Chapter

Promising Water Management Strategies for Arid and Semiarid Environments

Adel Zeggaf Tahiri, G. Carmi and M. Ünlü

Abstract

Water is the most limiting factor for crop production in arid and semiarid areas. The search of promising water management strategies is foremost for achieving highly productive and sustainable agriculture. Irrigation water management, water conservation, and nonconventional water use for agriculture are key issues to be considered by the National Agricultural Research Systems (NARS) in these areas. According to climate change scenarios and population growth predictions, these countries will undergo even severe water scarcity levels. Failure of resolving food production challenge will exacerbate tensions between countries, wars, and illegal immigration and compromise human, social, economic, and sustainable development in these areas. However, the search for innovative solutions to water scarcity must comply with societal values, environmental sustainability, and market growth.

Keywords: aridity, water management, irrigation water management, water conservation, nonconventional water use, crop production, sustainability, environment

1. Introduction

Most of the Earth's water resources comprise of saline water (97.5%) covering 70% of the Earth's surface. Only 1.2% of the remaining 2.5%, which is called freshwater, is surface water and other freshwater, and it is this water which can be used for all living organisms. Therefore, renewable freshwater resources are finite and unequally distributed geographically [1]. On the other hand, the world population is growing at a rate of ~73 million per year [2], while the freshwater withdrawal, which has already tripled since 1965, is increasing at a rate of 64 km^3 $year^{-1}$ [3]. Moreover, aridity is a major economic, social, and environmental concern to the international community. It is seriously constraining the global food security, ecosecurity, socioeconomic stability, as well as sustainable development.

These will be undoubtedly the major challenges for humanity in the twenty-first century and beyond. While aridity is a natural phenomenon, humans also impact indirectly water through land use change and alterations in climate through fossil fuel combustion [4]. The desiccation of the Aral Sea which started back to the period of the Soviet Union is one of the documented examples. Severe and widespread ecological, economic, and social consequences that are progressively worsening have resulted from the Aral's recession [5].

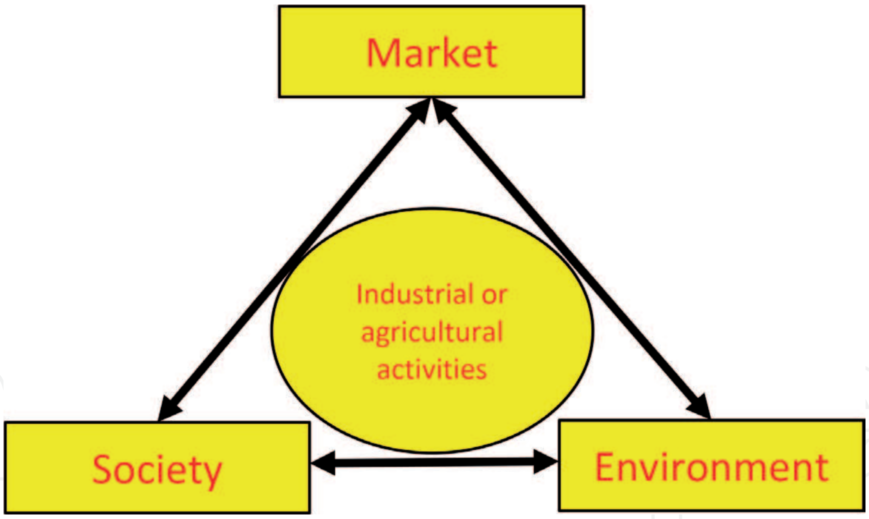

Figure 1.
A sustainable framework for industrial and agricultural activities.

To our understanding, a production model prioritizing only economic indicators such as market shares and huge benefits is one human action that exacerbates aridity, which has to be thoroughly considered. Such models could be profitable at short and medium terms but turn to the opposite at the long term since resources are undermined. In agriculture, they imply an intensive use of input resources: water, land, and plant material. This process causes water pollution, aquifer depletion, land salinization, forest clearance, etc. which leads ultimately to the habitat degradation of the Earth.

Instead, we propose the following framework as basis for any human activity (**Figure 1**). Only businesses following this pyramidal network will comply with societal values, environmental sustainability, and market growth.

