Irrigation in arid and semiarid regions

MedWater

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Abstract

Population increase will result in a sharp increase in food demand during the next decades and poses huge challenges for the crop production and its sustainability. Most of this increase will be met by the products of irrigated agriculture. Due to water scarcity and environmental concerns it will be indispensable to reduce the water input per unit irrigated.

The necessity to reduce the water input per unit irrigated due to water scarcity makes an increase
of **Water Productivity (WP)** essential. Water Productivity (WP) in general means the yield over the amount of total water applied. But there is no common agreement on the use of the term and Water Productivity can be defined in a number of ways. WP always represents the output of a given activity (in economic terms, if possible) divided by some expression of water input.

For example, WP can be defined as a physical ratio between yields and water use or between the value of the product and water use.

Increasing WP is a challenge at three levels:

- Increase crop yield without increasing transpiration (e.g. by Breeding, certain Agronomic practices)
- Reduce losses on field, farm and system level (e.g. by appropriate Irrigation Methods, Irrigation scheduling and irrigation control, and irrigation strategies like Controlled deficit irrigation (CDI))
- Increase economic productivity of water and profit (depends on the relationship between crop yields and applied water and, especially in the case of Drip irrigation, on the Field design)

Besides the increase of WP, there are more **challenges for irrigated agriculture** like:

- Decreasing groundwater tables
- Lower soil moisture levels due to temperature rise projected for climate change
- Salinization

To relate irrigation practices and yield, **Crop Water Production Functions** (CWPF) can be used. This graphics show the relationship between crop yield (on the ordinate) and the supplied irrigation water (on the abscissa) site-specific for one year. The general shape of a CWPF describes a sharp increase at the beginning but the productivity (grain yield) reaches its maximum at a certain amount of applied water and remains at this level or decrease with further increasing water supply. The reduction of the productivity with increasing water supply after the maximum follows from different losses, for example deep percolation, increased evaporation, reduced aeration in the root zone, leaching of nutrients and diseases associated with wet soils.

The goal of Irrigation is to recharge the soil water storage that has been depleted by evapotranspiration when natural precipitation is not sufficient.

Irrigation is defined by so called **irrigation control parameters**:

- timing of irrigation (Irrigation scheduling)
- the duration of irrigation event (Irrigation Control)
- the discharge rate or intensity (Irrigation Control)
- which leads to the amount of applied irrigation water

The setup of these parameters depends amongst others (meteorological conditions) from the soil type and the crop rooting system.

To achieve a sustainable and efficient irrigated crop production these control parameters, the Irrigation Methods and the Field design, means for example the drip line and row spacing, are the key elements.

One aim is to reduce losses of irrigation water, which can be caused by evaporation from the soil surface for example. The irrigation method determines to what extent it is possible to reduce this evaporation while maintaining adequate soil moisture levels.

Irrigation methods (or systems) can be characterized in two main groups:

- non-pressurized irrigation methods: gravity flow for application (Surface irrigation as basin, furrow or border irrigation)
- pressurized irrigation methods: application through a pipe system (Sprinkler irrigation, Drip irrigation, Subsurface drip irrigation (SDI))

To determine the efficiency for irrigation systems the water Application Efficiency (AE) can be used. It is defined as the average amount of irrigation water that contributes to a target (e.g. soil moisture deficit), divided by the average depth of irrigation water applied and is generally highest within drip irrigation. However, the choice of an irrigation method depends on economic factors, crop types and site conditions, as the soil type, slope of the field, the climate and the water quality and availability, as well as the management skills.

Nitrogen is one of the most important nutrient fertilizer. But only 30-50% of nitrogen is recovered in plants, which indicates huge losses by volatilization, leaching, surface runoff, and denitrification. These cause grave environmental pollution, especially of ground and surface water. Since the main sources of loss are surface water runoff and deep percolation, there is a strong link between Water Productivity (WP), Irrigation and Nitrogen Use Efficiency (NUE), so water use and nutrient management decisions should be appropriately combined.

Important tools to support decisions in agricultural management and to optimize irrigation and fertilizing are simulation-based modelling and so called **Soil-Vegetation-Atmosphere-Transport (SVAT)** Models. These models can help to determine the crop demand for irrigation or nitrogen and to put this demand into relationship to the spatial and temporal distribution of irrigation or nitrogen application. Especially in combination with simulation based-modelling, Multi-criteria optimization can help to solve the multidimensional (several goals are pursued) problem that arises from the optimization of Irrigation.

In many areas, as well for the simulation-based modelling as for decision making, problems with multiple, conflicting goals must be solved. This is also the case for the optimization of irrigation. To solve those problems **multi-objective optimization** algorithms are used to find Pareto optimal solutions. A Pareto-Optimum is a state in which it is not possible to improve one (target) property without worsen another at the same time. This means these solutions are the best compromise between all the considered targets. To find those Pareto optimal solutions multi-criteria Optimization is used.

