TARIMSAL YAPILAR VE SULAMA

Editör: Prof.Dr. Ahmet ERTEK

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İÇİNDEKİLER

IRRIGATION AND WATER MANAGEMENT STRATEGIES IN ARID AND SEMI-ARID AREAS

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1. INTRODUCTION

Arid and semiarid regions are defined as areas where precipitation is less than the amount of water lost through evaporation and transpiration. Semiarid regions, where annual precipitation ranges between 250 mm and 500 mm, have slightly more water than arid areas, but water management is critical for agricultural production (FAO, 2017). Arid regions, on the other hand, receive less than 250 mm of precipitation annually and water resources are extremely limited (UNEP, 2021). Globally, arid and semiarid regions cover approximately 41% of the Earth's land surface, and more than 2 billion people live in these areas. Farming in such regions presents significant challenges due to natural water scarcity and erratic rainfall. Water scarcity has encouraged the development of innovative irrigation strategies to increase agricultural productivity (WWAP, 2019). Water management in arid and semiarid regions is vital not only for the sustainability of agricultural output, but also for maintaining ecosystems and improving the quality of life of local communities. Effective water resource management in these

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areas increases agricultural productivity and enables more efficient water use (Kang et al., 2017). Climate change is increasing the pressure on water resources in arid and semiarid regions. Rising temperatures, changing precipitation patterns, and extreme weather events negatively affect the availability and quality of water resources. Therefore, developing flexible and sustainable irrigation strategies that can adapt to climate change is vital for the continuity of agriculture in these regions (IPCC, 2022). Effective water management in arid and semiarid regions requires the development of resilient strategies that integrate agricultural production systems with irrigation technologies and address future threats such as climate change and diminishing water resources (Kinzelbach et al., 2010). In this context, formulation of water management policies at regional and national levels plays a critical role in long-term water conservation and sustainable agriculture. Widespread adoption of modern irrigation methods, smart agricultural technologies, and water harvesting systems can be key solutions to future water scarcity challenges facing the agricultural sector in these regions

Efficient water management in arid and semiarid regions is important not only to increase agricultural productivity, but also to maintain soil health, ensure sustainability of water resources, and maintain environmental balance. Another important aspect of water management in these regions is to balance crop production and water conservation by providing the right amount of water at the right time (Wang et al., 2021). Accurately determining the water needs of plants and precisely planning the duration and amount of irrigation are among the key strategies that increase water use efficiency (Gu et al., 2020). These strategies also minimize water losses, allowing water to reach larger agricultural areas.

Nowadays, modern irrigation techniques and water management practices enable more efficient use of water resources and minimize water losses. Innovative methods such as drip irrigation, sprinkler irrigation, and smart irrigation systems increase water use efficiency and reduce water stress in plants. In this section, various irrigation strategies that can be applied to arid and semiarid regions, their advantages and disadvantages, and successful application examples will be discussed.

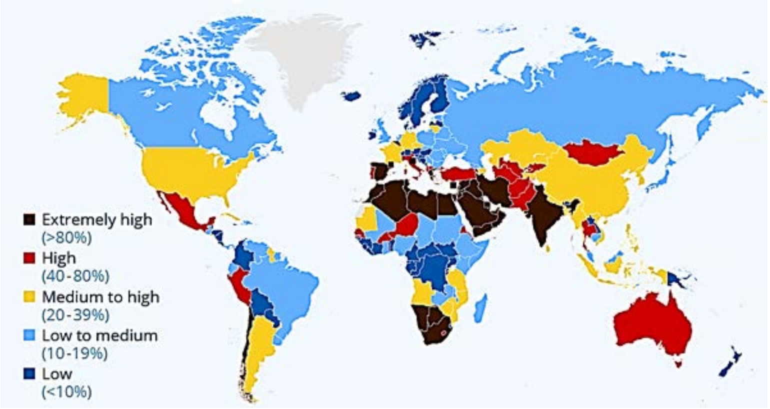
2. CHALLENGES OF WATER RESOURCES MANAGEMENT IN ARID AND SEMI-ARID REGIONS

Water management in arid and semi-arid regions poses significant challenges due to a combination of environmental, social, and economic factors. These areas, characterized by low and highly variable rainfall, high evaporation rates, and frequent droughts, are particularly vulnerable to water scarcity. The growing impacts of climate change exacerbate these challenges, leading to increased temperatures, altered precipitation patterns, and prolonged drought periods, further stressing already limited water resources (Garrido et al., 2010). This creates a pressing need for effective water management strategies to ensure the sustainability of agricultural production and water supply in these regions.

One of the most critical issues in water management is the over-extraction of groundwater resources, which is often the primary source of irrigation in arid and semi-arid areas. Over-extraction leads to a decline in groundwater levels, land subsidence, and the degradation of water quality due to salinization and the intrusion of seawater in coastal areas (Khorrami and Malekmohammadi, 2021). As groundwater reserves are depleted, the long-term sustainability of agriculture and other water-dependent activities becomes uncertain. Moreover, the reliance on fossil groundwater—water that has accumulated over thousands of years—makes replenishment through natural means impossible within human timescales (Wada et al., 2011). This unsustainable water use threatens the agricultural economy and food security in these regions.

Figure 1 illustrates the projected impact of current water consumption on future water resources. According to the World Resources Institute (WRI), this scenario represents a "business as usual" future, with global temperatures rising between 2.8 and 4.6 degrees Celsius by 2100, while inequality persists worldwide. In this scenario, countries such as Iran, India, and the entire Arabian Peninsula, along with most North African nations including Algeria, Egypt, and Libya, are expected to use at least 80% of their available water resources by 2050.

Figure 1. Where Water Stress Will Be Highest By 2050



Source: (WRI, 2024)

Compounding these environmental issues are the social and economic challenges. Rapid population growth, urbanization, and increasing demand for water-intensive crops place additional pressure on scarce water resources (Fader et al., 2016). Conflicts over water use between agriculture, urban needs, and industry are intensifying, leading to competition and inefficiencies in water allocation. This scenario highlights the necessity of integrated water resource management (IWRM) approaches that take into account the multiple uses of water while prioritizing sustainable practices.

The inadequacy of infrastructure and outdated irrigation techniques also contributes to inefficient water use. Traditional methods like flood irrigation, which is still widely used in many arid regions, result in high water losses through evaporation and runoff. According to Oweis and Hachum (2006), modernizing irrigation systems—such as adopting drip or sprinkler irrigation—can significantly reduce water losses and enhance water-use efficiency. However, the implementation of these technologies is often limited by financial constraints, lack of technical knowledge, and insufficient policy support.

In conclusion, the challenges of water management in arid and semi-arid regions are multifaceted, involving environmental degradation, unsustainable water extraction, population pressures, and infrastructural limitations. Addressing these challenges requires an integrated approach that combines modern technologies, sustainable practices, and supportive policy frameworks to mitigate water scarcity and ensure long-term resilience in these vulnerable regions.

3. SOIL MANAGEMENT AND INCREASING WATER RETENTION CAPACITY

The sustainability of agricultural production in arid and semi-arid regions heavily depends on the effectiveness of soil management strategies. Given the limited water resources in these areas, enhancing the soil's water retention capacity plays a crucial role in improving water efficiency and plant growth (Lal and Stewart, 2013). Water retention capacity varies depending on soil structure, organic matter content, soil texture, and local climatic conditions. Methods employed to increase soil water retention not only ensure efficient water use but also help plant roots remain moist for longer periods under drought conditions (Gupta et al., 2020).

One of the most effective ways to improve water retention capacity in soil management is by increasing the organic matter content. Organic matter improves soil structure, thus enhancing the soil's ability to retain water. Soils enriched with organic matter hold water for extended periods, making it accessible to plant roots. Additionally, organic matter promotes the formation of soil aggregates, which improves water infiltration (Yang et al., 2022). Incorporating compost, green manure, and plant residues into the soil are primary methods for increasing organic matter levels. These practices are key components that support both soil health and water management strategies. The water retention improvement rates of certain soil amendment practices are outlined in Table 1.

Table 1. Methods to Increase Soil Water Retention Capacity

Method	Increase in Water Retention Capacity (%)
Organic Matter Application	15-25%
Mulching	10-20%
Minimum Tillage	5-15%
Use of Compost and Green Manure	10-30%
Improvement of Soil Structure	10-25%
Reduction of Soil Salinity	5-10%

Another important soil management strategy is the optimization of tillage techniques. Minimal tillage methods help preserve soil structure, allowing water to remain in the soil for a longer period. While conventional deep tillage techniques can lead to water loss, minimum tillage strategies aid in retaining surface moisture in the soil (Lv et al., 2023). Additionally, surface covering techniques such as mulching reduce water loss through evaporation by conserving soil moisture and regulating soil temperature. Mulching contributes to the successful implementation of water management strategies by enhancing the soil's water retention capacity (El-Beltagi et al., 2022).