In the following, promising strategies will be discussed which aim to a better resource management and hence sustainable development with the objective to reduce the negative impact of aridity on humanity future.

2. Irrigation management

Globally, water withdrawal for agriculture is estimated to 70%, 11% for domestic, and 19% for industrial uses [3]. Although there is a slight variation among North and South Mediterranean countries (**Figure 2**), depending on whether a country is heavily industrialized or not, the agricultural sector remains the largest water user for the majority. Globally, the production of irrigated crops is a predominant water "consumer" given that ~70% (~3 trillion m^3) of totally abstracted fresh hydro-resources is exploited by the agricultural sector [7]. It is obvious that any economy on agricultural water will benefit largely to other sectors.

At a global scale, agricultural water losses are enormous (**Figure 3**) reaching 55% of available irrigation water. They are caused by irrigation system, farm distribution, and field water application mismanagement. Only 45% of irrigation water is effectively used by crops. There is an urgent need to address these deficiencies and to improve water use efficiency at crop field level.

Studies showed that localized irrigation of crops is better than continuous irrigation [8, 9]. A comparison between frequent and moderate irrigation regimes for maize crop was carried by [9]. **Figure 4** shows a summary of the typical patterns of energy balances over maize field, soil surface, and maize canopy by the double layer Bowen ratio energy balance (DOLBOREB) system during both water regimes. Globally, no major differences were observed for energy balance patterns between

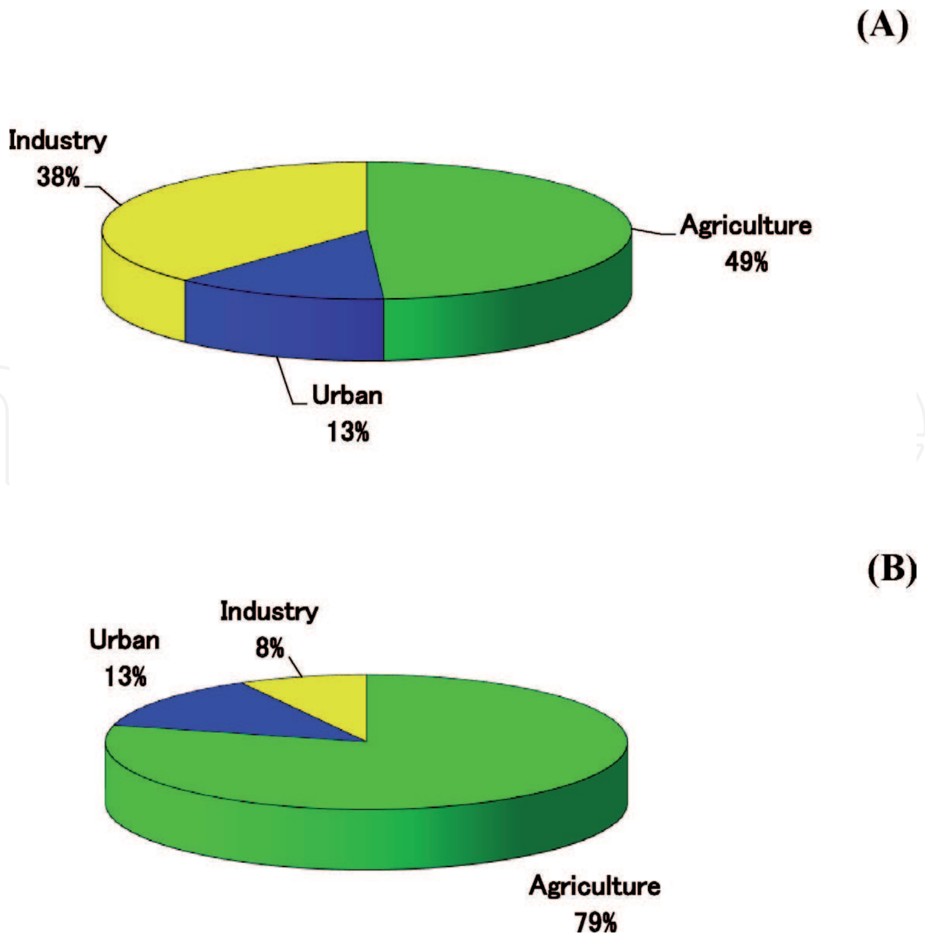

Figure 2.
Water sector allocation for North Mediterranean (A) and South Mediterranean countries (B) [6].