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Introduction

Population increase will result in a sharp increase in food demand during the next decades [Playán and Mateos, 2006] and poses huge challenges for the crop production and its sustainability [Seidel, 2012]. Most of this increase will be met by the products of irrigated agriculture. But due to water scarcity and environmental concerns it will be indispensable to reduce the water input per unit irrigated. [Playán and Mateos, 2006]

This makes an increase of Water Productivity (WP) essential [Seidel, 2012]. According to Kijne et al. [2003] and Seidel [2012], increasing WP is a challenge at three levels:

1. Increase crop yield without increasing transpiration (e.g. by Breeding, certain Agronomic practices)
2. Reduce losses on field, farm and system level (e.g. by appropriate Irrigation Methods, Irrigation scheduling and irrigation control, and irrigation strategies like Controlled deficit irrigation (CDI))
3. Increase economic productivity of water and profit (depends on the relationship between crop yields and applied water and, especially in the case of Drip irrigation, on the Field design)

Besides the increase of WP, there are more challenges for irrigated agriculture like:

- Decreasing groundwater tables
- Lower soil moisture levels due to temperature rise projected for climate change
- Salinization

Nitrogen is one of the most important nutrient fertilizer [Sepaskhah et al., 2006]. But only 30-50% of nitrogen is recovered in plants, which indicates huge losses by volatilization, leaching, surface runoff, and denitrification [Tilman et al., 2002; Fageria and Baligar, 2005]. These cause grave environmental pollution, especially of ground and surface water. Since the main sources of loss are surface water runoff and deep percolation [Seidel, 2012], there is a strong link between Water Productivity (WP), Irrigation and Nitrogen Use Efficiency (NUE), so water use and nutrient management decisions should be appropriately combined.

Important tools to support decisions in agricultural management and to optimize irrigation and fertilizing are simulation-based modelling and so called Soil-Vegetation-Atmosphere-Transport (SVAT) Models. These models can help to determine the crop demand for irrigation or nitrogen and to put this demand into relationship to the spatial and temporal distribution of irrigation or nitrogen application. Especially in combination with simulation based-modelling, Multicriteria Optimization can help to solve the multidimensional (several goals are pursued) problem that arises from the Optimization of Irrigation.

Water Productivity (WP)

Water Productivity (WP) in general means the yield over the amount of total water applied [Seidel, 2012]. But there is no common agreement on the use of the term and Water productivity can be defined in a number of ways. WP always represents the output of a given activity (in economic terms, if possible) divided by some expression of water input. [Playán and Mateos, 2006]

WP can be defined as a physical ratio between yields and water use or between the value of the product and water use [Rodrigues and Pereira, 2009; Zwart and Bastiaanssen, 2004], or it can be expressed in terms of money [Vazifedousta et al., 2008]. The meaning of WP may differ between scales (from crop to fields or whole areas) and depends on the regarded period, considering the total water applied from sowing to harvesting, of one year, and if water application for salt leaching is considered or not [Molden et al., 2003; Vazifedousta et al., 2008].

In the following, six common definitions of WP according to Seidel [2012] are listed:

$$WP = \frac{Y}{P+I} \quad in \left[{}^{kg}/_{m^3}\right]$$

$$WP_{SW} = \frac{Y}{P+I+SW} \quad in \left[{}^{kg}/_{m^3}\right]$$

$$WP_{IRR} = \frac{Y}{I} \quad in \left[{}^{kg}/_{m^3}\right]$$

$$WP_{SW} = \frac{Y}{ET_c} \quad in \left[{}^{kg}/_{m^3}\right]$$

$$WP_{RF} = \frac{Y - Y_{RF}}{P+I} \quad in \left[{}^{kg}/_{m^3}\right]$$

$$WP_{€} = \frac{P_c}{ET_c} \quad in \left[{}^{€}/_{m^3}\right]$$

With Y actual yield (at 15% humidity) in $\left[{}^{t}/_{ha}\right]$

Y_{RF} actual yield (humidity of 15%) of a non-irrigated (rainfed) treatment with similar plant density and row spacing in $\left[{}^{t}/_{ha}\right]$

P effective precipitation in $[mm]$

I amount of applied irrigation water in $[mm]$

SW soil water depletion from the root zone during the growing season due to soil moisture measurements in $[mm]$

ET_c crop evapotranspiration in $[mm]$

P_c price of the marketable yield in $\left[{}^{€}/_{ha}\right]$

While the first equation for WP, which considers irrigation and precipitation is the most common one, it is also possible to ignore precipitation for the Definition of WP (WP_{IRR}), or to additionally include the soil water depletion from the root zone during the growing period (WP_{SW}). Furthermore, WP can be defined using the crop evapotranspiration (WP_{SW}), which relates yield to the actual seasonal crop water consumption. If the total amount of yield is composed of a non-irrigated (rainfed) treatment and an irrigated treatment, this should be considered in the definition of WP (WP_{RF}). $WP_{€}$ can be used to observe economic effects.

The factors influencing WP are among others the crop type, climatic demand, soil characteristics, irrigation system, water management and agronomic practices [Seidel, 2012]. An increase WP results from either achieving more yield per unit of water (Increase Crop Yield), or by converting non-beneficial depletion to beneficial depletion (water savings), or by reallocating to higher-valued uses [Molden et al., 2003]. However, the last point should be seen very critical. For example, one possibility to reallocate to higher-valued uses is using the available water to irrigate higher valued crops. But this can have serious potential consequences: Since a large part of the food demand of the world population is covered by lower valued crops, the trend towards higher valued crops could endanger the ability to feed the human population. [Letey, 2007]

Crop Water Production Functions (CWPF)

To relate irrigation practices and yield, Crop Water Production Functions can be used. This graphics show the relationship between crop yield (on the ordinate) and the supplied irrigation water (on the abscissa) site-specific for one year [Schütze et al., 2011b]. The general shape of a CWPF describes a sharp increase at the beginning but the productivity (grain yield) reaches its maximum at a certain amount of applied water and remains at this level or decrease with further increasing water supply [Zahng, 2003]. The reduction of the productivity with increasing water supply after the maximum follows from different losses, for example deep percolation, increased evaporation, reduced aeration in the root zone, leaching of nutrients and diseases associated with wet soils [Englisch, 1990]. Another type of loss can be due to lodging [Englisch, 1990]. This means the bending over of the stems near ground level of grain crops, which can lead to great losses of yield because it makes them very difficult to harvest.

