure. Transmission and distribution efficiency is high in a well-maintained

and appropriately designed irrigation system when water is taken from the source and transported to the field.

Water application efficiency: It is related to how evenly and effectively water is distributed in the area. It is the ratio of the water stored in the root zone to the water delivered to the field. Non-uniform distribution can result in over-irrigation in some areas and under-irrigation in others. Pressurized irrigation methods increase water application efficiency.

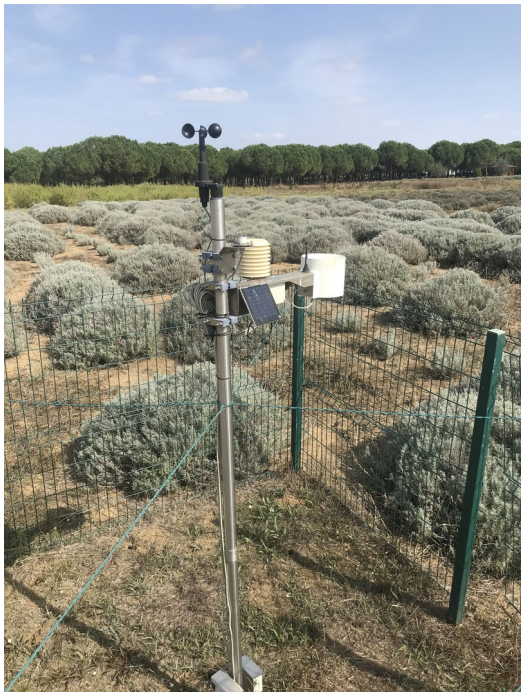


Figure 8.10. Automatic smart weather station (Photo: Erhan GOCMEN).

Water use efficiency: Water use efficiency expresses how effectively plants use the water provided to them. In other words, it is defined as the ratio of the water used by the plant to the amount of water applied to the root zone. Improving soil quality through selecting drought-tolerant plants or adding organic matter can increase water use efficiency.

Total irrigation efficiency: It is the expression of all efficiencies together. It is expressed as the ratio of the plant's water consumption to the water diverted from the source.

Irrigation Strategies

Due to the increasing population, the need for food also increases. Increases in crop production are achieved through agricultural irrigation. However, it is clear that water resources are under great pressure. Irrigated agriculture will need to adopt a new management paradigm based on the economic goal of maximizing net benefits rather than the biological

goal of maximizing yield (English et al. 2002). Therefore, some irrigation strategies have emerged.

Full irrigation: Full irrigation is a strategy that meets all of the plant's water needs without stressing the plant. The goal of full irrigation is to maintain soil moisture at or near field capacity to maintain adequate soil moisture for plants. This means providing adequate water to maximize plant growth and yield potential. It is applied in areas where the amount of water is abundant.

Key features of full irrigation:

- Water is provided in quantities that meet all the water requirements of the plants.
- Optimum growing conditions are provided by maintaining soil moisture at or near field capacity.
- Full irrigation is often used for high value crops where maximizing yield is crucial.
- Water and energy usage is at its highest level

Full irrigation has been studied very widely and there is sufficient detailed information in the literature. For example, in wheat, under full irrigation conditions, the highest average grain yield was obtained at 830 kg/da, while the lowest yield was obtained at 290 kg/da from the non-irrigated (only rain-fed) application. The efficiency increased approximately 3 folds (Sezen and Author 2006). Al-Ghobari and Dewidar (2018) explained that maximum tomato yield was obtained from full irrigation application in both surface and subsurface drip irrigation in their research conducted under different level of full irrigation in two different methods. In all applications, it has been stated that water savings are higher in the subsurface drip irrigation method compared to the surface drip irrigation method.

Deficit irrigation: It can be defined as an irrigation strategy that does not fully meet the water needs of a plant in cases where water resources are scarce, but causes an acceptable decrease in yield. In order to save water, a deficiency can be created in the full irrigation level of the plant. The idea here is to establish a relationship between the amount of irrigation water applied and the yield obtained and to find the condition where water use efficiency is highest. Thus, both water savings and optimum efficiency are achieved with a small yield loss.

Key features of restricted irrigation:

- It is generally used in areas where there is water scarcity or limited water resources.

- Water is deliberately applied at a level below full irrigation, creating a controlled water deficit.
- Careful monitoring and decision making is required to avoid excessive stress that could damage the product.