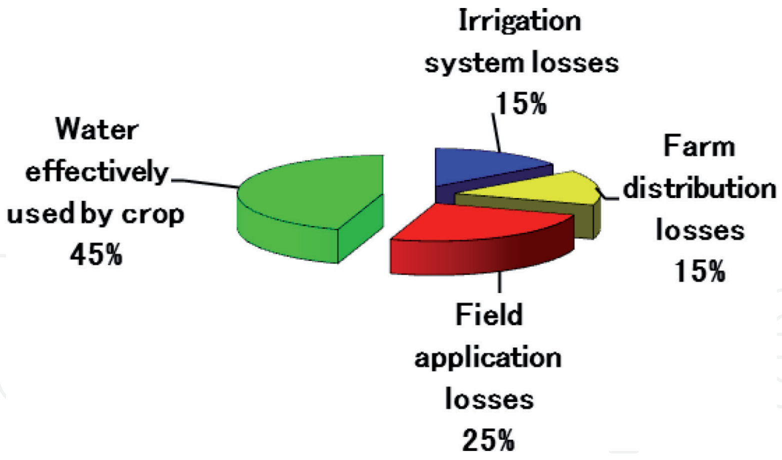

Figure 3.
Water usage by crop and losses in irrigation system [6].

the two water regimes since evapotranspiration at maize field level remained high during both regimes. In fact, maize field energy balance measurements alone provide virtually no information on how soil surface and canopy energy balances are partitioned. This shows clearly the limitations of considering crop field evapotranspiration as a whole, especially when addressing such important issues as would be water use efficiency improvement in arid areas. A number of factors have contributed to this situation. The high cost of the equipment involved in such experiments and the inherent errors associated with the use of different measurement devices and measurement scales tremendously hinted the large-scale adoption of such techniques either by research scientists and/or by irrigation practitioners

[9]. The DOLBOREB system indicated that soil had a major impact on maize canopy energy balance. It also showed that a frequent irrigation regime is not necessarily a synonym of maximum plant transpiration (**Figure 4**). Ham et al. [8] also concluded that a wet soil appears to reduce crop transpiration (λE_c) by acting as a sink for advective energy while reducing the radiation load on the canopy.

Future studies for other crops and under different climatic conditions are needed to improve our knowledge of water relations at crop field level. Examining the effect of factors such canopy size, crop type, plant water stress, etc. on soil surface and canopy energy balances is of considerable importance. Energy flux data generated by the DOLBOREB system would be useful for building evapotranspiration and crop growth models. This irrigation management system would save about 30–35% of the water used at crop field level [10].