Controlling soil salinity is another crucial soil management strategy that enhances water retention capacity. In arid and semi-arid regions, excessive irrigation and poor drainage conditions can lead to salt accumulation in the soil. Soil salinity restricts the ability of plant roots to access water, thereby increasing water stress. To prevent salinization, it is essential to establish proper drainage systems and implement controlled irrigation techniques (Singh, 2021). These strategies support the more efficient use of water in the soil and ensure suitable moisture conditions for plant growth.

4. DETERMINATION OF IRRIGATION STRATEGIES

4.1. Soil and Plant Water Relations

The relationship between soil and plant water dynamics is critical for the healthy growth of plants and productive yields. The water retention capacity of the soil varies depending on its structure, texture, and organic matter content. Well-structured soils can efficiently retain water and deliver it to the root zone, where plants can access it as needed. The soil's water retention capacity is a key factor in determining irrigation strategies used in agricultural production (Brady & Weil, 2017).

The water requirements of plants depend on the species, growth stage, and environmental conditions. Plants require water for essential processes such as photosynthesis, growth, and other vital functions. When the soil does not provide sufficient water, plants experience water stress, leading to yield losses (Figure 2). Water is absorbed from the soil by plant roots and transported to the leaves, where it is returned to the atmosphere through transpiration. This process is fundamental for plant water use and irrigation planning (Kirkham, 2023).

Figure 2. The Impact of Water Stress on Maize Growth

a- Irrigation up to field capacity

b- 30% water deficiency

c- 60% water deficieny

d- Rainfed irrigation

Source: (Gültekin et al., 2022)

A study conducted in Turkey during 2019-2020 investigated the effects of four different water stress levels on maize growth. The study concluded that water stress significantly limited maize development; however, under conditions where water is a scarce resource, up to 30% water deficit can be applied without severely impacting growth (Gültekin et al., 2022).

4.2. Water Resource Management

Water resource management is crucial for the sustainability of agricultural production in arid and semi-arid regions. Effective management of surface water and groundwater resources is necessary to maintain water availability and quality. Surface water sources, such as rivers, lakes, and reservoirs, provide a significant portion of the water supply, while groundwater is extracted from aquifers. The sustainable management of both types of water resources is vital for the continuation of agricultural production (Gleick, 2014).

Water storage methods are essential strategies for increasing water availability in arid and semi-arid areas. Dams, reservoirs, and ponds allow for water to be stored during rainy periods and used during droughts. Water harvesting techniques, such as rainwater collection and groundwater recharge, enable the efficient use of water resources. These techniques support the sustainable use of water and improve water efficiency in agricultural production (FAO, 2013).

4.3. Irrigation Techniques

- **Traditional irrigation methods**

Traditional irrigation methods are employed in approximately 60% of the world's agricultural areas (FAO, 2017). Flood irrigation is one of the simplest and most common methods, in which water is allowed to flow freely over the field, with the soil absorbing the water. This method is often used in large areas where water is abundant. However, it results in high water loss due to surface spread and evaporation, with water use efficiency being around 30-40% (Kahlown and Kemper, 2004).

Furrow irrigation, on the other hand, involves directing water through furrows dug along the field, allowing the water to reach the plant's root zone more directly. While this method can still lead to water losses, it improves water use efficiency by 30% compared to flood irrigation (Fahong et al., 2004). Traditional irrigation methods are advantageous due to their low investment costs and ease of implementation. However, they also have drawbacks such as soil salinization, unequal water distribution, and water waste.

- **Modern irrigation methods**

In order to maximize water efficiency and reduce water loss, modern irrigation techniques are developed. Drip irrigation systems, which deliver water directly to the plant’s root zone in the form of droplets, can achieve water use efficiencies of 90-95% (Capra & Scicolone, 2008). This method prevents water wastage and reduces water stress in plants. As of 2020, approximately 10% of agricultural areas globally that use modern irrigation methods are irrigated with drip irrigation systems (FAO, 2017).

Sprinkler irrigation involves applying water to plant surfaces through pressurized pipes and sprinklers, ensuring even distribution across a wider area. This method is suitable for various plant species and soil conditions, maintaining water use efficiency between 70-85% (Evans and Sadler, 2008).

Modern irrigation techniques have been developed to maximize water efficiency and reduce water loss.

- **Subsurface drip irrigation**

Subsurface drip irrigation systems involve delivering water directly to the plant’s root zone through underground pipes. This method prevents water loss through evaporation and allows plants to utilize water more efficiently. Subsurface irrigation systems can achieve water use efficiencies of up to 95%, offering the highest efficiency compared to other irrigation methods (Ayars et al., 1999). However, the installation and maintenance of subsurface irrigation systems are more expensive and complex than other methods.

The applicability of subsurface irrigation systems depends on soil characteristics, plant species, and water availability. When properly managed, subsurface irrigation systems increase water use efficiency and support the sustainability of agricultural production. Globally, only 1-2% of agricultural areas are irrigated using subsurface systems, but this figure is increasing due to climate change and water scarcity (Skaggs et al., 2010).

4.4. Irrigation Management

- **Determining irrigation amounts**

Accurately determining irrigation amounts is critical to meet the optimal water needs of plants. Various methods and formulas are used to calculate irrigation water amounts. These methods include calculations based on soil moisture content, meteorological data (ET0), and other empirical approaches.

- **Determining irrigation amount based on soil moisture content**

In this method, the soil's water holding capacity and current moisture status are considered. Irrigation amounts are calculated by determining the difference between the current water content and the field capacity of the soil. Generally, irrigation water requirements are calculated based on soil water deficits, as outlined in Equation 1 (Allen et al., 1998).

$$I = (FC - \theta)\ x\ D\ x\ Bd \qquad \text{Equation (1)}$$

Where;

- I: Irrigation amount to be applied (mm)

- FC: Field Capacity (%)
- θ: Current soil moisture content (%)
- D: Root depth (cm)
- Bd: Soil bulk density (g/cm³)

- **Determining irrigation amount based on meteorological data (ET0)**

In determining the irrigation amount based on meteorological data, reference evapotranspiration (ET0) calculations are used. ET0 is a measure used to estimate plant water consumption and water loss under varying environmental conditions. According to the Penman-Monteith equation, ET0 can be calculated using Equation 2 as follows (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad \text{Equation (2)}$$

In equation:

- ET_0: Reference evapotranspiration (mm/day)
- Δ: Slope of the saturation vapor pressure curve (kPa/°C)
- R_n : Net radiation (MJ/m²/gün)
- G: Soil heat flux (MJ/m²/gün)
- γ: Psychrometric constant (kPa/°C)
- T: Daily average temperature (°C)
- u_2: Wind speed at 2 meters height (m/s)
- e_s : Saturation vapor pressure (kPa)

- e_a : Actual vapor pressure (kPa)

After calculating ET0 using these values, it is multiplied by the crop coefficient (Kc) to determine the plant-specific water consumption (ETc) according to Equation 3 (Allen vd.1998, Irmak vd.2014, Çetin ve Üzen 2018).:

$$ET_c = K_c \ x \ ET_0 \qquad \text{Equation (3)}$$

In equation:

- ET_c : Crop-specific evapotranspiration (mm/day)
- K_c: Crop coefficient (varies depending on plant species and growth stage)

- **Determining irrigation amount based on other empirical methods**

Another method used to determine irrigation water amounts is based on experimental data and empirical formulas. For example, the method recommended by FAO for calculating water requirements can be applied using the formula expressed in Equation 4 (Allen et al., 1998):

$$I = \frac{ET_c}{E_a} \qquad \text{Equation (4)}$$

Where;

- I: Irrigation water amount (mm)
- ET_c : Crop-specific evapotranspiration (mm/gün)
- E_a: Irrigation efficiency (%)

Irrigation efficiency varies depending on the irrigation method and system efficiency. In drip irrigation systems, it typically ranges between 85-95%, while in traditional irrigation methods, this value can be between 50-70%.

- **Determining irrigation timing and amount based on plant physiological parameters**

Irrigation management based on plant physiological parameters is an approach that determines irrigation timing and amount by directly monitoring the water status and stress levels of plants. These methods are used to prevent plants from entering water stress and to ensure efficient water use. Below, methods such as the Crop Water Stress Index (CWSI), sap flow measurements, and stomatal conductance, as well as other physiological parameters and calculation methods, are discussed.

- **Crop water stress index (CWSI)**

The Crop Water Stress Index (CWSI) determines the water stress level of plants by measuring the difference between the surface temperature of plant leaves and the air temperature. CWSI is a commonly used indicator in plant water management. It quantifies water stress levels and can be calculated according to Equation 5 (Idso et al., 1981):

$$CWSI = \frac{T_C - T_a - (T_c - T_a)_{min}}{(T_c - T_a)_{max} - (T_c - T_a)_{min}} \qquad \text{Equation (5)}$$

In equation:

- T_c : Leaf surface temperature (°C)
- T_a : Air temperature (°C)
- $(T_c - T_a)_{min}$: Temperature difference when the plant is fully hydrated (°C)

- $(T_c - T_a)_{max}$: Temperature difference under maximum water stress (°C)

The CWSI value ranges between 0 and 1. A value of 0 indicates that the plant is fully hydrated with no water stress, while a value of 1 indicates that the plant is under maximum water stress. Irrigation timing is determined when the CWSI value exceeds a certain threshold.