Revenue Functions

Revenue Functions are similar to Crop Water Production Functions (CWPF), but relate the applied water to gross income, not to yield. However, as the crop yield is proportional to the gross income (by the factor crop price), the general shape of the revenue function is equivalent to the CWPF [Seidel, 2012]. In Other words, the revenue function is the product of the CWPS and the crop price:

$$R(I) = P_c \cdot Y(I) \quad in \left[{}^{€}/_{ha}\right]$$

With $R(I)$ revenue per hectare in $\left[{}^{€}/_{ha}\right]$

$Y(I)$ crop yield per unit land, expressed as a function of applied irrigation water in $\left[{}^{t}/_{ha}\right]$

I depth of irrigation water applied per unit land in $[mm]$

P_c price per unit weight paid for the crop in $\left[{}^{€}/_{t}\right]$

Often the revenue function is complemented by a cost function, which represents fixed and operating costs. The profit can be obtained by subtracting costs from revenue and is represented in the graphical display of the revenue and cost functions as the vertical differences between these two functions. [Seidel, 2012]

Figure 1 shows an example for a revenue and a cost function in one plot. The costs are represented by a straight line (straight cost function). Where the revenue function shows the inflection point, no further increase of yield can be reached by an additional application of water. This Point is the yield maximizing amount of water applied (W_m). At the point W_l, the maximal return is reached, which means the profit per unit land is maximized (land limited case). But there is a point W_{el}, where the net income per unit land equals the net income from full irrigation, if the applied water will be reduced below W_l. Equivalent to the point W_{el}, the point W_{ew} is the applied amount of water where the net income equals the income at full irrigation, when water is limited. According to Seidel [2012] deficit irrigation will be more profitable than full irrigation within the range between W_m and W_{el}, or W_{ew}. But an essential problem of controlled deficit irrigation are the highly variable and unpredictable CWPFs and hence the revenue functions [English 1990]. The cause lies on one hand in the variability of weather, soils, initial soil moisture and distribution uniformity, which make the soil water in the root zone difficult to predict. On the other hand, the responses of the crop to weather and diseases are very variable and thus the yield water relations are not easy to determine. These uncertainties cause an economic risk, which can be minimized through proper irrigation scheduling and avoiding water stress during drought sensitive stages of the crop. Seidel [2012]

If the revenue function or the CWPF shows a long constant phase (plateau) at the end, the risk by using deficit irrigation is less than in other cases, as the irrigation amount can be reduced without significant yield or gross revenue losses compared to full irrigation [Zhang, 2003].

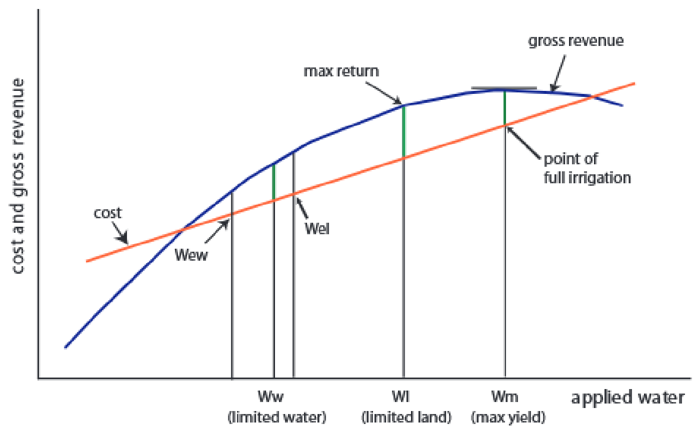


Figure 1: Revenue (blue line) and cost (red line) functions according to English and Raja [1996] adapted by Seidel [2012].

Increase Crop Yield

To increase the Water Productivity (WP) one possibility is to achieve more yield per unit of water. An increase of crop yield can be obtained by breeding or adequate agronomic practices, whereas breeding has been the major source of increase WP in the past three decades [Barker et al., 2003].

Breeding

The increase of crop yield by breeding have been realized by improvements of the ratio of grain to biomass (Harvest Index, HI) and not by the increase in total biomass. Currently, the HI may be approaching its theoretical limit for many of the major crops. [Kijne et al., 2003]

Further goals of breeding are the improvement of photosynthesis, improving spike fertility, the increase of radiation use efficiency, the minimization of floret abortion. Another point is the prevention of yield losses, which can be achieved by the improvement of the resistance to diseases of cultivars and their adaption to abiotic stresses like drought, water-logging, soil acidity, salinity and extreme temperatures. [Reynolds et al., 2009]

Promising adaptions to cop drought stress lie in

- changing the length of the growing season and the timing of the sensitive stages
- selecting for small leaves and early stomata closure to reduce transpiration
- selecting for high root activity and deep rooting systems
- selecting for tolerance to salinity.