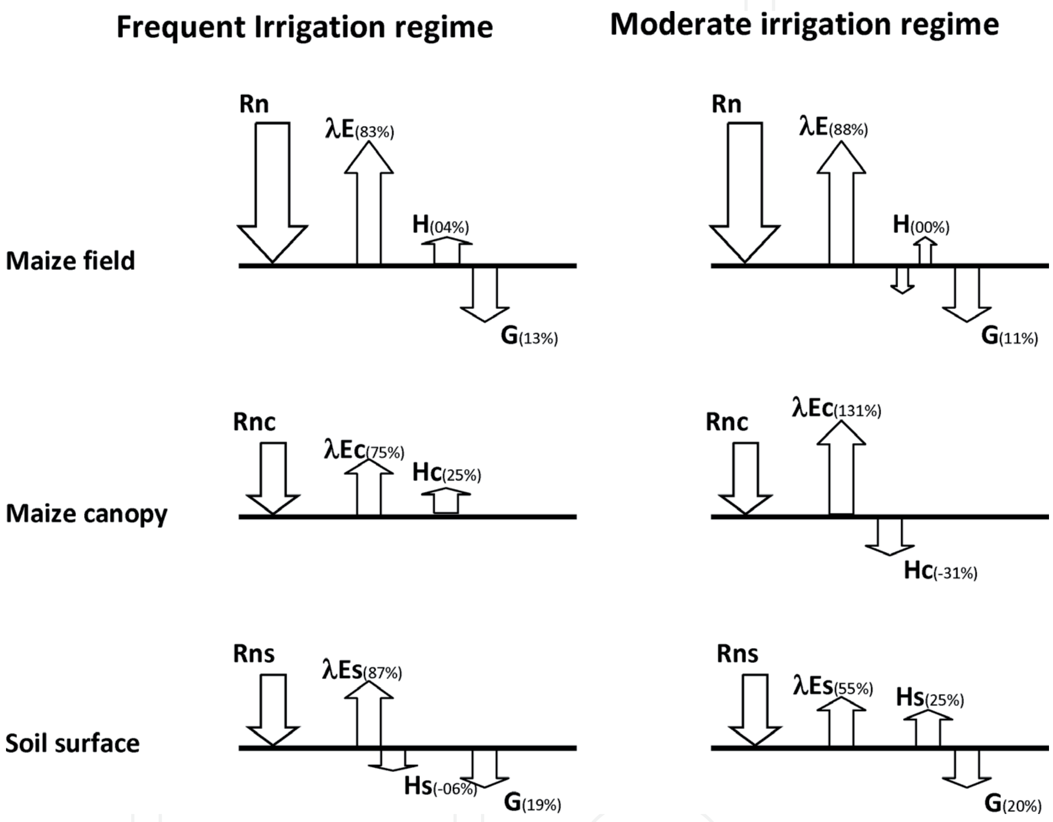

Figure 4.
A summary of the typical patterns of energy balances over maize field, soil surface, and maize canopy by the DOLBOREB system during frequent and moderate irrigation regimes.

With (R_n) net radiation; (λE) latent heat flux, (H) sensible heat flux, and (G) soil heat flux at maize field level. (R_{ns}) net radiation reaching the soil surface; (λE_s) soil surface latent heat flux, and (H_s) sensible heat flux from the soil surface. (R_{nc}) net radiation absorbed by the canopy; (λE_c) latent heat flux, and (H_c) sensible heat flux from the maize canopy.

3. Water conservation

Dryland regions occupy about 41% of the Earth's terrestrial surface and are home to more than a third of the world's population (e.g., [11]). Water is a primary limiting factor to agricultural development in these regions where the local population is suffering from food shortage. Runoff generated as a result of rainfall occurrence infiltrates to the shallow soil depth and is mostly being lost to after-rain evaporation, and the rest of the runoff is lost by strong flows to seas. Intensive agricultural practices and civil project development result in large impermeable areas, soil compaction, and crust generation that cause more runoff to be lost. Increasing runoff velocities lead to intensive erosion processes and land degradation and eventually make the region more arid. Over 17.5% of the global land area is exposed to wind and/or water erosion processes [12].

More efficient management of runoff known as runoff harvesting or runoff farming may be used for food and energy production, flood and erosion control, and landscape development [13–15]. In terms of combating desertification and land degradation, water harvesting appears to be a viable solution [13]. Runoff farming allows agricultural activity in areas that normally do not receive enough rainfall [16, 17]. This is achieved by concentrating rainfall from a collecting area (catchment) into a smaller and lower lying receiving area, where the water is stored in the soil profile, allowing its cultivation.

Hydrological aspects of these systems, especially with respect to runoff generation, have been reviewed [14, 18].

However, the use of the collected water for agricultural purposes and preventing land degradation has received little attention. The salient feature of this technique is that large amounts of water are collected a few times during the short rainy season. The collected water is ponded in walled fields and percolates to considerable depths. During the dry season, no water is added. These conditions affect plant production. To use stored water as efficiently as possible, soil evaporation and deep percolation should be minimized, and transpiration regulated to allow plants to produce biomass throughout the dry season [19].

Evaporation can be controlled by increasing tree density or mulching the soil, thus reducing the radiation that reaches the soil surface [20]. Alternatively, a similar effect may be achieved by introducing an annual intercrop. Such a crop is likely to consume water from the upper layers, part of which would otherwise evaporate directly from the soil surface. Deep-percolating water can be exploited by plant species with deep-root systems, without necessarily competing with the annual crop. The combined cultivation of shallow rooting annuals and deep-rooting perennials is proposed as a system that uses the stored water efficiently.