- **Stem flow measurements**

Stem flow measurements are used to directly measure the water consumption of plants. Stem flow determines the water requirement of the plant by measuring the amount of water passing through the plant stem. These measurements can be conducted using thermal dissipation or gravimetric methods. The thermal dissipation method measures sap flow by detecting the temperature difference between heated and unheated points, while the gravimetric method measures changes in the water content of the plant stem.

- **Stomatal conductance**

Stomatal conductance measures how much the stomata on plant leaves allow the exchange of water vapor and carbon dioxide. High stomatal conductance indicates sufficient water availability, while low conductance signals water stress. Stomatal conductance measurements can be conducted using pyrometers or gas exchange analyzers. These data are used to optimize irrigation timing.

- **Plant water potential**

Plant water potential provides direct information on the water status of the plant and is used to determine plant water stress. It can be measured as leaf or stem water potential. These measurements are carried out using pressure chambers or psychometric methods. Plant water potential is a critical indicator for determining amount of water and irrigation scheduling.

- **Empirical equations and determination of irrigation amount**

One of the empirical equations used in determining irrigation scheduling and amount based on plant physiological parameters is provided below (Allen et al., 1998):

$$I = K_s \ x \ \mathrm{ET}_c \qquad \text{Equation (6)}$$

In equation:

- I: Irrigation water amount (mm)
- K_s : Water stress coefficient (determined based on CWSI or other physiological parameters)
- ET_c: Crop-specific evapotranspiration (mm/day)

The Ks value is adjusted according to the water stress level determined by CWSI or other physiological parameters. For example, if the CWSI value is 0.5, the Ks value may also be set to 0.5, and the irrigation amount is adjusted accordingly.

Another method is irrigation management based on plant water potential (Equation 7). Irrigation is applied when the plant water potential falls below a certain threshold. These threshold values vary depending on the plant species and growing conditions (Allen et al., 1998).

$$I = \frac{(\Psi_{wp} - \Psi_{\min})}{\Psi_{wp} - \Psi_{fc}} \ x \ ET_c \qquad \text{Equation (7)}$$

Where;

- I: Irrigation water amount (mm)
- Ψwp: Wilting point water potential (MPa)
- Ψ_{min}: Actual water potential (MPa)
- Ψ_{fc}: Field capacity water potential (MPa)
- ET_c: Crop-specific evapotranspiration (mm/day)

These methods and equations help optimize irrigation timing and amounts by directly monitoring the water status of plants. In doing so, water resources are used more efficiently, and plant water stress is minimized.

5. EFFICIENCY AND SUSTAINABILITY

5.1. Water Use Efficiency

Water use efficiency refers to the effective and efficient utilization of water in agricultural irrigation systems. Modern irrigation techniques deliver water directly to the plant root zone and minimize evaporation losses. For instance, drip irrigation systems can achieve water use efficiencies of 90-95%, whereas traditional flood irrigation methods range between 30-40% (Fereres & Soriano, 2007). Table 2 presents some general water use efficiency rates for various irrigation methods.

Table 2. Water Use Efficiency for Selected Irrigation Methods

Irrigation Method	Water Use Efficiency (%)
Flood Irrigation	30-40
Furrow Irrigation	40-50
Sprinkler Irrigation	70-85
Drip Irrigation	90-95

Reducing water losses requires maintenance and modernization of on-farm water delivery systems. The use of closed pipe systems instead of open canal systems can significantly reduce water leakage and evaporation losses. For example, closed pipe systems can reduce water losses by 15-25% (Kalua, 2012).

5.2. Sustainable Practices

Sustainable water management includes the conservation, reuse, and recycling of water resources. Conserving water resources is essential for preventing the overuse of surface and groundwater sources and for maintaining water quality. Water harvesting, which involves collecting and storing rainwater, is an effective method to enhance water availability during dry periods (Table 3).

Table 3. Water Application and Saving Rates According to Water Sources

Method	Application Rate (%)	Water Saving (%)
Rainwater Harvesting	20-30	10-20
Recycled Water Use (Grey Water)	10-15	30-40
Closed Pipe Systems	15-25	15-25

Reuse and Recycling Techniques refer to the treatment of wastewater to allow its reuse in agricultural irrigation. Treated wastewater can be utilized as a source of irrigation water, which alleviates pressure on freshwater resources (Qadir et al., 2007).

5.3. Climate Change and Adaptation

Climate change significantly influences agricultural irrigation needs. Rising temperatures, shifting precipitation patterns, and extreme weather events negatively impact the availability and quality of water resources (IPCC, 2022). For instance, global agricultural water demand is projected to increase by 20-30% by the year 2100 (Table 4) (Kang et al., 2009).

Table 4. Global Water Demand from Present to Future

Year	Global Agricultural Water Demand (km³)	Increase Rate (%)
2020	2,400	-
2050	2,880	20
2100	3,120	30

Adaptation strategies include the development of climate-resilient crop varieties, the use of water-saving irrigation technologies, and the adoption of flexible practices in agricultural water management. Irrigation planning based on climate change projections can help optimize irrigation strategies by forecasting future water demands (Kang et al., 2009). Moreover, the implementation of training and capacity-building programs is crucial to ensure that farmers can adapt to climate change.

5.4. Case Studies and Application Examples

- **Successful Practices**

Various successful irrigation projects have been implemented to efficiently use water resources in arid and semi-arid regions. These projects demonstrate the effectiveness of modern water-saving irrigation techniques. For instance, in the Almeria region of Spain, greenhouse agriculture projects have achieved significant water savings through the use of modern irrigation technologies. Almeria is one of the largest greenhouse centers in Europe, and through the implementation of drip irrigation and water harvesting techniques, water use efficiency has reached up to 90%. The region has more than 30,000 hectares of greenhouse area, where modern irrigation techniques have reduced water consumption by over 30% compared to traditional methods. These practices have made agricultural production in the region more sustainable and alleviated the problem of water scarcity (Garcia-Caparros et al., 2017). Table 5 presents some studies that have successfully achieved water savings and management in arid and semi-arid regions. After all articles were examined and analyzed on water saving and yield, recommended irrigation deficit ranges were decided according to the results.

Tablo 5. Successful Applications in Water Saving

Plant	Location	Year	Water Resource	Water Potential of the Region	Irrigation Method	*Recommended Amount of Irrigation Deficit	Literature
Sugar Beet	Albacate / Spain	2000	NA	Semi-Arid	Drip Irrigation	Ranged (20% and 30%) of aETc	(C.Fabeiro et al., 2003)
Sugar Beet	Xinjiang/ China	2017/2018	NA	Arid	Drip Irrigation	50% of FC	(Yangyang Li et al., 2019)
Sugar Beet	Kahramanmaras/ Turkiye	1999/2000	NA	Semi-Arid	Sprinkler	Ranged (15% and 25%) of aETc	(Ucan and Gencoglan (2004)
Sugar Beet	Xinjiang/ China	2014/2015	NA	Arid	Drip Irrigation	50% of dFC	(Yangyang Li et al., 2019
Sugar Beet	Idaho / USA	2011/2012/2016	NA	Arid	Drip Irrigation	35% of aETc	(Tarkalson D., & King B.A., 2017)
Sugar Beet	Nubaria/ Egypt	2011/2012	NA	Semi-Arid	Drip Irrigation	40% of bETo	(Abdel-Nasser G et al., 2014)
Sugar Beet	Nebraska / USA	2008/2011	NA	Semi-Arid	Sprinkler	Ranged (25% and 50%) of aETc	(Haghverdi, A et al., 2017)
Corn	Nebraska / USA	2003/2004	NA	Arid	Sprinkler	Up to ~28 of cETa	(Payero J et al., 2006)
Corn	Gavkhuni/ Iran	2000/2003	NA	Arid	Furrow Irrigation	Up to 40% of aETc	(Salemi, H et al., 2011)
Cotton	Xinjiang/ China	2010/2011	NA	Arid	Drip Irrigation	Ranged (15% and 20%) of aETc	(Chuanjie, Y. A. N. G et al., 2015)
Cotton	Adana/ Turkey	2005/2008	NA	Arid	Drip Irrigation	Up to 30% of aETc	(Unlu, M et al., 2011)
Cotton	Apodi/ Brasil	2012/2013	NA	Semi-Arid	Sprinkler	Up to 30% of aETc	(Zonta, J. H et al., 2015)
Cotton	Pali/ India	2009/2011	NA	Arid	Drip Irrigation	Up to 20% of aETc	(Rao, S. S et al., 2016)

*Recommended Irrigation Deficit represents the best water deficits according to articles which are shown in the table. **a)** ETc indicates (Crop Evapotranspiration), **b)** ETo (Reference Evapotranspiration), **c)** ETa (Actual Crop Evapotranspiration), **d)** FC (Field Capacity)

The importance of water resources in our earth has been steadily increasing due to various factors including climate change, population growth and drought or water crisis in the world. Despite some skepticism from segments of the global population, water scarcity is a tangible threat with profound implications for our future. When we examine the reports or articles about the water scarcity, we can clearly notice that the world need to get an action to figure fresh water issue out as soon as possible. According to a report was published by Massachusetts Institute of Technology, an additional 1.8 billion people can live in water stressed regions by 2050 (Schlosser et al., 2014). Furthermore, another report estimates that 2.7 billion people can live in water scarce areas (Anonymous, 2024). As a result of the scientific reports and academic studies in the table above, the importance of freshwater resources is emphasized once again. Furthermore, it is demonstrated that deficit irrigation plays a critical role in maintaining the equilibrium between water use and agricultural productivity in arid and semiarid areas.