To achieve this adaptions, wild relatives of crop plants are often used as sources for drought tolerance. [Seidel, 2012]

Agronomic Practices

Another way to increase Water Productivity (WP) besides the results of breeding is the use of adequate agronomic practices. One important point is the soil management, which can improve precipitation use efficiency and subsequently the WP. Other ways to increase WP are:

- Water-conservation practices like alternate-row irrigation
- Reduced or zero tillage
- Raised beds mulching
- Residue management
- Appropriate fertilization
- Direct seeding
- Deficit Irrigation
- Supplemental irrigation
- Water harvesting for productive purposes [Seidel, 2012]

Some of these practices are location-specific or only applicable for a certain type of soil and crop conditions. Another point is the higher management demand of some of these measures, which leads to trade-offs regarding the economic point of view. [Kijne, 2003]

Irrigation

The goal of Irrigation is to recharge the soil water storage that has been depleted by evapotranspiration when natural precipitation is not sufficient. Decreases the soil water content below a level, that the plant can extract water at a rate to meet the transpiration rate, the plant closes its stomata. This will reduce the water losses, but also the CO_2 intake, which in turn reduces the photosynthesis of the plant. Long-term a reduced photosynthesis leads to reduced plant surfaces. And as a consequence, the total dry matter production in plants is linearly related to Evapotranspiration, which has been shown in many studies. However, not all parts of the plant are linearly related to total dry matter production. So, the marketed product might be achieved or possibly increased by soil water levels below the apparent optimum in certain time periods (see chapter Controlled Deficit Irrigation (CDI)). [Letey, 2007]

Irrigation is defined by so called irrigation control parameters:

- timing of irrigation (Irrigation Scheduling)
- the duration of irrigation event (Irrigation Control)
- the discharge rate or intensity (Irrigation Control)
- which leads to the amount of applied irrigation water

The setup of these parameters depends amongst others (meteorological conditions) from the soil type and the crop rooting system. If for example the soil and the rooting system have both low water storage capacity, the irrigation quantity should be small, but more frequent, whereas high storage capacity allows less frequent irrigation but with higher amounts of water. [Letey, 2007]

To achieve a sustainable and efficient irrigated crop production these control parameters, the Irrigation Methods and the Field Design, means for example the drip line and row spacing, are the key elements. [Seidel, 2012]

One aim is to reduce losses of irrigation water, which can be caused by evaporation from the soil surface for example. The irrigation method determines to what extent it is possible to reduce this evaporation while maintaining adequate soil moisture levels [Kijne, 2003].

Irrigation Methods

Irrigation methods (or systems) can be characterized in two main groups [Letey, 2007]:

1. non-pressurized irrigation methods: gravity flow for application (Surface Irrigation as basin, furrow or border irrigation)
2. pressurized irrigation methods: application through a pipe system (Sprinkler Irrigation, Drip Irrigation, Subsurface Drip Irrigation (SDI))

Figure 2: Irrigation types (from left to right: furrow irrigation, sprinkler system, drip irrigation) [from left to right: Photograph by Cuauhtemoc Beltran/Imperial Valley Press/AP, Bobby Haas, James L. Stanfield on www.nationalgeographic.com].

Water Application Efficiency (AE)

The water application efficiency (AE) is defined as the average amount of irrigation water that contributes to a target (e.g. soil moisture deficit), divided by the average depth of irrigation water applied [Burt, 2000]. It could be used as a measure of efficiency for irrigation systems and is generally highest within drip irrigation. As showed by O'Neill et al. Subsurface irrigation saved 30% water and Sprinkler Irrigation 8% compared to furrow irrigation.

However, the choice of an irrigation method depends on economic factors, crop types and site conditions, as the soil type, slope of the field, the climate and the water quality and availability, as well as the management skills [Burt, 2000]. There is a high potential for saving water while maintaining or increasing yields in changing from surface irrigation to localized irrigation in general [Seidel, 2012], but the most lucrative investment in water efficient technologies appears if the water is valuated and priced appropriately [Tilman et al., 2002].

Surface Irrigation

As surface irrigation all irrigation practices are denoted, which use gravity flow for the application of the water to the surface of the field. There are three types:

4. Basin irrigation: the entire field is flooded (e.g. to grow rise)
5. Furrow irrigation: the water is discharged into small channels (e.g. to grow corn or vegetables)

Border irrigation: the water is fed to stripes of land (e.g. for growing pasture or alfalfa)

With these irrigation types the soil evaporation is supposed to be high and therefor there could be high losses, which leads to a low Water Application Efficiency (AE). Surface irrigation is suitable for evenly, not sloped fields and clay soils with low infiltration rates. [Seidel, 2012]

At the wiki platform Energypedia (https://energypedia.info/wiki/Main_Page), the Advantages and disadvantages of the different irrigation systems are summarized. For surface irrigation the following points are listed:

Advantages:

- Irrigation management is very easy and does not require modern technology and can largely build on local traditional knowledge;
- Adapts well to small land holdings and does not require high financial input;
- Adapts easily to flat topography and can function without outlet drainage facilities;
- Works well with short-term water supplies;
- Irrigation allows full utilization of rainwater and can achieve high application efficiencies;
- Adapts well to moderate to low infiltration rates and allows easy leaching of salts.