There are macro-catchment systems (**Figure 5**) designed to collect runoff from relatively large catchment areas used for water storage in the root zone for a group of trees or plants and micro-catchment systems designed to collect runoff from relatively small catchment areas, used for enhancing soil moisture storage in the crop rooting zone for individual crop planted in a shallow pit or micro-basin [21].

Micro-catchments for water harvesting have been tested in the Negev Desert, Israel, for decades [14]. The idea was to use runoff water for growing trees in such

Figure 5.
Flooded macro-catchment.

Figure 6.
Traditionally designed micro-catchment system: (a) schematic of the system and (b) flooded micro-catchment.

a way that each tree had its own small catchment area, typically less than 100 m, and store it in the root zone of an adjacent infiltration basin where a tree or bush or an annual crop is grown [14, 22–24]. The system can be built on almost any slope, enabling the farmer to use large flat areas [13] that might be a significant advantage for application in the areas where collecting large amounts of runoff is not possible.

The infiltration basin is usually a shallow depression located at the low end in the immediate vicinity of the runoff generating area (**Figure 6**).

Runoff generation at micro-catchments is affected both by the total rain amounts and average rainfall intensity [18], while the relatively absolute amount of water collected at micro-catchments is low anyway. In such circumstances, the central idea behind any micro-catchment design should be enhancing infiltration and reducing evaporation of already collected water and thus improving soil moisture storage in the crop rooting zone through the dry season. The second component of the system is the water conservation efficiency at the collection plots, i.e., in the soil profile and its further availability to trees/shrubs. The deeper the harvested water moves in the soil profile, the less part of it is exposed to evaporation [15].

The size of the runoff production area directly determines the total amount of runoff water that can be stored in the pit together with soil and rainfall characteristics, topography, etc. [25]. Reported sizes of a single plot are 100–250 m^2 in Israel, 250–400 m^2 in India, and 1000 m^2 in Mali [16].

Runoff generation at micro-catchments is also affected by the rainfall characteristics. It was shown that there is a clear relationship between runoff yields and average rainfall intensity and the degree of correlation between them improves with a decrease in the length of the gap between the rainstorms [18].

The rate of water losses by evaporation is mainly affected by radiation, climate, soil texture, soil structure, soil hydraulic properties, etc. [15]. Because of relatively low absolute amount of water collected at micro-catchments, special attention should be paid to the prevention of the stored soil water from evaporation.

Long-term micro-catchment experiments carried out at Mashash runoff harvesting experimental farm of Ben Gurion University of the Negev showed that the change of collection plot design from a flat surface to a deeper and narrower pit makes the system much more effective. Being collected in the pits, water may infiltrate deeper due to repetitive concentration of relative large water amounts at the limited area and the increased waterhead. Most trees planted inside the pits showed the much higher surviving ability comparing with trees planted at the flat plots.

Infiltration and evaporation have a different pattern in the case of water collection in the pits. Soil water infiltrates through the pit bottom and the walls, where also the surface evaporation occurs through. Additionally water is lost to evaporation through the soil surface around the pit.

Deeper pits enable water to be stored in deeper soil layers around the pit, increase the distance between the stored water and soil surface, and therefore conserve more water in soil for further use by plants.

4. Seawater agriculture

The increasing deficiency of freshwater combined with the ever expanding world population will exacerbate water use pressure between the different water user sectors (urban, industrial, and agricultural). Solving this problem will undoubtedly be the twenty-first century challenge and is necessitating that marginal quality waters including saltwater and/or seawater are strategically used to meet the water shortage without any detriment to the environment and natural resources for increasing crop production worldwide.