Scientific studies reveal deficit irrigation more clearly. For example, Tejero et al. (2011), in their study on citrus orchards grown under full and limited irrigation, stated that the most stressful limited irrigation should not be applied during flowering or fruit growth periods in order to provide similar yield in fully irrigated plants. They stated that yield very close to full irrigation were achieved with partial irrigation strategies that save up to 1000 m^3 ha^{-1} of water (100 mm/ha). Karam et al (2011) examined the response of eggplants irrigated with drip irrigation in a semi-arid climate to water stress. They stated that the decrease in fresh yield due to insufficient irrigation was compensated by the increase in average fruit weight and water efficiency. They further indicated that in cases where water resources are limited, deficit irrigation before flowering and after the plant completes leaf development will lead to the least decrease in yield.

Supplementary irrigation: In cases where rainfall cannot provide sufficient moisture for normal plant growth, a limited amount of irrigation water should be applied to plants to increase and balance the yield. Since water scarcity mainly affects spring-planted plants and plants grown in shallow soils, both of which may require supplementary irrigation (Debaeke and Aboudrare 2004). Supplementary irrigation, especially during critical plant growth stages, can increase plant yield and water efficiency.

Key features of supplemental irrigation:

- It complements natural precipitation and is used when necessary, adjusted according to seasonal and weather changes.
- Helps prevent drought stress and crop failure during dry periods.
- Supplementary irrigation can save water compared to full irrigation because it prevents overwatering during rainy periods.
- It is widely used in regions with variable rainfall patterns or limited water resources.

Considering the studies conducted with supplementary irrigation, supplementary irrigation of peach (Oweis and Hachum 2012) and olive (Razouk et al. 2013) fruit trees grown under rain-fed conditions increased fruit yield and fruit quality. In addition, supplementary irrigation did not affect the oil content of olive trees and water use efficiency increased. In their study

conducted for 3 years on different varieties of Cactus pear trees, Zegbe and Servin-Palestina (2021) stated that fruit yield, average fruit mass, marketable fruit, water use efficiency, irrigation water use efficiency and water efficiency were similar between plants irrigated under Supplementary irrigation and Full irrigation. Therefore, they reported that, compared to full irrigation, supplementary irrigation application provided 51-52% water savings on average for all varieties. Oweis et al. (2020) grew lentils under Mediterranean conditions with 3 different rates of supplementary irrigation and under no irrigation conditions. The results showed that lentil grain and biomass yield increased with increasing amount of supplementary irrigation water. The average grain yield was 1.42 t ha^{-1} at 1/3 supplementary irrigation, 1.69 t ha^{-1} at 2/3 supplementary irrigation and 1.81 t ha^{-1} at full supplementary irrigation, compared to 1.04 t ha^{-1} under rain-fed conditions. The results of the study showed that the 2/3 supplementary irrigation level provides maximum water use efficiency for both grain and biomass.

In summary, full irrigation aims to provide plants with all the water they need, deficit irrigation aims to strategically reduce the water supply to achieve specific goals, and supplemental irrigation aims to supplement natural rainfall to maintain optimum soil moisture levels. The choice of irrigation approach depends on factors such as plant species, local climate, water availability, and specific goals for plant production and quality.

8.4. AGRICULTURAL WATER DISTRIBUTION & TECHNOLOGY

8.4.1. Conveyance and distribution of irrigation water to the area

Structures that allow water to be collected from structures such as streams, dams, ponds and wells, and to be transmitted and distributed to the required areas are called water conveyance and distribution systems.

Water conveyance and distribution systems may be classified as open channel systems, canalets and pipe systems.

The system must apply a volume of water that will fully meet the needs of the plants, without causing erosion and with high efficiency.

Open canal systems: They are made as soil or concrete lined channels. They are generally produced with trapezoidal section.

In these systems where water is transmitted by gravity, it consists of the following components:

- transmission canal,
- main canal,
- secondary canal,
- tertiary canal and
- in-field water transmission canal.

Transmission channel: It is the canal that takes irrigation water from the storage structure and transmits it to the main canal. There is no irrigation from this canal.

Main canal: It is the canal that carries irrigation water within the irrigation area and transmits it to secondary canal (Figure 8.11). It is parallel to the counter lines. The speed of the water flowing in the main canal should not be less than 0.30 m/s to avoid clogging and sedimentation, and should not be higher than 2.4 m/s to avoid erosion. The length of the main canal can be up to 100 km. The main canal slope is a very small value, varying between 0.0002-0.0005.

Secondary canal: It takes the water from the main canal and delivers it to the tertiary units. It travels perpendicular to the contour lines in the irrigation area. Canal spacing may be around 5-6 km. Canal slopes should be below 0.0007.