Disadvantages:

- Requires level land to achieve high efficiencies (maximum land elevation fluctuation should not be greater than half the applied irrigation depth);
- Soils with high infiltration rates require small field sizes, which interferes with mechanization.
- Difficulty to apply small irrigation quantities, excess water is difficult to evacuate, particularly during times of excess rainfall;
- Plants are partly covered with water sometimes over extended periods (in low infiltration rate soils);
- Small basins require extensive delivery channels and are not easily adaptable to tractor mechanization. [Energypedia, 2018a]

Sprinkler Irrigation

Sprinkler irrigation systems use pumps and pipe systems to distribute the irrigation water and then spray it over or under the crop canopy. They are suitable for most row, field and tree crops and especially appropriate for sandy soils with high infiltration rate and irrigation water free of suspended sediments. Moreover, they can be adapted to any farm-able surface-slope. However, sprinkler irrigation is not suitable for soils which form crusts and under very windy conditions. [Seidel, 2012]

There are different types of sprinkler irrigation, for example:

- Center pivot
- Under or over tree orchard sprinkler systems
- Hand or lateral move portable systems [Seidel, 2012]

For sprinkler irrigation the wiki platform Energypedia outlines the following advantages and disadvantages:

Advantages:

- Expansive land levelling or terracing is not required;
- No loss of cultivable area due to channel construction;
- Suitable for almost all soil types;
- Water saving irrigation intensity can be changed in accordance with the infiltration capacity of soil and crop water requirements;
- High efficiency due to uniform water distribution, crop water management can be adapted to growth stage and conditions;
- Possibility of adding fertilizers or pesticides to irrigation water in an economic way;
- Possibility of irrigating for other purposes: sprouting, frost protection or cooling during hot periods;
- Lower labour requirements as compared to traditional surface irrigation approaches.

Disadvantages:

- High initial capital costs (investment in equipment - sprinklers and pipes) and high operation costs due to energy requirements for pumping and labour costs.
- Sensitivity to wind, causing evaporation losses (under high wind condition and high temperature distribution and application efficiency is poor);
- Unavoidable wetting of foliage in field crops results in increased sensitivity to diseases;
- Highly saline water (>7 millimhos/cm) causes leaf burning when temperature higher than 35 degrees (Celsius).
- Debris and sediments in irrigation water can cause clogging of sprinkler nozzles. [Energypedia, 2018b]

Drip Irrigation

Drip irrigation systems consist of a pipe system, through which the water is conveyed under pressure to the fields, and emitters or drippers, to drips the water slowly onto the soil, which are located close to the plants. Only the immediate root zone of each plant is moistened and therefore the Water Application Efficiency (AE) is very high. It is suitable for the irrigation of individual plants, trees or row crops such as vegetables and sugarcane. [Seidel, 2012]

The advantages and disadvantages of drip irrigation are according to the wiki platform Energypedia the following:

Advantages:

- Extensive land levelling and bunding is not required, drip irrigation can be employed in all landscapes;
- Irrigation water can be used at a maximum efficiency level and water losses can be reduced to a minimum;
- Soil conditions can be taken into account to a maximum extent and soil erosion risk due to irrigation water impact can be reduced to a minimum;
- Fertilizer and nutrients can be used with high efficiency; as water is applied locally and leaching is reduced, fertilizer/nutrient loss is minimized (reduced risk of groundwater contamination);
- Weed growth is reduced as water and nutrients are supplied only to the cultivated plant;
- Positive impact on seed germination and yield development;
- Low operational costs due to reduced labour requirement, in particular energy cost can be reduced as drip irrigation is operated with lower pressure than other irrigation methods.

Disadvantages:

- High initial investment requirements;
- Regular capital requirement for replacement of drip irrigation equipment on the surface (damage due to movement of equipment, UV-radiation);
- Drip irrigation emitters are vulnerable to clogging and dysfunction (water filters required, regular flushing of pipe system);
- High skill requirements for irrigation water management in order to achieve optimal water distribution;
- Soil salinity hazard.

Subsurface Drip Irrigation (SDI)

As the drip irrigation explained above, also the subsurface drip irrigation (SDI) applicate small amounts of water through drippers. But in this case the drip lines are placed below the soil surface and the water is applied directly to the root zone. This leads to even less water loss due to evaporation or the moistening of plant unavailable parts of the soil and hence the Water Application Efficiency (AE) can be increased compared to drip irrigation. With SDI the water requirement is lower and the crop yield was greater or equal to other irrigation methods, as shown in many studies like Camp [1998], Camp et al. [2000] and Lamm and Trooien [2003]. However, the investment costs for SDI are much higher than other irrigation systems.

Advantages:

- equivalent to Drip Irrigation, but:
- even less water loss due to evaporation
- easier conduction of field operations than with Drip Irrigation

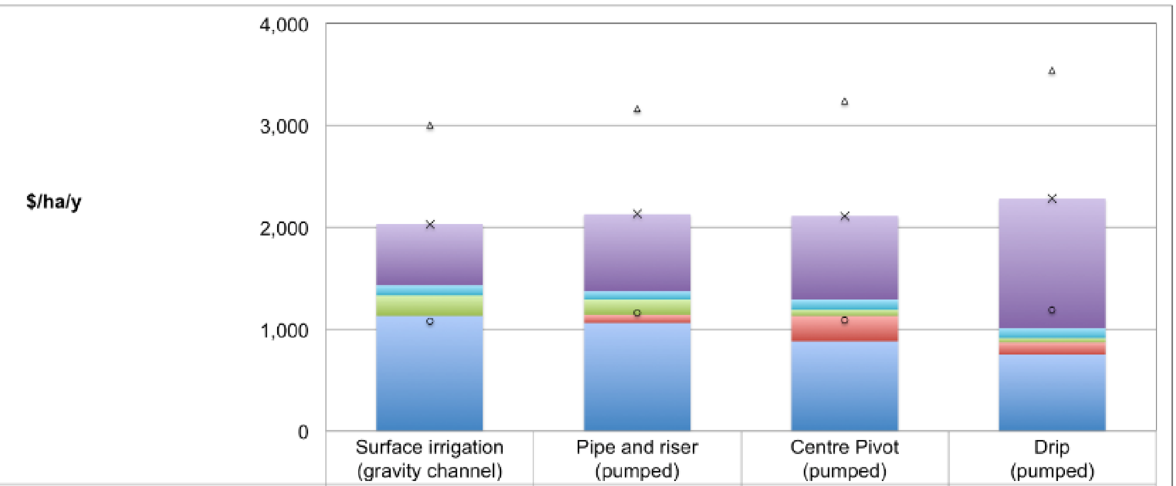
Disadvantages:

- equivalent to Drip Irrigation, but:
- higher installation effort and investment costs

Choice of Irrigation System

In addition to the geological and geographical conditions, as well as the amount of irrigation water available (see chapters according the different irrigation systems), the choice of irrigation system depends on the resulting costs in relation to the expected benefits. Since the installation of a new irrigation system is always a site-specific task, the investment costs and therefore the choice of irrigation system or the decision for modernization of an existing irrigation system cannot be generalized. However, there are some site-specific studies regarding the topic investment costs for irrigation modernization. The Food and Agriculture Organization of the United Nations (FAO) summarize in their Water Report “Irrigation Technology Transfer in Support of Food Security” the economics of crop production for different irrigation systems on sites in Tanzania, Malawi Zambia and Zimbabwe [FAO, 1997]. The resulting costs differ in a wider range for the different sites and conditions. In conclusion they found that the annual capital costs per hectare differs from US$ 16 to US$ 585 for gravity driven surface irrigation. For manually operated treadle pumps they ascertain US$ 49 annual cost per hectare compared with US$ 212 for diesel and US$ 152 for electric powered pumps. If Sprinklers are used the costs increase from US$/ha 1144 to US$/ha 1077. For Zimbabwe they established a direct comparison for surface, sprinkler and drip irrigation: the total irrigation costs (annual and variable costs, excluding labor and energy costs) was US$ 1 518/ha for the sprinkler system; US$ 1 417/ha for the drip irrigation system and US$1 520/ha with the surface system.

A cost report for the federal state Victoria in Australia summarized the costs for surface-, pipe and riser, center pivot and drip irrigation systems as in the following graphic:



	Surface irrigation (gravity channel)	Pipe and riser (pumped)	Centre Pivot (pumped)	Drip (pumped)
Ownership costs	600	760	820	1,270
Repairs, maintenance & motorbike	100	80	100	100
Labour	200	150	60	40
Power	0	80	250	120
Water	1,130	1,060	880	750
× Total	2,030	2,130	2,110	2,280
○ Total optimistic (low estimate)	1,080	1,160	1,090	1,190
△ Total pessimistic (high estimate)	3,000	3,160	3,240	3,540

Figure 3: Comparison of Total Costs (AU$) of Irrigation Systems in Victoria, Australia [Flood Victoria, 2015]

In Conclusion it must be pointed out, that the investment costs and the cost-benefit analysis must be determined for every case and site individually.

Beside the points mentioned above, another very important topic for the choice of irrigation system is level of sophistication or operational capacity of the users. Furthermore, it must be considered how the user will operate the system to provide the optimum combination of efficiency in water use and cost-effective operation and maintenance. For this the consideration of how the user will cultivate his land is important too. For example, it is possible, that the design which involves the lowest investment cost per hectare may not be the most cost-effective solution if it also involves large numbers of staff for its operation, or the design does not fit to the way the farmer has to operate his land. [FAO, 1997]

Another point is that pressurized systems (sprinkler and dripper) require an energy supply that may not always be present in the field [Letey, 2007].

To put the resulting costs in relation to the expected benefits as mentioned above, a cost benefit analysis should be carried out. Baranchuluun et al. [2014] illustrates in their study a schematic outline of such a cost benefit analysis (see Figure 4). They divide the costs and benefits of the crop farming in the following components:

1. Costs
    - Economic costs: Investment cost, fixed cost, operating cost
    - Environmental cost: Water loss
2. Benefits
    - Economic benefits: Revenue (see Revenue Functions), additional yield
    - Environmental benefit: Water saving
    - Social benefits: Labour saving, social insurance

Furthermore, Baranchuluun et al. [2014] define three main indicators to identify the most efficient approaches:

The net present value (NPV):	the difference between the present value of the costs and the present value of the benefits
The benefit - cost ratio (BCR):	the ratio of the present value of benefits and the present value of costs. The benefits and cost are each discounted a chosen discount rate.
The internal rate of return (IRR):	the discount rate where NPV equal to zero. Whereas the higher an approach's IRR, the more desirable it is.