- **Regional approaches**

In various geographical regions, irrigation strategies have been developed that are suited to local climate and soil conditions. In the Middle East, irrigation projects implemented in Israel's Negev Desert present significant examples of efficient water resource use. Despite limited water resources, Israel has achieved high agricultural productivity through advanced drip irrigation systems and wastewater recycling technologies. The Negev Desert encompasses over 200,000 hectares of agricultural land, where drip irrigation systems have reduced water usage by 50% while increasing crop yields by 30%. Additionally, Israel’s wastewater recycling systems meet 85% of the country's total water demand (Yermiyahu et al., 2007).

In Africa’s Sahel region, irrigation strategies based on water harvesting and subsurface water usage were developed. The "Zai" method applied in Burkina Faso involves retaining rainwater in the soil to meet the water needs of plants. This method creates pits that capture rainwater, storing it in the soil to provide water to crops during dry periods. The Zai method has increased water use efficiency by 30%, leading to significant improvements in agricultural productivity. In regions where the Zai method is used, crop yields were increased by up to 50%, and soil fertility has improved (Sawadogo, 2012).

In Latin America, water management is achieved through a combination of traditional and modern irrigation techniques in the Andean region of Peru. The "qanat" system, which transports and stores water through underground channels, is integrated with modern drip irrigation techniques to ensure the efficient use of water resources and sustainability in agricultural production. The qanat system efficiently utilizes 70% of the region's water resources, while increasing agricultural production by 40% (Gelles, 2000).

In Australia's Murray-Darling Basin, water use efficiency was enhanced through modern irrigation techniques and water management policies. More than 500,000 hectares of agricultural land in this region are irrigated using drip and sprinkler irrigation systems. These projects were reduced water consumption by 40% and increased agricultural production by 30% (Grafton & Wheeler, 2018).

6. CONCLUSION AND RECOMMENDATIONS

6.1. General Evaluation

The successful implementation of irrigation strategies in arid and semi-arid areas is critical for the sustainability of agricultural production and the efficient use of water resources. Modern irrigation techniques, particularly drip and sprinkler irrigation systems, play a significant role in improving water use efficiency and minimizing water losses. For instance, projects implemented in countries such as India, Spain, Israel, and China have resulted in a 30-50% increase in water use efficiency. These projects have also led to a 20-40% increase in agricultural productivity. Additionally, sustainable practices such as water harvesting and wastewater recycling contribute to the conservation of water resources and ensure long-term water security.

The effects of climate change present a major challenge for agricultural water management. Rising temperatures, changing precipitation patterns, and extreme weather events negatively impact the availability and quality of water resources. Therefore, the development of climate-resilient crop varieties and the adoption of water-saving technologies are vital for ensuring the sustainability of agricultural production.

6.2. Policy Recommendations

The development and implementation of water management policies in arid and semi-arid areas are critical to ensuring the efficient use of water resources and the sustainability of agricultural production. Below are some strategic policy recommendations:

1. **Promotion of modern irrigation technologies:** Water-saving technologies such as drip and sprinkler irrigation should be promoted, and financial support should be provided to farmers for the installation of these systems. Training programs and technical support services should be provided to ensure that farmers can use these technologies effectively.
2. **Support for water harvesting and recycling practices:** Rainwater harvesting and wastewater recycling projects should be encouraged to diversify and sustainably manage water resources. Public-private partnerships should be established to provide funding and technical support for these projects.
3. **Development of climate change adaptation strategies:** Adaptation strategies should be developed to minimize the effects of climate change on water resources. This includes the cultivation of climate-resilient crop varieties, the use of technologies that improve water use efficiency, and the creation of water management plans based on climate change projections.

4. **Integration of water management policies:** Water management policies should be integrated with agricultural, environmental, and water resource management to adopt a holistic approach. Coordination at local, regional, and national levels should be ensured, and collaboration between stakeholders should be encouraged to promote the sustainable use of water resources.

5. **Support for research and development:** Research and development in irrigation technologies and water management should be supported to foster the development and implementation of innovative solutions. Collaboration between universities, research institutions, and the private sector should be encouraged.

These policy recommendations provide a strategic framework for the effective and sustainable management of water resources in arid and semi-arid regions. Efficient water use and sustainable agricultural production are vital for ensuring long-term food security and economic development.

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CLIMATE CHANGE AND ALTERNATIVE WATER RESOURCES

Tuğba YETER[1]

Ceren GÖRGİŞEN[2]

1. INTRODUCTION

Water is an essential natural resource for plants, human being and various other species that exist on our Earth. Humanity's survival and reliable access to water resources are only possible by understanding that water can be depleted for various "strategic" reasons. When we look at human being history, we see many examples of civilizations collapsing due to the misuse of water.

Although much of the world's surface is covered with water, freshwater resources constitute only 2.5% of this amount. A minimal amount of this rate, such as 1.2%, is used to sustain human, plant, and animal life (Figure 1). The misconception that the amount of water, which is the primary source of life for living things on earth, is abundant and continuous is one of the obstacles that must be overcome to ensure conscious water consumption. The question that needs to be asked is, "What is the source of our water, and when will it be enough for us?" For this reason, it is essential to pay attention to water use and consumption globally and nationally.

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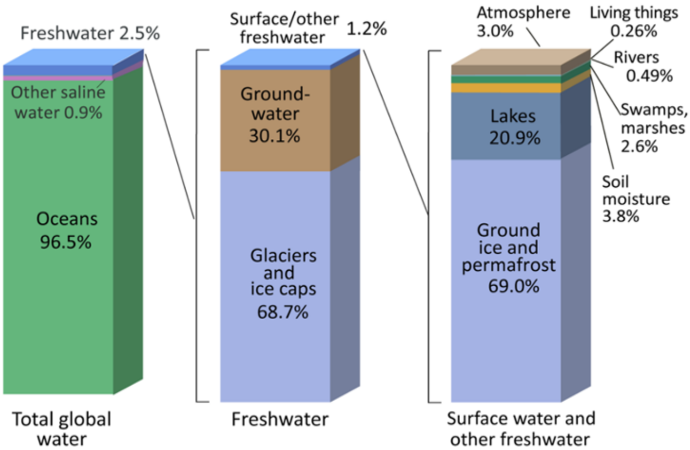
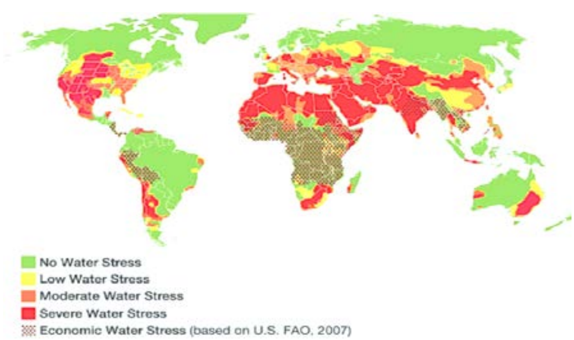
Figure 1. World Water Distribution



Source: (Anonymous,2019)

Water consumption has increased considerably due to factors such as industrial development and population growth, and it is expected that this increase will continue in the coming years, with the effect of climate change, by 30% in the first quarter of the 21st century. As a result of this increase, it is estimated that 2/3 of the world's population can face water scarcity in 2025. Also, another scientific report showed that almost half of the world's population will struggle to survive water scarcity in 2030 (FAO, 2007). Estimated water scarcity scenario for all countries is demonstrated in Figure 2 (OECD, 2008).