Tertiary canal: It is the canal that transmits the water received from the secondary canal to the irrigation area. It is parallel to the contour lines. Its slope varies between 0.0002-0.0005. The distance between tertiaries is 300-400 m. Tertiaries can be up to 2-3 km in length. A tertiary canal serves a maximum of 120 ha of irrigation area. There is a socket every 200-250 m above the tertiary. The water taken from the outlet is given to the field or field main canal.

Figure 8. 11. Main canal (Source: https://www.dsi.gov.tr/Haber/Detay/6932 Accessed 20.10.2023).

In-field water distribution and transmission structures: These are canals that take water from the tertiary socket and distribute it within the field. It is built by farmers. It is at most 500 m long. Their range is up to 200 m.

Canalet irrigation systems: These are prefabricated irrigation canals with an elliptical or semi circular cross-section (Figure 8.12).

Figure 8.12. Canalet system (source: ?).

Piped irrigation systems: Piped irrigation systems are low-pressure systems buried underground. Irrigation water is brought from the source to the field by a buried main pipeline and distributed to the field parcels through buried lateral pipelines. At the beginning of the field, water is raised to the soil surface through structures called chimneys. In this system, land loss is eliminated. Since the system is pressurized, water transmission is also provided uphill. Leakage and evaporation losses in pipelines are negligible. Water transmission efficiency is very close to 100%. Figure 8.13 shows the construction of the irrigation water transmission line.

Seepage losses in soil channels can be over 50% depending on the soil type. This value is lower in concrete-lined channels. Although an average transmission loss of 10% is stated in irrigation networks, it is stated that these losses are much larger in practice (Çakmak et al. 2008).

Figure 8. 13. Closed irrigation water transmission line.

(Source :https://www.dsi.gov.tr/Galeri/ResimgaleriDetay/2863 Access:21.10.2023).

The total area of the irrigation systems developed by DSI (Turkish State Hydraulic Works) 2,623,908, of this area, 34.2% ha is the classical system, 35.3% is the canal system, and 30.5% is the piped system. The pipe system has increased over the years. While the efficiency of irrigation facilities operated and transferred by DSI was 43% in 2015, it became 48% in 2020 (DSI 2021). According to these figures, if the conditions under which surface irrigation water is transmitted and distributed through open canals and applied on the land are shifted with pressurized pipe lines and pressurized irrigation methods, the irrigation efficiency may increase to at least 80%, which corresponds 40% of the total water diverted to the area (DSI 2021).

8.4.2. Irrigation methods

Various methods are used to deliver irrigation water to the soil to satisfy moisture deficiency in the soil. These methods are divided into two: surface irrigation methods and pressurized irrigation methods.

In surface irrigation methods, water moves in the direction of a slope and by gravity, enters into the soil profile and is stored. Surface irrigation methods are basin irrigation method, border irrigation method and furrow irrigation methods. In pressurized irrigation methods, water is delivered to the field by a pump unit and released into the soil as required. Since the system is pressurized, it is not affected by topographic conditions. Pressurized irrigation methods are sprinkler and drip irrigation methods. Of the total 1 843 125 ha irrigation system developed by DSI, surface irrigation is used in 61%, sprinkler irrigation method is used in 21.6%, and drip irrigation method is used in 17.3% (DSİ 2021).

Basin irrigation method: In the method, basin are surrounded by embankments of a certain height around the field in order to prevent water from flowing into adjacent fields. It is generally applied to plants in rows and frequently, and especially to plants that are not affected by stagnant water, such as rice. A view of basin irrigation is shown in Figure 8.14.

Border irrigation method: Irrigation of the land by dividing it into multiple strips separated by sets along the field is called the border irrigation method (Figure 8.15). In this method, irrigation water coming from the field canal is taken between the borders by simply creating a field outlet or by using siphons or covers. Thanks to the embankment on both sides, it flows as long as the borders and reaches the end of the land, thus irrigating the land. Excess water drains into the drainage ditches due to the open end of the land.

Figure 8.14. A view of the paddy fields where the basin irrigation method is applied. (Source: Anadolu Agency, 2023. https://www.aa.com.tr/tr/ekonomi/bafra-ovasinda-bereketli-yaz-sezonu-icin-hazirlik-yapilerini/2601033. Access: 12.10.2023).

Figure 8.15. Border irrigation method. (Source: Ankara Municipality, 2023. (https://www.ankara.bel.tr/files/7814/3893/6464/SULAMA_SEZA-OKCU.pdf. Access: 12.10.2023).

Furrow Irrigation method: This irrigation method is commonly used for row crops that need adequate drainage and adequate moisture. Furrows are small canals built along the field slope to convey water between plant rows (Figure 8.16). Plants are often grown on the ridges between furrows. This method is suitable for plants that cannot stay in water for a long time as it cuts the plant's contact with water.