According to the Food and Agriculture Organization (FAO) of the United Nations [26] and World Resources Institute (WRI) in collaboration with the United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), and World Bank (WB) [27], most of the West Asia and North Africa countries are expected to fall below the water scarcity level (1.000 m^3 $capita^{-1}$ $year^{-1}$) by the year 2030. The most affected countries are Kuwait, United Arab Emirates, Saudi Arabia, Yemen, and Libya where renewable water resources (RWR) per capita will fall well below 100 m^3 $capita^{-1}$ $year^{-1}$ [26–28]. Of course, reverse osmosis factories are blooming in the Middle East and North Africa, producing almost half of the 95 million m^3 day^{-1} of desalinated water for human use worldwide [29], but will not be able to meet not in the present nor in the future the growing agricultural water demand. Undoubtedly, nonconventional water use will contribute to partially alleviate water scarcity in regions where renewable water resources are extremely scarce [28].

Halophytes have demonstrated their capability to thrive under extremely saline conditions and thus are considered as one of the best germplasms for saline agriculture [30]. Few researchers have examined halophytes under special topics as sustainable cultivation, saline agriculture, and integrative anatomy [31–34]. Much practical work remains to be done, as well as developing the basic science of halophytology [35]. Apart from the cultural and sometimes the political constraints related to it, we think that there is still a big deal of scientific and technical knowledge to be studied and discovered for a better development of seawater agriculture in desert areas.

Novel approaches to mangrove planting in desert countries have been published [36, 37]. They prove establishing mangrove trees in salty coastal lands is possible providing an appropriate mineral nutrition, i.e., nitrogen, phosphorus, and iron. Based on this finding, they devised a planting method (**Figure 7**) and used mangrove nurseries. This discovery has permitted plantation of about 1 million mangrove trees, chiefly *Avicennia marina*, in the intertidal zone of the Red Sea coast of Eritrea [36]. However, this assumption has not made the unanimity among the scientific community and is contested by some other scientists [38]. Nevertheless, such forests can provide feedstuffs and serve as nurseries for fish reproduction. These important findings deserve to be considered for future mangrove plantings and/or mangrove restoration projects in Africa's desert countries.

Figure 7.
Forestation of desert area by mangrove transplants.

Figure 8.
Two-year-old mangrove forest (El Gahra, Mauritania).

Also, other projects confirmed that even with low fertilization amounts, some plant species like *Avicennia germinans*, *Nitraria retusa*, and *Sesuvium portulacastrum* can grow in extremely salty areas as well [39]. As a result, tens of thousands of mangrove trees were planted in the Mauritanian side of the Senegal River Delta and Nouakchott seaport [39]. Two years after planting, the mangrove trees reached a height of about 2 m and constitute already a source of forage foodstuff (**Figure 8**).

Thus, certain parts of the Earth's great deserts and other water-stressed areas might be converted to mangrove forests with seawater irrigation, which might be one of the possible and relatively cost-effective approaches to mitigate desertification under global warming.

5. Conclusion

Water is the most limiting factor for crop production in arid and semiarid areas. Appropriate water resource management will undoubtedly enhance crop production and accomplish sustainable development. These objectives could be achieved by adopting the following water management strategies:

- Enhancing agricultural water use efficiency by avoiding water losses at all scales, adopting efficient irrigation scheduling, and using environment adapted crops and varieties, etc.

- Water conservation for better crop production
- The use of nonconventional water resources, i.e., wastewater, brackish water, and seawater along with the corresponding resistant or tolerant species to produce forage and food

Certainly, no single strategy is currently able to thrive by itself in arid environments. Each one is adapted to a physical and social environment, as well as aridity intensity. Sometimes combined water management strategies could improve crop production in water-scarce areas. Nevertheless, in these environments, the search for better water management strategies and water use habits should be a priority for both research institutions and society.

As the world population grows and climate change consequences worsen, water scarcity will intensively affect some regions more than others. North Africa and West Asia countries, among others, will be dramatically affected, as seen above. It is the responsibility of these countries to make the bulk of research in the field for no one undergoes their level of water scarcity. In this review, we showed a set of strategies, in which combination and application greatly improve plantation and water management in arid and/or desert areas. Some strategies are still not widely implemented, and others are under investigation. However, for a particular water management strategy to be successful, it should be economically viable, respectful of social values, and environmentally sustainable. The search of innovative solutions aiming for better integrated water resource management is a big challenge for National Agricultural Research Systems (NARS), the private sector, and the society as a whole.

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