Figure 2. Nations Affected By 2030 Water Scarcity

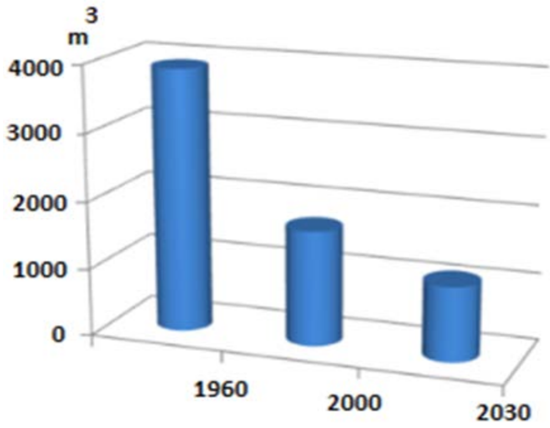


Agricultural water use, which is approximately 70% on average globally, increases to around 82% in underdeveloped and developing countries. On the other hand, the biggest issue is using outdated irrigation strategies have low water use efficiency. For example, flood irrigation is still largely preferred by local farmers because of the economical or technical issues. As a result of this, large amount of water evaporates from the surface and this increases the threat of drought. Therefore, using less water for more agricultural products of better quality or using alternative water sources (rainwater, gray water, wastewater, etc.) for irrigation indicates that the agricultural sector has entered a difficult period.

In these periods, when climate change manifests itself, it is estimated that the increasing population in the world and the remaining water resources may cause severe water scarcity in the coming years. Especially climate change is widely recognized as one of the most serious issue on the global scale. It will directly impact water resources as it will cause fluctuations in the amount of precipitation and evaporation. It is seen that today; we are consuming more than twice the water we consumed thirty years ago. Water use in Türkiye was 27 billion m^3 in 1990 and 57 billion m^3 (77%) in 2023. When we look at the sector usage, the agricultural sector's highest water usage is used in irrigation, with approximately 44 billion m3 in 2023 (Anonymous, 2023). While the 2023 water year rainfall in Türkiye was 374 mm, the average of 1991-2020 was 431 mm, and the 2022 water year rainfall was 408 mm. According to the data, rainfall decreased by 13% and 9% compared to 2022 (Anonymous, 2023). The most important effect of this decrease in the precipitation regime is seen in the agricultural sector. If the conditions causing drought continue, these problems will continue to increase in the coming years (Türkeş, 1999).

The annual amount of usable water per capita in Türkiye is given in Figure 3 (Anonymous, 2012). Accordingly, it has been reported that Türkiye is in the water stress class, and the amount of water per capita, which was 1,322 m^3 in 2022, will be 1,120 m^3 in 2023. Climate change will negatively affect Türkiye due to global warming, significantly decreasing water resources, drought, and ecological deterioration.

Figure 3. Türkiye's Water Potential Per Person



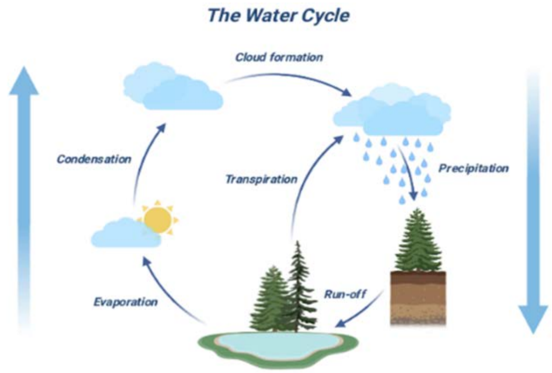
Suppose sufficient measures are not taken against climate change in our country, located in the arid and semiarid climate zone. In that case, sustainable use of water resources will be in danger. The need for drinking water, especially in cities, will increase even more. While global warming and increases in precipitation variability play an active role in water supply, this situation will create essential problems in the agricultural sector. While increasing temperature will accelerate the hydrological cycle, it will also cause an increase in precipitation and evapotranspiration (ET) amounts. Some of these changes are occurring today, and their regional effects have yet to be fully known. Therefore, the complete picture of global warming brings new uncertainties and essential problems to society and researchers. When all of these factors come together, they have created an increasingly worsening water crisis environment (Hoffman and Evans, 2007). While the presence of water, which has an essential place in every area of our lives, from agriculture to energy, from industry to tourism, provides societies with a better quality of life, water-related problems in regions experiencing water scarcity must be resolved with long-term solutions.

2. CLIMATE CHANGE IN TÜRKİYE AND EFFECTS ON WATER RESOURCES

The possible effects of climate change are environmental, economic, and social. While it creates dangerous and irreversible consequences on water resources, it can sometimes destroy agricultural lands with excessive rainfall and floods and cause soil erosion. This situation can reduce soil quality, making it unsuitable for agricultural production. These negativities in question cause product prices to increase, leading to a deepening economic uncertainty.

The impact of climate change on water resources is evaluated in terms of the hydrological cycle (Figure 4) and the resulting change in water quality. Although the total amount of water in our world remains constant with the hydrological cycle, changes in the type of precipitation, the location and time of precipitation, changes in the recharge amounts of underground water resources, or changes in the amount of surface runoff can have serious consequences.

Figure 4. Water Cycle

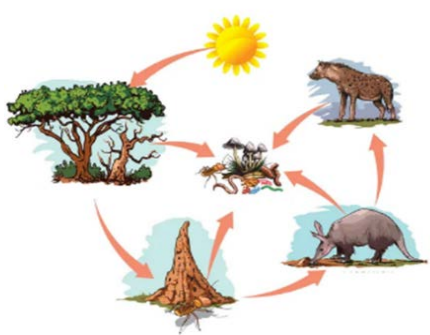


Changes in biological, chemical, and physical parameters manifest the impact of climate change on the quality of water resources. Along with changing temperatures, factors that cause climate change, such as sudden and heavy rainfall and weather events (drought, flood, tornado, etc.), cause physicochemical changes in water resources. For example, each 3°C temperature increase in water reduces the oxygen content by 10%. The impact of climate change on the quality of water resources and on drinking water demand has been examined. As a result, it has been revealed that there will be difficulties in meeting the demand for drinking water due to flood and drought risks. One of the most common impacts on water resources is the increase in the amount of dissolved substances in water due to the change in the amount of water and the deterioration of water quality accordingly. This situation will negatively affect food and energy security and mainly cause the failure to meet drinking water quality standards (Delpla et al., 2009). On the other hand, this negative impact on water resources seriously affects other sectors, such as agriculture, animal husbandry, energy, and tourism, directly affected by water. Moreover, meteorological changes such as precipitation regime, evaporation, sudden and extreme weather events, and increased risks of drought and floods are among the possible effects of climate change. Especially in agricultural production, soil loss due to excessive precipitation and decreased soil fertility due to salinization or inability to provide irrigation water due to drought and insufficient precipitation will endanger food supply and security.

Türkiye is among the countries that will be affected by climate change caused by global warming due to its different climate structure. Seas surround Türkiye on three sides and have different topographic features, so it is expected to be affected by climate change in different ways and proportions. The regions most affected by the temperature increase will be arid and semi-arid regions and semi-humid regions where water resources are insufficient (Türkeş, 1998). The expected or actual effects of climate change on Türkiye can be listed as follows:

Climate changes will disrupt the natural ecological system and its productivity, causing an increase or decrease in biodiversity. There may be increases in biodiversity due to changes in the habitats of fauna, flora, and new species. At the same time, adverse conditions (fires, epidemics, etc.) may lead to a decrease in biodiversity and an increase in unwanted wild species. Climate change and all related changes will affect the material and nutrient cycle, water quality, river regime and flow, soil erosion, and ecosystems that contribute to air quality (Türkeş, 1996).

Figure 5. Ecological Cycle



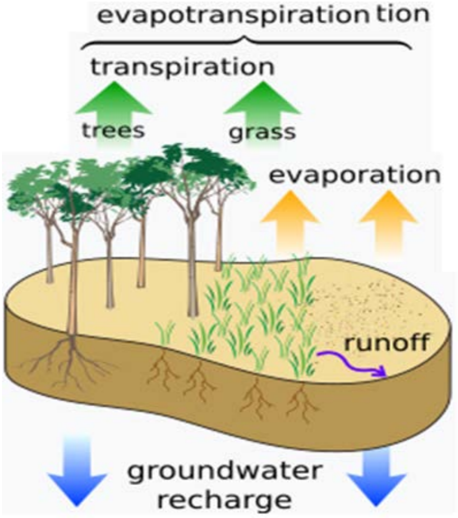
Forests are the systems most sensitive to climate change due to decreases in carbon content, especially in the precipitation regime. In Türkiye, where forest destruction is very high, it is estimated that forests may decrease due to possible climate changes such as temperature, precipitation, and fire. Therefore, destroying forests that form the basis of the ecological balance or their inadequate protection will create significant problems for Türkiye. Due to the indispensability of water in agricultural production, clean water shortage has become the most significant restriction on agricultural production. The negative impact of the decrease and deviations in the precipitation regime on agricultural production in Türkiye is seen more in winter plantings.