Figure 8.16. Furrow Irrigation Method (Source: Jeff Vanuga, USDA. https://www.usgs.gov/media/images/irrigation-methods-furrow-or-flood-irrigation. Access: 10.12.2023).

Sprinkler irrigation method: Sprinkler irrigation method is the controlled application of water over plants, similar to rain (Figure 8. 17). Water is distributed in the area through many equipment consisting of pumps, valves, pipes and sprinklers. In general, sprinkler irrigation is a method that can be used to irrigate all kinds of plants, except for a few plants that may be sensitive to wetting of their leaves and stems.

In a study conducted in the USA, furrow, sprinkler and drip irrigation methods were compared in the irrigation of onions. The highest irrigation efficiency was obtained from the sprinkler irrigation method and this method was recommended for water saving in onion irrigation (Al-Jamal et al. 2001). Uygan et al. (2021) grew sugar beet under full and deficit irrigation conditions using linear action sprinkler irrigation. Full irrigation provided the highest sugar beet yield, but did not provide the highest net profit. They explained that the main reason for this is that the sales price of sugar beet is determined according to its sugar content. In the experiment, it was explained that the sugar content of sugar beet decreased with increasing irrigation water. The highest net profit was obtained from the subject where 80% of full irrigation was applied. This also resulted in 20% lower irrigation water savings compared to full irrigation. They also reported that in case of a serious shortage of irrigation water, 40% water saving should be taken into consideration with a very small net profit decrease.

Figure 8.17. Sprinkler irrigation method. (Source: Anadolu Agency 2020. https://www.aa.com.tr/tr/sirkethaberleri/enerji/dicle-elektrikten-elektrik-tasarrufu-icin-tarimsal-sulama-arastirmasi/658755. Access: 10.12.2023).

Drip irrigation method: In the drip irrigation method, water is given to the soil as drops under a certain pressure through drippers on thin pipes. Only the root area of each plant is wetted. Therefore, it is an effective irrigation method with high irrigation efficiency (Figure 8.18). Higher efficiency is achieved with subsoil drip irrigation. Evaporation losses are less. A diagram of the subsoil drip irrigation method is given in Figure 8.19. In a study on the irrigation of olive gardens, surface drip irrigation and subsurface drip irrigation methods were compared. When compared in terms of olive yield and olive oil yield, higher results were obtained in trees irrigated with subsurface drip irrigation. According to the results, up to 20% water savings were achieved with the subsurface drip irrigation method (Martinez and Reca 2014). This method can be used to irrigate all plants and all soil conditions.

Figure 8.18. Drip irrigation method (Source: Erhan GÖÇMEN).

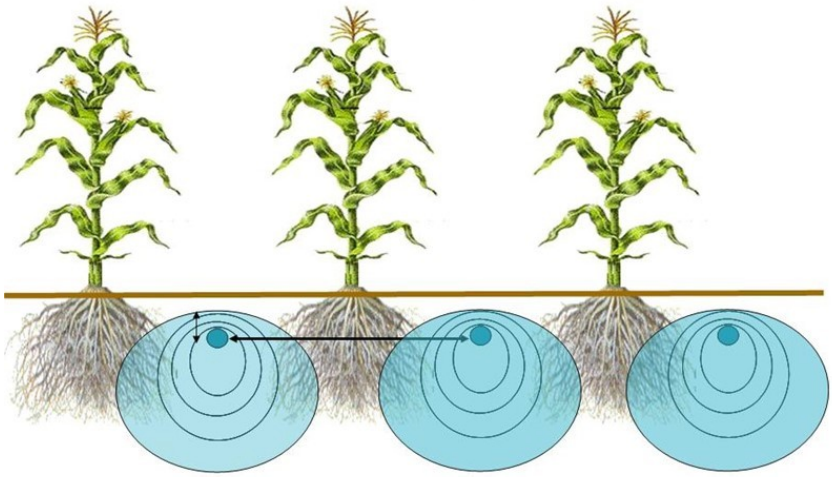


Figure 8.19. Subsurface drip irrigation. (Source Figure: Roberto Bartolini. https://www.ilnuovoagricoltore.it/i-sistemi-a-goccia-su-mais-e-soia-unirrigazione-a-regola-darte/ Access: 13.10.2023)

8.5. AGRICULTURAL WATER MANAGEMENT & GOVERNANCE

Water management aims to develop water resources in a planned manner, distribute them fairly and use them effectively. Irrigation management is a system that organizes the distribution and use of water for agricultural irrigation purposes. The study areas of agricultural irrigation management in Turkey cover the preparation, implementation and monitoring of water distribution programs during the irrigation season and their evaluation at the end of the irrigation season (Çakmak et al., 2008).