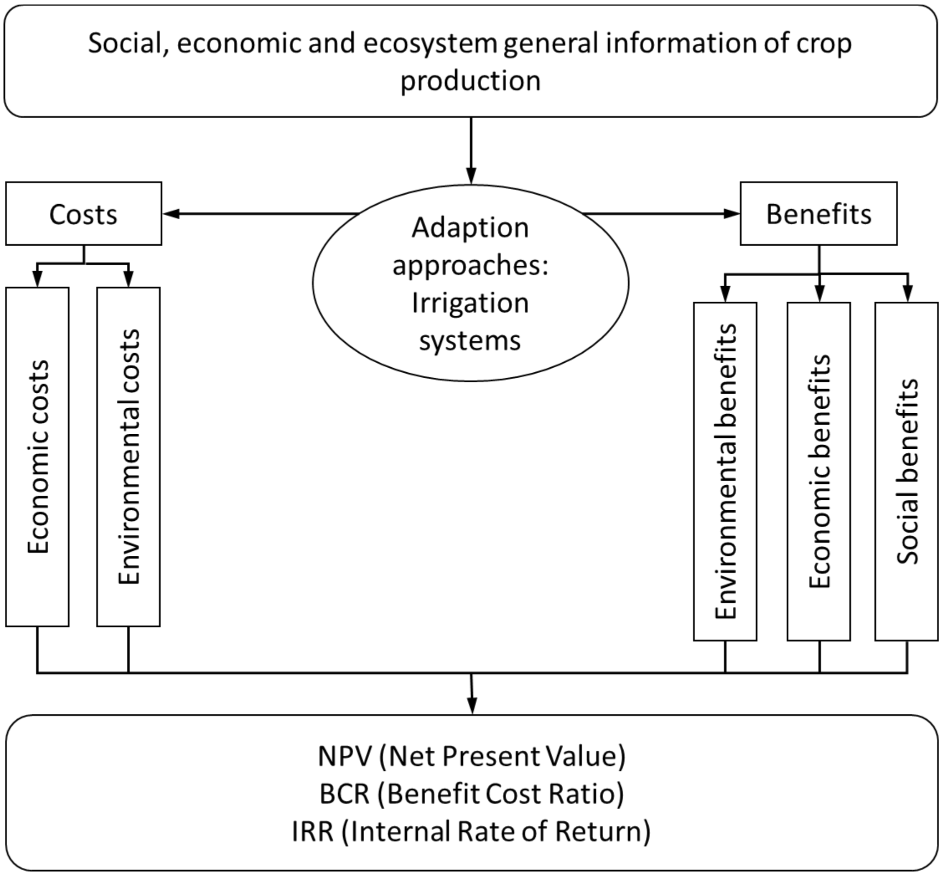


Figure 4: Schematic outline of a cost benefit analysis [Baranchuluun et al., 2014].

Irrigation Scheduling and Irrigation Control

Irrigation Scheduling

The irrigation scheduling defines the timing of the irrigation and should be determined depending on the actual soil water content and the crop water demand. It is especially important under limited seasonal water supply to ensure an optimal distribution of water during the growing season, adapted to the actual weather conditions, the soil properties and the drought susceptibility of the crop [Schmitz et al., 2007; Schütze and Schmitz, 2010].

There are different ways to determine irrigation schedules (Figure 5): based on evapotranspiration, or pan evaporation (observed or calculated), based on direct measurements of soil and plant properties, simulation based or sensor based. For the sensor-based irrigation scheduling, instrumentation, for example tensiometers installed in the root zone, is used to control if a certain threshold (e.g. soil tension) is reached. If the threshold is exceeded, irrigation water will be applied. [Seidel, 2012]

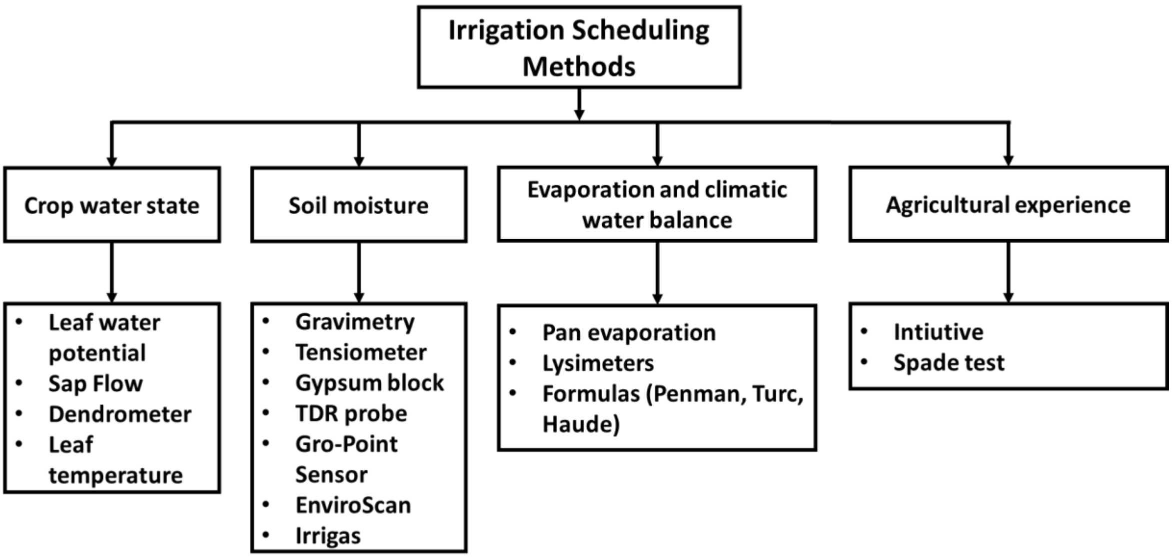


Figure 5: Irrigation Scheduling Methods.

There are three different main irrigation scheduling strategies:

1. Full irrigation: the crop water demand is matched and drought stress is completely avoided
2. Partial root drying: implicates alternate wetting and drying of parts of the root zone [Kirda et al., 2005]
3. Controlled deficit irrigation: where water is applied mainly during drought sensitive growth stages of a crop and is limited outside these periods [English, 1990]

For the decision regarding the irrigation scheduling strategies, Crop Water Production Functions (CWPF) and Revenue Functions can be useful. Furthermore, simulation-based modelling and so called Soil-Vegetation-Atmosphere-Transport (SVAT) Models can help to find an adequate irrigation strategy as well as to determine an appropriate irrigation scheduling and control. They can support a better matching between the crop demand for irrigation and the spatial and temporal distribution of irrigation.