Changes in agricultural production are directly related to the amount of usable water in the soil. Studies have indicated that 80-90% of drought-related damage occurs in areas where planting is done due to insufficient precipitation, especially in the Central Anatolia region (Öztürk, 2002). Climate change will lead to changes in the natural habitats of animals and plants; it will cause significant migrations, and many species that cannot adapt to new conditions will disappear. In addition, climate change will force farmers to change their production patterns, will create significant changes in planting and sowing dates, and climate changes may cause lower yields in the production of many products, especially wheat, corn, and soybeans, in irrigated and non-irrigated areas. Changes in seasonal and annual rainfall are crucial for storing water resources and regulating the moisture regime in the soil.

Any climate change will change the amount of precipitation, evaporation, surface runoff, and usable water in the soil. Water stress that may occur during flowering, pollination, fruit formation, and grain filling in plants will cause a significant decrease in yield. In addition, due to increasing temperature, evaporation in the soil and transpiration in the plant (evapotranspiration) will increase, which will cause stress in the plant.

This will make it necessary to develop drought-resistant plant species. The potential effects of global warming and climate change began to be felt in the late 20th century and have continued to increase in the 21st century. Türkiye is among the countries at risk in terms of the potential effects of climate change and is expected to be affected by hotter and drier climate conditions in the coming years. This situation indicates that water supply difficulties, especially in agricultural production, will be severe in the coming years. Any disruptions in managing water resources will lead us to use alternative water resources in every field.

Figure 6. Evapotranspiration



3. ALTERNATIVE WATER RESOURCES

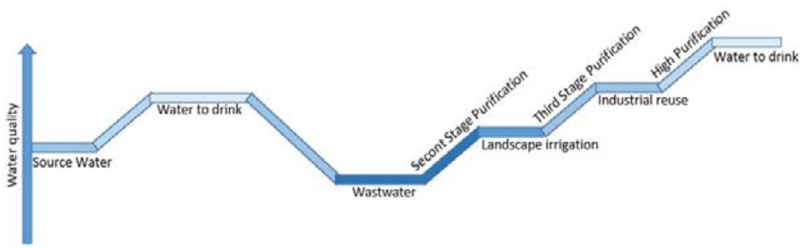
The biggest problem experienced in the 21st century is the inability to meet the water demand of an increasing population with limited water resources. Today, we are in a world where 2 billion people drink polluted water, 700 million people suffer from water scarcity, and almost half the world's population will experience water stress by 2050 (Anonymous, 2024a). For this reason, we have to use clean water resources economically. The most important measure for this situation is to increase awareness of pressurized irrigation methods that save water, primarily in the agricultural sector, where water is used the most. In addition, studies on the use of treated wastewater, rainwater, drainage and seawater, and gray water, which are called alternative water sources, in agricultural areas should be expanded.

Water consumed by different sectors (urban, agricultural, industrial, etc.) is discharged into receiving environments (lakes, rivers, seas, etc.) with or without treatment in treatment facilities. As seen in Figure 7, water quality and usage areas are summarized according to purification levels. Accordingly, for surface and groundwater to be used as drinking water, water quality must be improved (purified), or better quality surface or groundwater must be used. After the water consumed as drinking/usable water turns into wastewater, it is brought to suitable water quality for different reuse alternatives with the second, third, or advanced purification stages.

The decrease in the quality and quantity of water, which we consider an inexhaustible resource, will cause severe problems in the supply of water resources. This situation has brought alternative water resources to the agenda instead of using clean water resources in many areas. One of these alternatives is the use of treated wastewater. The reuse rate of treated wastewater is 5% in 2023, which is expected to increase to 15% by 2030 (Anonymous, 2024b).

Reusing wastewater after treatment has an important place in terms of water sustainability both nationally and internationally. It has more application areas, especially in arid regions where water scarcity is experienced. (Demirer, 2011; Koyuncu and İmer, 2016; Zaibel et al., 2016). The treatment processes required for the reuse of wastewater (Figure 7) vary depending on the characteristics of the wastewater and the purpose for which it will be used after treatment (Erdoğan et al., 2009).

Figure 7. Phases of Using and Purifying Water



Treated wastewater is used intensively in the irrigation of parks, gardens, landscape areas, and sports fields; in cooling and washing in the industrial sector; in the irrigation of green areas on the roadsides; in decorative structures such as ornamental pools and waterfalls; and in processes such as fire extinguishing. Using treated wastewater as an alternative to clean water sources means both water needs are met and clean water resources are saved (Kitis et al., 2009; Özbay and Kavakli, 2008).

Agricultural activities are the main culprit in the consumption of water resources in Türkiye, as in the rest of the world. Therefore, to protect the decreasing water resources today, the reuse of treated wastewater in agricultural irrigation has gained importance (Perez et al., 2015; Aşik and Özsoy, 2016). The most crucial issue to be considered in the use of wastewater for irrigation purposes is the health aspect. Diseases and high mortality rates due to lack of hygiene are seen in developing countries. Therefore, care should be taken to ensure that water quality values are within the permitted limits in the use of wastewater for agricultural purposes.

In Türkiye, the suitability of treated wastewater as irrigation water should first be evaluated within the limits specified in the "Communiqué on Technical Procedures for the Implementation of the Water Pollution Control Regulation (1991). As a result of this evaluation, if the necessary criteria are met, wastewater as irrigation water is encouraged. By using wastewater in irrigation, an alternative water source will be created in dry seasons, the pollution level of surface waters will be reduced, and the use of artificial fertilizers will be minimized by meeting the organic matter needs of the soil. In addition, urban wastewater will be removed economically without harming the environment, and the pressure on water resources, which tend to be consumed, will be reduced by recycling a resource that will be wasted (Yurtseven et al., 2010; Belhaj et al., 2016).

Another alternative water source is domestic wastewater. Pathogenic microorganisms, indicators, and coliform concentration are the most critical factors in using domestic wastewater as irrigation water. Table 1 shows the treatment technologies applied to domestic wastewater and the pollutants it removes. Depending on the development of treatment technologies, ensuring the healthy reuse of wastewater is closely related to the quality of treated wastewater. Criteria must be considered when reusing wastewater in agricultural irrigation. These are the accumulation of heavy materials that may occur in the plant where the irrigation is made, the risk of bacteria and microorganisms still living, and the accumulation of chemical substances. Since there are risks in the irrigation of landscape areas, such as the public entering this area and the accumulation of trace elements, these risks should be considered and used. In case of reuse, these risks must be taken into account.

Table 1. Treatment Technologies Applied to Domestic Wastewater and the Pollutants They Remove

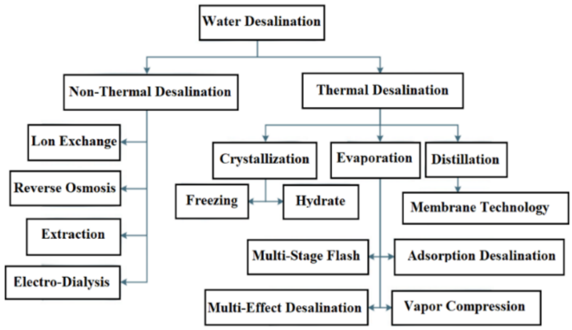
Purification	Suspended Solid Matter	Colloidal Substances	Particulate Organic Matter	Dissolved Organic Matter	Nitrogen	Phosphorus	Trace Substances	Total dissolved Matter	Bacterium	Protozoa	Virus
Secont Stage Purification	X			X							
Nutrient Removal				X	X	X					
Filtration	X								X	X	
Surface filtration	X		X						X	X	
Microfiltration	X	X	X						X	X	
Ultrafiltration	X	X	X						X	X	X
Flotation	X	X	X							X	X
Nanofiltration			X	X			X	X	X	X	X
Reverse Osmosis				X	X	X	X	X	X	X	X
Electrodialysis		X						X			
Carbon Adsorption				X			X				
Ion Exchange					X		X	X			
Advanced Oxidation				X			X		X	X	X
Disinfection				X					X	X	X

Source: (Anonymous, 2010)

Another source we can use today as an alternative water source is the water obtained from rainwater harvesting. Especially in buildings with large roof areas, collecting rainwater, putting it through simple purification processes, and offering it for use are some of the precautions that can be taken to protect clean water resources (Alpaslan et al., 2008). Half of the precipitation that falls on the surface generally evaporates, while the other half feeds groundwater or rivers. This precipitation can cause floods and inundations and increase the water pollution risk. Studies show that using rainwater for domestic purposes can reduce these risks by 30% (Öztürk et al., 2015). The provisions of the European Union carry out the use of rainwater in European Countries Directive 76/160/EEC. If rainwater is not to be used as drinking water, it is sufficient to comply with this regulation. Rainwater can be used for many purposes, such as landscape irrigation or car washing. One of the prerequisites for good rainwater quality is that the tanks in which the water is collected comply with technical standards. Any error in the design or structure of the tanks will cause the water to have a specific odor and reduce water quality.