Irrigation is an important agricultural practice to meet the food needs of the increasing population. However, it is very important how this water, which is a scarce resource, is managed from the source to the plant.

8.5.1. Water Management in Türkiye

In Turkey, the General Directorate of State Hydraulic Works (DSI) and the General Directorate of Water Management are responsible for water management. Special Provincial Administrations and Metropolitan Municipalities are also authorized to manage water to some extent. In addition, General Directorate of Environmental Management, General Directorate of Nature Conservation and National Parks, General Directorate of Renewable Energy, Energy Market Regulatory Authority, Ministry of Health, Ministry of Agriculture and Forestry, Bank of Provinces, Irrigation Associations, Ministry of Culture and Tourism and Ministry of Development are directly or indirectly responsible for the management, development and protection of Türkiye's water resources.

DSI General Directorate was established on 18 December 1953 by Law No. 6200 and was organized in 1954.

As a public institution, in order to effectively fulfil the objectives of flood protection, popularizing irrigated agriculture, generating hydroelectric energy and supplying drinking water to big cities as well as to the settlements with municipal organizations, its priority activities are on dam works, which are the common point of these four objectives. For this reason, DSI General Directorate is known as an organization that builds dams in Türkiye. At the same time, it is the authority in the allocation of water resources for various usage purposes.

DSI General Directorate carries out its activities in accordance with Laws No. 6200, 167 and 1053. These laws are summarized below:

With the Law on Organization and Duties No. 6200 dated 28/02/1954:

- Drilling wells for groundwater surveys and research,
- To allocate groundwater,
- Protection and registration of groundwater,
- To issue exploration, use and reformation certificates,

With the Law No. 1053 dated 03/07/1968 on the Supply of Drinking Water to Ankara, Istanbul and Cities with a Population of More than 100 000;

- Building dams and water conveyance structures
- Constructing water evacuation structures,
- Building water storage structures,

However, as a result of the amendment of Article 10 of Law No. 1053 with the Law No. 5625 dated 18/04/2007, the population criterion was abolished and DSI was authorized for the construction of drinking water and industrial water and, if necessary, waste water facilities in all settlements with a municipality, and the name of Law No. 1053 was amended as "Law on the Supply of Drinking, Domestic and Industrial Water to Settlements with Municipal Organizations".

The duties and powers of the General Directorate of Water Management, which was established in 2011, described in Article 421 of the "Presidential Decree on the Presidential Organization" No. 1 dated 10/7/2018, are as follows:

- To carry out studies to determine policies regarding the protection, improvement and use of water resources,
- To prepare and have prepared river basin management plans on a basin basis in order to ensure the protection and development of the ecological and chemical quality of the aquatic environment by considering the protection-use balance of water resources, including coastal waters, and to carry out legislative studies on holistic river basin management,
- To follow the processes arising from international agreements and other legislation regarding the protection and management of water resources, to carry out works related to transboundary and border-forming waters in cooperation with relevant institutions,
- To Create a national water database,

- To identify and monitor sensitive areas in terms of water pollution and nitrate sensitive areas,
- To determine the design principles, norms and criteria of drinking and utility water treatment facilities, to determine the institutions and organizations authorized to approve the projects, to provide training for the personnel who will operate the facilities and to issue their certificates,
- To conduct studies on the impact of climate change on water resources,
- To determine, evaluate and update the measures regarding the prevention of pollution at the basin level together with the relevant institutions and organizations and to follow up the practices,
- To determine the targets, principles and receiving environment standards for the protection of the quality and quantity of surface and underground waters, together with relevant institutions and organizations, and to monitor or have water quality monitored,
- To carry out studies to determine strategies and policies regarding floods and to prepare relevant legislation and flood management plans,
- To allocate water resources on a sectoral basis in accordance with river basin management plans.

8.5.2. Water Management around the World

Many institutions and organizations, especially the United Nations (UN), the UN Food and Agriculture Organization (FAO), the World Water Council (WWC), the Business World and Sustainable Development Council, the European Union (EU), and the World Nature Conservation Union, have a say in water management in the world.

The Water Framework Directive, whose foundations began in Europe in 1975, came into force on 22 November 2000. The main principle of the directive defines water as "... not a commercial product, but rather a heritage that must be protected, defended and treated accordingly". The Directive envisages a new and holistic approach based on this basic principle. The aim is to protect all waters in Europe and improve their condition (Kibaroğlu et al. 2006).

Problems encountered in irrigation management and solution suggestions

It can be said that problems in water management arise at all stages, starting from the development of water resources to the delivery of water in the field.

Problems related to Lack of Physical Infrastructure

- In the field of irrigation, sustainable water management cannot be carried out because on-farm development services (such as land consolidation, levelling and drainage) cannot be completed.
- Irrigation channels, flumes, etc. all art structures cannot be used efficiently because they are exposed to both climate and user damage.
- In irrigation, transmitting more water than the need of the irrigation area causes waste of water and energy.
- Irrigation with insufficient water resources increases the tendency of farmers to turn to illegal groundwater wells, causing a decrease in irrigation efficiency.
- Since there is no intermediate storage in most of the canal networks, and there is no night irrigation, especially during peak periods, the water transmitted to the network is discharged.
- Excessive sedimentation accumulation or damage occurs in the channels. Therefore, it causes high maintenance and repair costs.

Problems Related to the Operation of Irrigation Systems:

- Low irrigation water prices in Türkiye, for instance, cause excessive water use in agriculture. Current water charges are not sufficient to cover operating and maintenance costs.
- Unconscious irrigation practices and the fact that most irrigation networks are old lead to excessive water use in agriculture. Excessive use of water reduces irrigation efficiency and causes environmental problems such as salinization, rise in ground water, ponding and pollution, and the entire irrigation area cannot be irrigated.
- Surface irrigation methods are still used by farmers.
- While plants should be irrigated when and in the amount they need for optimum development, excessive water is used. This value can be 2-3 times the need.

Problems with pollution

- In Türkiye, water pollution in streams, lakes and seas is increasing rapidly due to population growth, urbanization, industrialization and agricultural pesticides and fertilizers.
- It should be taken into consideration that groundwater may also be exposed to this danger.

Administrative problems

- The institutional structure required for the integrated management of water resources in Türkiye exists only at the central government level. In water quality management, there is no similar coordination between relevant organizations.
- There are significant overlaps in the areas of responsibility and authority boundaries between organizations, which causes coordination deficiencies and disruption of services.
- Today, the training of irrigation engineers and water distribution technicians working in irrigation unions is insufficient, despite relevant studies.

Solution offers:

- In order to ensure sustainable water management in agriculture, in-field development works such as levelling, land consolidation and drainage should be constructed together with irrigation systems. It should not be forgotten that the success of irrigation projects depends on the regulation of soil-water-human relations in the physical infrastructure project area.
- Closed pipe systems should be used instead of open channel systems in the transmission of water. Sprinkler and drip irrigation methods should be used instead of surface irrigation methods in delivering water to the plant. Thus, a water saving of 20% to 30% is achieved.
- Misuse of agricultural lands should be prevented.
- Tools and techniques that ensure effective water use in agriculture should be used. In addition, with advanced irrigation technologies, it is possible to produce the same amount or more products with less irrigation water and labour, without harming the environment.
- Laws, regulations and regulations regarding the development of soil and water resources do not comply with today's conditions. For the effective use of soil

resources, legal regulations should be made to prevent non-agricultural use of agricultural lands and pollution and loss of soil and water resources.

- In order to ensure effective water use, priority should be given to the necessary structuring and training activities to inform farmers, ensure the economic sustainability of farmer organizations and provide them with a strong financial structure (Çakmak and Aküzüm, 2006).

8.6. TAILOR-MADE BUSINESS MODEL FOR AGRICULTURAL WATER MANAGEMENT

As discussed in the first chapter, the world population will be around 9.1 billion people by 2050, which will significantly increase global demand for food. it is expected that food production will increase by 60% worldwide, and if only developing countries are considered, it could increase by up to 100% (FAO 2011, 2021). Currently, 70% of the freshwater extracted from aquifers, streams, and lakes is used for crop irrigation (FAO 2011, 2017, 2021) and that percentage would need to increase to sustain the expected rise in food production. The depletion of land, available water, and biodiversity, combined with climate change, are already impairing the growth of agricultural productivity, leading to fears that in the future agricultural productivity will not be sufficient to meet global food demand (FAO, 2011, 2017, 2021).

To avoid such a crisis and detect anticipated water shortages, Smart water management needs to be implemented urgently. Most existing water plants are governed by legacy SCADA models (Supervisory Control and Data Acquisition). These industrial plants are inefficient and largely unable to monitor, detect or operate water distribution due to practical limitations.

Here, new-age technologies for providing efficient and effective farming methods and investigate Smart IoT-based water management will be identified.