Today, it is seen that drinking and utility water is produced from sea water in countries with water shortages and in arid regions. The increase in population, industrialization, climate change, drought, and differences in precipitation regimes will make the groundwater saline. This situation will cause the water demand in city centers to increase and the existing water resources to be insufficient to meet the demand. The intense salt and chemical substances in seawater significantly reduce the usability of seawater in living areas. However, it is possible to use seawater on condition that it undergoes various analyses and controls (Figure 8). Sea water can be used directly in the industry, hotels, and homes for sinks, toilets, and car washing without any processing, and thus, 30% of the daily utility water can be met from seawater (Baran, 2017)

Figure 8. Categories of Desalination Processes



Source: (Mohammed et al., 2019)

Removing salt from seawater is a very costly process. However, installing these facilities becomes mandatory in regions where water scarcity is high and water fees are high. The sea is the wealthiest water source. In order to benefit from this source at the highest capacity, all freshwater production methods should be used. Creating solar energy facilities will reduce high costs, and water saving in drinking and utility water will be encouraged.

Gray water is another water source that we call wastewater and can be used as an alternative water source. This wastewater produced from homes is called black water and gray water. While wastewater produced from toilets is called black water, fresh water contaminated for use in bathrooms, laundry, sinks, and dishwashers is known as grey water (Eriksson et al., 2002).

The amount of grey water produced in homes varies depending on lifestyle but is generally between 50% and 80% of total water consumption (Al-Geethi et al., 2018). Among the pollutants in grey water are oil, food waste, and surfactants from personal and cleaning products. However, it contains lower amounts of suspended solids (pathogens and nitrogen) than black water (Gross et al., 2015). Since the quality of grey water is poorer than that of drinking water but higher than that of sewage water, it is easier to recycle and treat (Khanam et al., 2022). Due to this feature, the reuse of grey water is essential in domestic water saving. Grey water is preferred in many areas worldwide (landscape and garden irrigation, toilet cleaning, and other non-potable uses).

The use of grey water can be done directly or through purification. Grey water can be used directly in landscape or garden irrigation. Grey water can be purified with physical, chemical, and biological purification technologies and reused by reaching the desired standards. Grey water use will contribute to the water balance in nature and help protect natural resources. Purifying and reusing grey water will significantly reduce water consumption, especially in the agricultural sector, where water is consumed the most. This will also provide economic benefits and support sustainable development.

4. CONCLUSION

Water is the most fundamental element of all living things. Despite being a cycle and renewable, the changing and developing world population, industrialization, unconscious use of water resources, and climate change increase the demand for water resources and negatively affect existing water resources. For this reason, the use of water resources considered alternatives is increasing today. Especially countries experiencing water scarcity have no choice but to use alternative water resources. The most significant savings that can be made to water resources are the purification of wastewater, collection of rainwater, and reuse of domestic wastewater called gray water. Such waters should be increasingly widespread, especially in the agricultural sector, where daily water consumption is the highest. When using such water, the source of the water and the place where it will be used should be considered. However, when the necessary purification processes are carried out and the desired standards are reached, the use of these waters should be ensured. In order to protect and ensure the sustainability of water resources, not only the use of alternative water resources but also the conscious use of clean water resources, their importance for other living things, difficulties in their supply, pollution, and purification, and the costs of these should be raised, and water literacy should be increased.

The pressure on water resources, which are important to countries' sustainability, is increasing daily. However, technological developments require a balance between economic, ecological, and sociological goals in wastewater management. Therefore, wastewater management will provide this balance and the appropriate infrastructure with the developing technology for water sustainability.

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PHYTOREMEDIATION AND PLANTS USED IN WASTEWATER POLLUTION

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Aydın ADILOĞLU[2]

1. INTRODUCTION

Water scarcity is increasingly becoming a critical issue due to global population growth and climate change, leading to global warming. A significant portion of global water consumption is used for agricultural irrigation. As freshwater resources continue to decline, alternative solutions such as wastewater reuse for irrigation are gaining attention. Phytoremediation is an innovative and environmentally friendly approach that has gained importance in recent years for treating and reusing wastewater. This natural technique is both easy to apply and more cheaper for removing pollutants from wastewater. During phytoremediation, contaminants are transported from the roots to the upper parts of the plant. The primary mechanisms for contaminant removal include storage and/or evaporation within the plant. Phytoremediation can effectively eliminate various organic and inorganic pollutants, such as pesticides, pharmaceuticals, heavy metals, metalloids, and radionuclides. Several plant families known as hyperaccumulators are

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particularly effective for this purpose, including Brassicaceae, Asteraceae, Lamiaceae, Fabaceae, Poaceae, Araceae, Euphorbiaceae, Violaceae, Polygonaceae, and Salvinaceae. Approximately 400 hyperaccumulator species have been identified that can absorb pollutants exceeding 0.2% of their plant weight.

The harmonious existence of soil, air, water, and living organisms within ecosystems is crucial for the continuous and healthy functioning of metabolic processes. Various chemicals can disrupt human metabolic functions and health in both natural and artificial ecosystems. Environmental degradation through chemical pollution threatens the survival of living organisms. Soil, water, and air interact in complex ways within the biosphere, maintaining ecological balance under normal conditions. Therefore, pollution in one environment can spread to others, leading to broader contamination. Pollution often results from the gradual accumulation of these harmful substances over time (Adiloğlu and Gürgan, 2020).

Advancements in technology directly impact agricultural practices, leading to the extreme use of chemical fertilizers, hormones, soil amendments, and pesticides, as well as the irrigation of crops with sludge and wastewater. Additionally, rapid population growth, unplanned urbanization, land misuse, hazardous waste generation, and the decline of green spaces and forests contribute to significant environmental challenges. The unregulated production and consumption of energy sources, industrialization, and heavy metal pollution from industries, factories, and mining exacerbate these issues. Consequently, environmental pollution can be viewed as a negative consequence of modern life. Various remediation methods exist, with phytoremediation standing out due to its practicality and cost-effectiveness (Adiloğlu, 2018).

The availability of alternative hyperaccumulator plants enhances the application of phytoremediation techniques. For these methods to be effective in removing pollutants, the roots, leaves, and stems of the plants should be incinerated, repurposed as animal feed if feasible, or stored properly after the phytoremediation process (Çarşambalı, 2019). This study evaluates the effectiveness of phytoremediation in treating wastewater.

2. PHYTOREMEDIATION

Phytoremediation, also known as green remediation, is a more straightforward method to implement compared to physicochemical techniques. Its advantages include cost-effectiveness in both the initial setup and ongoing remediation, along with its ability to efficiently address both organic and inorganic pollutants. This system is applicable in both natural and artificial conditions, and the size or distribution of the polluted area does not pose a disadvantage. As a result, using plants for remediation emerges as a cost-effective alternative to other methods (Sadowsky, 1999; Adiloğlu and Yinanç, 2017).

One of the key benefits of phytoremediation is its low cost. A study estimated the costs associated with remediating a 0.4-hectare area contaminated with lead over 30 years as follows: $12,000,000 for land scraping, $6,300,000 for soil washing, $600,000 for soil covering, and only $200,000 for phytoremediation (Cunningham, 1996).

Pollutants can adhere to plant roots through abiotic and biotic processes, or be taken up directly by the roots. During these processes, pollutants can enter the plants and be transferred throughout. A crucial aspect of this method is the immobilization of the pollutant on or within the plant. These contaminants can later be retrieved from the plants. This remediation process through plant roots can be applied to surface water, groundwater, or wastewater (Abdullahi, 2015).

Remediation systems that utilize aquatic plants include stabilization pools, lagoons, and artificial wetlands. The effectiveness of pool systems is influenced by microorganisms and lower plants, such as algae. In contrast, the remediation performance of wetlands is impacted not only by microorganisms but also by the presence of rooted plants (Yinanç and Adiloğlu, 2017).

3. HYPERACCUMULATORS FOR WATER PURIFICATION

Hyperaccumulator plants are using for phytoremediation to clean polluted soils and waters has increased significantly, lately. However, the drawbacks of this method are often due to the low biomass production of the plants used and their challenges in adapting to various environments. To address these issues, it is essential to have a thorough understanding of the metal accumulation mechanisms in these plants (Adiloğlu and Göker, 2021; Adiloğlu and Pamay, 2021). Notably, plants from the Fabaceae and Araceae families stand out among the hyperaccumulator species utilized for wastewater remediation.

3.1.Fabaceae Family

The Fabaceae family, commonly known as the legume family, is a diverse group that includes not only herbaceous plants but also trees and shrubs. The name "Fabaceae" is derived from the genus Faba, which belongs to the Vicia genus. An older name, Leguminosae, is still widely accepted. According to the Royal Botanical Gardens, Fabaceae is the third largest flowering plant family, encompassing 730 genera and over 19,400 species, following Orchidaceae and Asteraceae. The largest genera include Astragalus, which contains more than 2,000 species, Robinia with over 900 species, and Indigofera with nearly 700 species. Other notable genera include Crotalaria and Mimosa, which have 600 and 500 species, respectively. The Vigna genus, also part of the Fabaceae family, features many traditional uses (Nofel, 2016).