Smart water management with sensor-based technologies performs efficient and effective operations with minimum human intervention. Smart water management can aid in optimising the water usage eliminate challenges of resolving remote irrigation system issues with remote monitoring and use of IoT sensors and connected field nodes, which provide quick response as per the real-time landscape and weather conditions. The key benefits of using smart water management in water plants are optimisation of resource consumption and component monitoring. From detecting leakage, water wastage, and quality, component, and device

uptimes to match water supply demands of the smart water management provides the best implementation options (Bhardwaj 2022).

In order to use irrigation water efficiently, we have to understand the dynamics of plant water use, together with weather, plant physiology, and soil properties. Among the various irrigation scheduling methods developed and suggested, three types are most important: weather-based, soil moisture-based, and plant water status-based in traditional approaches (Ahmad et al 2023).

An innovative smart irrigation system consists of firmware, software, and hardware interconnected via various computational techniques, including artificial intelligence (AI) and deep learning (DL) etc., which ensures the right amount of water at the appropriate time in crops to improve WUE, increase yield, reduce fertilizer use, reduce labour cost, and save energy. Various control methods are employed to improve irrigation system efficiency by monitoring variables such as canopy and air temperature, evapotranspiration, rainfall, and solar radiation. By integrating information from multiple sources, smart irrigation systems can significantly improve crop production and resource management. The following section presents various recent techniques associated with smart irrigation systems in agriculture (Ahmad et al 2023).

Artificial Intelligence (AI) and Deep Learning (DL)

AI is a machine's ability to learn and implement tasks similar to those of a human brain, and it is powered by computers. When applied to a certain problem domain, AI algorithms can mimic human decision-making. Irrigation systems have been integrated with AI for adaptive decision-making through fuzzy logic, expert systems, and an Artificial Neural Networks (ANNs) (Ahmad et al 2023).

An ANN is an algorithm for processing information that is inspired by the working of the human brain. Like human brain neurons, an ANN also contains a neural network, but synapses are substituted with biased connections and weights. This facilitates the mapping of input and output relationships. ANN-based control systems can learn and adapt to the variable dynamics, making them ideal for irrigation systems. Additionally, ANNs have been used as smart strategies in dealing with the issue of formulating mathematical models based on first principles. Recently, many researchers have employed ANN methods for irrigation scheduling. Using the AQUACROP model integrated with a dynamic neural network, Adeyemi et al. (2018) simulated soil moisture for a potato crop. Karasekreter et al. (2013)

demonstrated energy and water savings up to 23.9% and 20.5%, respectively, by implementing an ANN integrated with soil physical properties and moisture content in a strawberry field. Umair and Muhammad designed (2010) an ANN-based controller model in MATLAB using climate variables as input.

Tsang et al. (2016) employed seven different machine-learning algorithms, known as hybrid AI, to assess soil moisture conditions using aerial images of agricultural fields to control irrigation. The results demonstrated a 52% reduction in water consumption by reducing timing, irrigation level, and location errors.

The deep learning method, on the other hand, is now applied to deal with millions of weights among neurons for a better understanding of behaviours owing to recent developments in computing technology in parallel processing, software and hardware. DL has developed a revolutionary epoch, since it can solve the problems confronted by artificial intelligence for a long period. Deep learning has been applied in the agriculture and hydrology fields due to difficulty in software data availability, budget, and complexity, such as crop evapotranspiration modelling and approximation (Ahmad et al 2023).

Model Predictive Control (MPC) system

MPC refers to a category of advanced computer-controlled algorithms that use an explicit process model to predict a plant's future response. Developed in the 1960s, Model Predictive Control emanates from optimal control. The basic principle of MPC is to use a dynamic model to predict system behaviour and optimize the prediction to decide the control move at the current time. In addition to its flexibility, Model predictive control repeatedly solves constrained optimal control problems online.

The model predictive system has been employed in irrigation scheduling, irrigation canal control, soil moisture, and stem water potential regulation. Model predictive control (MPC) has manifested applicability to gate operation and control the canal flow. The management goal of model predictive control for canals is to maintain the level of water as close to the set-points as possible. Thus, an appropriate model regulating the dynamics of canal-water levels is required. A model predictive control system has been employed to model water movement in the canals, keeping a specific level of water at different locations and the flow of water that affects these water levels. The controlling instruments maintain the flow of water, by which the regulator can attain the management goals. Nonetheless, attaining this goal is not straightforward, as variations in inflows and outflows interrupt the whole water system. To

estimate future water flows and levels in response to control actions and disturbances, the water system (controller, canal reaches, disturbances and structures) needs to be modelled. Several authors have applied MPC in driving irrigation flows of canals. For instance, Puig et al. applied MPC to create flow control approaches from the source of water to the user and Guadiana River's irrigation territory. The results exhibited the usefulness of the MPC application (Ahmad et al 2023).