Hydroponic experiments were conducted to examine the effects of various arsenic (As) concentrations on the seedlings of Pongamia pinnata L. The results indicated that P. pinnata can tolerate arsenic concentrations ranging from 0.2 to 1.0 mM without significant reductions in growth or chlorophyll content. However, these parameters did decline when exposed to 1.5 mM As. During exposure to arsenic levels of 0.2-1.5 mM, the roots accumulated between 1,129 and 3,322 mg kg^{-1} dry weight, while the sprouts accumulated 345 to 3,662 mg kg^{-1} dry weight. Moreover, bioaccumulation and translocation factors greater than 1 obtained that this plant possesses a high capacity for arsenic accumulation. A visual representation of Pongamia pinnata L. can be seen in Figure 1.

Figure.1. Pongamia pinnata L.

Source: (Anonim, 2021)

Abid et al. (2019) investigated the growth and development of *Pongamia pinnata* L. in wastewater from a local tannery, using concentrations of 20 and 40 mL L^{-1}. The physicochemical analysis of the wastewater revealed elevated metal concentrations, particularly significantly high levels of chromium (Cr). While root length, dry sprout biomass, leaf area, and chlorophyll and carotenoid contents of P. *pinnata* were significantly reduced, sprout length, dry root weight, and collar radius remained unaffected. The roots of *P. pinnata* uptaken 6 and 11 times more Cr than the control conditions at the 20 and 40 mL L^{-1} concentrations, respectively. This study highlighted the phytoremediation potential of *P. pinnata*, suggesting its use for reducing metal contamination in wastewater, enabling it to be reconsidered for irrigation purposes.

Prosopis juliflora, a member of the Fabaceae family, is another plant capable of accumulating high levels of heavy metals in its sprouts. Reports indicate its ability to accumulate Cr (VI), lead (Pb), and other metals. Furthermore, studies utilizing X-ray emitting spectroscopy have shown that it can convert Cr (VI) into a less toxic Cr (III) form. Due to high heavy metal uptake capacity, P. juliflora is recommended as a green solution for soils polluted with cadmium (Cd), chromium (Cr), and copper (Cu). The effectiveness of P. juliflora extracts has also been reported for remediating harmful elements and compounds such as chloride (Cl), Cr (VI), sulfate (SO_4), and nitrate (NO_3) in tannery wastewater. Under natural conditions, P. juliflora is known to accumulate substantial amounts of metals (Keeran et al., 2019). A visual representation of *Prosopis juliflora* can be shown in Figure 2.

Figure 2. Prosopis juliflora

Source: (Gallaher & Merlin, 2010)

3.2.Araceae Family

Pistia stratiotes L. was utilized in a study to assess its ability to accumulate copper (Cu), iron (Fe), and mercury (Hg) from water bodies. Concentrations of 5, 10, and 15 mg L^{-1} were tested for each metal. The results indicated that the highest accumulation occurred with the 5 mg L^{-1} applications, showing percentages of 53.20% for Cu^{2+}, 83.20% for Fe^{3+}, and 62.14% for Hg^{2+}. Additionally, the highest levels of plant biomass, chlorophyll content, develpoment rate, and root length were observed at the 5 mg L^{-1} concentration.

This research demonstrated that P. stratiotes is an effective bioaccumulator at this concentration and possesses the capacity for remediation of Cu^{2+}, Fe^{3+}, and Hg^{2+} heavy metals. It is suggested that this plant could assist in the remediation of synthetic and industrial wastewaters (Kumar et al., 2019).

A visual representation of Pistia stratiotes can be seen in Figure 3.

Figure 3. Pistia stratiotes L.

Source: (Howard, 2020)

Duckweed (Lemna minor) is a freshwater plant frequently found in lakes, rivers, and other aquatic environments. Its small biomass, no complex structure, rapid development rate, short life cycle, and sensitivity to environmental pollutants make it an excellent candidate for ecotoxicology research. Lemna minor has been utilized to accumulate and remediate heavy metals such as cadmium (Cd), copper (Cu), zinc (Zn), nickel (Ni), and cobalt (Co) (Lu et al., 2018). A visual representation of Lemna minor can be seen in Figure 4.

Figure 4. Lemna minor

Source: (Armstrongs, 2015)

A study involving Lemna minor, a member of the Araceae family, investigated boron accumulation under salt stress, using 2 mg L^{-1} boron and sodium chloride (NaCl) amounts ranging from 0 to 200 mM. The findings indicated that the boron accumulation capacity initially decreased with increasing salt concentration but then increased again. This plant was identified as suitable for boron accumulation at a salt concentration of 100 mM (Liu et al., 2018).

In a separate research, Daud et al. (2018) examined the phytoextraction of zinc, copper, lead, iron, and nickel from leakage water in regular storage areas, sampling every three days over two weeks. They calculated the bioconcentration factor and remediation efficiency, finding that Lemna minor significantly reduced heavy metal concentrations in the leakage water. The highest remediation efficiency for L. minor was detected for copper, exceeding 70%, with a maximum of 91%. The bioconcentration factor (BCF) values were below 1 at most, indicating that this plant is a middle accumulator for these metals. L. minor has emerged as a sustainable candidate for the remediation of leakage water in regular storage areas.

Amare et al. (2018) studied the simultaneous uptake of eight heavy metals by two aquatic macrophytes (Lemna minor and Azolla filiculoides) in semi-arid regions of Ethiopia. Both plants accumulated various concentrations of heavy metals within a significant range. Manganese (Mn) and iron (Fe) exhibited the highest bioconcentration factors for both species. The results revealed that L. minor had a high bioconcentration factor for Fe, Mn, zinc (Zn), and cobalt (Co), while exhibiting moderate accumulation for cadmium (Cd), copper (Cu), nickel (Ni), and chromium (Cr). Conversely, A. filiculoides demonstrated high accumulation for Fe, Mn, Zn, and Cu, moderate performance for Co, Cr, and Ni, and lower performance for Cd. Both species showed significant differences in terms of Co, Zn, and Mn (p <

0.05). Strong correlations were noted between heavy metal amounts in A. filiculoides tissues and in the surrounding water. A visual representation of Azolla filiculoides can be seen in Figure 5.

Figure 5. Azolla filiculoides

Source: (Vanderhoff, 2011)

Rana and Maiti (2018) assessed the heavy metal remediation potential of Colocasia esculenta L. Schott, specifically for municipal wastewater treatment. Their study found that heavy metals such as copper, cadmium, cobalt, lead, and nickel uptaken primarily in the root tissues, while manganese and zinc were predominantly found in the sprout tissues. Colocasia esculenta L. Schott demonstrated effectiveness in stabilizing Cu, Cd, Co, Pb, and Ni, with a bioconcentration factor (BCF) greater than 1 and a translocation factor (TF) less than 1. Additionally, it was shown to be suitable for treating municipal wastewaters containing manganese and zinc. A visual representation of Colocasia esculenta L. Schott can be seen in Figure 6.

Figure 6. Colocasia esculenta L. Schott

Source: (Krishnapriya and Suganthi, 2017)

Epipremnum aureum Engl., a member of the Araceae family, was evaluated for its phytoremediation potential regarding zinc (Zn), which can be toxic to plants at high concentrations. Various concentrations of $ZnCl_2$ were applied to the selected plants, as Zn is known to inhibit plant growth and development at elevated levels. The study found that concentrations of 10, 20, and 30 ppm $ZnCl_2$ led to chlorophyll degradation, a decrease in leaf area, and growth inhibition of both leaves and shoots. Since the roots did not show significant signs of Zn toxicity, it was suggested that the plant transfers Zn to its above-ground parts, accumulating it in the shoots and leaves. Therefore, Epipremnum aureum Engl. was recommended for use in the phytoremediation of Zn contamination (Abbas et al., 2019). A visual representation of Epipremnum aureum Engl. can be seen in Figure 7.

Figure 7. Epipremnum aureum Engl

Source: (Flora Fauna Web, 2019)

4. CONCLUSION

The continuous evolution of technology significantly impacts agricultural practices. Various applications, including chemical fertilizers, hormones, soil amendments, and pesticides, are widely used, along with the application of sludge and wastewater for irrigation. In addition to these agricultural practices, heavy metal contamination from factories and mining activities directly or indirectly pollutes water sources.

Phytoremediation emerges as a primary method for addressing water pollution. However, there is a need for expanded research on hyperaccumulator plants suitable for this approach, particularly those effective in water remediation. It is essential to prioritize studies that create an inventory of plants suited to specific regions and climates, as water sources are increasingly threatened by environmental pollution. Consequently, focusing on hyperaccumulator plants in relation to heavy metal pollutants is crucial for mitigating water pollution and enabling the reuse of wastewater after remediation.

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TARIMSAL YAPILAR VE SULAMA

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yayınları

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