Variable-Rate Irrigation (VRI)

VRI is a method of applying irrigation at variable rates in different irrigation management zones over the entire field in an optimized way. Normally, the application of irrigation water is uniform in the entire field. However, owing to soil spatial variability in soil topography, hydraulic properties and vegetation condition, the soil moisture content remains nonuniform. When such soil spatial variability becomes significant, the field is split into different management zones consisting of those field areas with the same soil properties and crop conditions. Then, irrigation is applied at differential rates in different management zones. Such variable irrigation management may enhance the economic value of irrigation by improving WUE, increasing productivity and reduction in nutrient leaching. This enables an accurate and timely water application based on soil spatiotemporal properties and plant demand (Ahmad et al 2023).

In other words, VRI technology ensures the application of the right amount of water at the right time in the right field zone, resulting in significant water savings. The main components of VRI technology include sensors, prescription maps, spatial information, and a unit system to apply VRI prescription (lateral irrigation) in the crop field. Optimization of VRI prescriptions is usually determined by using remote sensing, yield maps, topography, soil apparent electrical conductivity and soil maps. VRI also supports fertilizer application at variable rates that would benefit in matching the variability in crop nutrient requirements (Ahmad et al 2023).

Besides its several advantages, VRI also has some disadvantages, including higher cost, complexity in developing soil maps, and maintenance of the system. Overall, VRI technology is a good option to precisely utilize precious water resources, but considerable efforts are needed to make this technology affordable and more user-friendly (Ahmad et al 2023).

Unmanned Aerial Vehicles (UAVs) for irrigation management

UAVs, also called drones, are frequently linked with military operations, as they are used as weapons for targeting aircraft and involved in intelligence services. Drones are also useful for irrigation monitoring, as they use infrared or thermal imaging cameras in the IOT network

Recently, UAVs with IoT-based sensor networks have been used for smart irrigation purposes, thus significantly improving crop productivity. The research results indicated that the UAV-based multiband images are useful and showed substantial ability for precise irrigation and agriculture management. RGB (red, green and blue) cameras can be used with a drone to determine crop biomass using visible reflectance for assessing vegetation indices (Ahmad et al 2023).

Forecasting smart irrigation technology with Decision Support Systems (DSS)

A decision support system (DSS) is an interactive software-based system used to identify, analyse, and improve decisions based on raw data, documents, and personal knowledge. Various decision support systems (DSSs) have been designed for managing irrigation water to improve WUE. A smart and efficient DSS has to consider several factors, such as soil water status, crop type, irrigation method, weather information, and application, to develop irrigation scheduling. To facilitate precise irrigation scheduling by minimizing errors in field soil moisture estimates, DSSs provide irrigation schedules not only for the current day but also to forecast irrigation events for future days (Ahmad et al 2023).

Based on the idea of forecasting irrigation, recently a prototype of an irrigation scheduling DSS called decision support system for irrigation scheduling (DSSIS) has been developed for arid regions. This DSSIS has the ability to predict irrigation events for the current day as well as forecast irrigation for the future by using the weather information of the next 4 days (Chen et al 2019).

This system (DSSIS) has been tested for cotton irrigation scheduling under full, deficit, experience, and sensor-based irrigation treatments in an arid region. Under deficit irrigation, DSSIS saved 50% of irrigation water with a 4% increase in yield and up to 80% increase in water productivity over experience-based irrigation (Chen et al 2022).

Challenges for designing smart, sustainable and user-friendly irrigation systems

There are some challenges that are important to consider for designing smart, sustainable and user-friendly irrigation systems. These are:

- Variability in soil texture is a vital source of uncertainty because it influences the current and potential soil water storage estimates both vertically and latterly in a field. Therefore, site-specific soil analysis is one way to rectify this problem and obtain the exact soil parameter information needed for accurate irrigation scheduling.
- Most of the experiments related to smart irrigation systems were conducted on a small scale in research fields or under controlled environmental conditions, which cannot represent commercial farming practices. On-farm studies in large fields are needed
- Affordable and user-friendly equipment should be manufactured at a local level.
- Most of the farmers in dryland regions are not well educated and should be trained through practical demonstration of smart irrigation systems by expert extension workers.
- Furthermore, governments should provide subsidies to farmers for dissemination of such technologies on a large scale.

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