Controlled Deficit Irrigation (CDI)

Controlled deficit irrigation is a promising irrigation scheduling strategy to maximize Water Productivity (WP), which can be applied by different types of irrigation application methods. Especially in regions where water scarcity prevails it can be more profitable to maximize crop water productivity instead of maximizing the harvest. The concept is, to save irrigation water by reducing the irrigation periods mainly to drought sensitive growth stages of a crop [English, 1990]. CDI aims for optimal water supply in drought sensitive stages while water restriction is limited to drought-tolerant phenological stages. So, it is possible to save water with only small profit cuts or even without decreasing yields.

For example, Kirda et al. [2005] obtained in their study about maize grain yield response to deficit irrigation water savings of 50% by only 10 – 25% less grain yield compared to full irrigation. But to minimize or avoid the risk of profit cuts it is essential for this schedule strategy to get a thorough understanding of sensitivity to drought stress for the cultivated plant. For most crops, the critical crop growth stages are the seedling and flowering stages [Barker et al., 2003].

According to English and Raja [1996] the advantage of CDI is not only the saved amount of water, but also a beneficial effect on the quality of some crops: it can improve the protein percentage of wheat and other grains, increase fiber length and strength of cotton and increase the sugar percentages in grapes, sugar beets and other crops. But for some crops for example potatoes caution regarding drought stress is advised and CDI is inappropriate.

Irrigation Control

While irrigation scheduling is determining the timing of irrigation, irrigation control uses the control parameters discharge rate or intensity and duration of the irrigation to determine the amount of irrigation water and thus affects the soil moisture distribution. The aim of an optimal irrigation control is to reach a homogenous soil water distribution in the root zone and to minimize losses due to deep percolation or surface runoff. [Seidel, 2012]

In drip irrigation the soil water distribution mainly depends on the discharge rate, whereas high discharge rates result in an increased lateral component of the wetting front. The discharge rate is often predetermined by the used irrigation system and only the irrigation timing, duration and thus the water amount can be varied. The three-dimensional water flow of drip irrigation can be reduced to a two-dimensional perspective, if the drip irrigation is considered as a line source (e.g. parallel drip lines). [Seidel, 2012]

Field Design

The Design of the field, for example row spacing and the localization of sources (e.g. drip line or furrows), is important for the optimization of irrigation control and it affects the Water application efficiency (AE) and Water Productivity (WP) and thus the yields and the profit of irrigation system. Especially for drip irrigation systems, the field design is essential for their potential to increase WP and yields, as well as for saving installation and material costs. So, this can be seen as an optimization problem (see chapter Optimization of Irrigation) where the optimization goals are to determine a field design and an irrigation schedule and control which maximizes yields or maximize the amount of saved water, while minimizes costs. [Seidel, 2012]

For example, to save investment costs of an expensive Subsurface drip irrigation (SDI) system one way is to increase the spacing between drip lines [Lamm and Trooien, 2003]. But too much distance between corn rows and SDI driplines has a negative influence on the crop growth and grain yield. Both, the crop growth as well as the yield decreases with growing line distance [Stone et al., 2008]. The optimal drip line spacing depends according to Lamm and Trooien [2003] on the crop and its rooting pattern, the soil characteristics, soil water distribution, in-season precipitation, the comparative costs of drip lines, yields and possible off-site hazards caused by deep percolation.

Some studies regarding the topic drip line spacings have been conducted. Camp [1998] published a review of several studies, which investigate different drip line spacings for SDI. The author recommends for uniformly spaced row crops an alternate row spacing of about 1,5m, which delivers one drip line for every two rows (located between the rows).

Infiltration

Since the applied water can only be available for plants when the root zone has been reached, infiltration rate becomes an important factor in irrigation management [Letey,2007]. Related to the infiltration is the pattern of the moisture soil around the water source, which can be determined by direct measurements of the soil wetting fronts or by simulation modelling [Elmaloglou and Diamantopoulos, 2009].

Infiltration behavior (amount, time course and pattern) depends on soil properties and the Irrigation Control, but also on the used Irrigation Methods. For example, Surface Irrigation systems deliver water in a manner that causes free-standing water on the soil [Letey,2007]. For this case applies a certain behavior and therefore mathematical description of infiltration (type of source). But Drip Irrigation represents another type source, which causes other patterns of infiltration.

In the project “SAPHIR” (Saxonian platform for high performance irrigation) at the TU Dresden, the infiltration behavior of different types of irrigation in different soil types was investigated simulation-based using the HYDRUS [Šimůnek et al., 2008; Šimůnek et al., 2016] soil water flow model (see Software Examples). So-called irrigation atlases were created, listing these distribution-patterns of water in the soil. There are four irrigations atlases, respectively for

1. Furrow irrigation: distribution of water in the soil in trapezoidal and triangular furrows (respectively single and double row, as well as for the soil types sand, loam and silt) [Saphir, 2014a]
2. Sprinkler irrigation: distribution of water in the soil applicable for all customary sprinkler systems (impact, spray, bubbler) for the soil types sand, loam and silt [Saphir, 2014b].
3. Drip irrigation: distribution of water in the soil for surface and subsurface dripper for the soil types sand, loam and silt [Saphir, 2014c].
4. Leaching: Leaching practice for different cases of soil salinization (surface-, root zone- and mixed salinity) and different types of irrigation (drip, flood and sprinkler irrigation) for the soil types sand, loam and silt [Saphir, 2014d]. (see chapter Salinization and Leaching)

These atlases are provided for download by the chair of hydrology on the homepage of TU Dresden:

https://tu-dresden.de/bu/umwelt/hydro/ihm/hydrologie/forschung/projekte/saphir/atlanten-der-bewaesserung

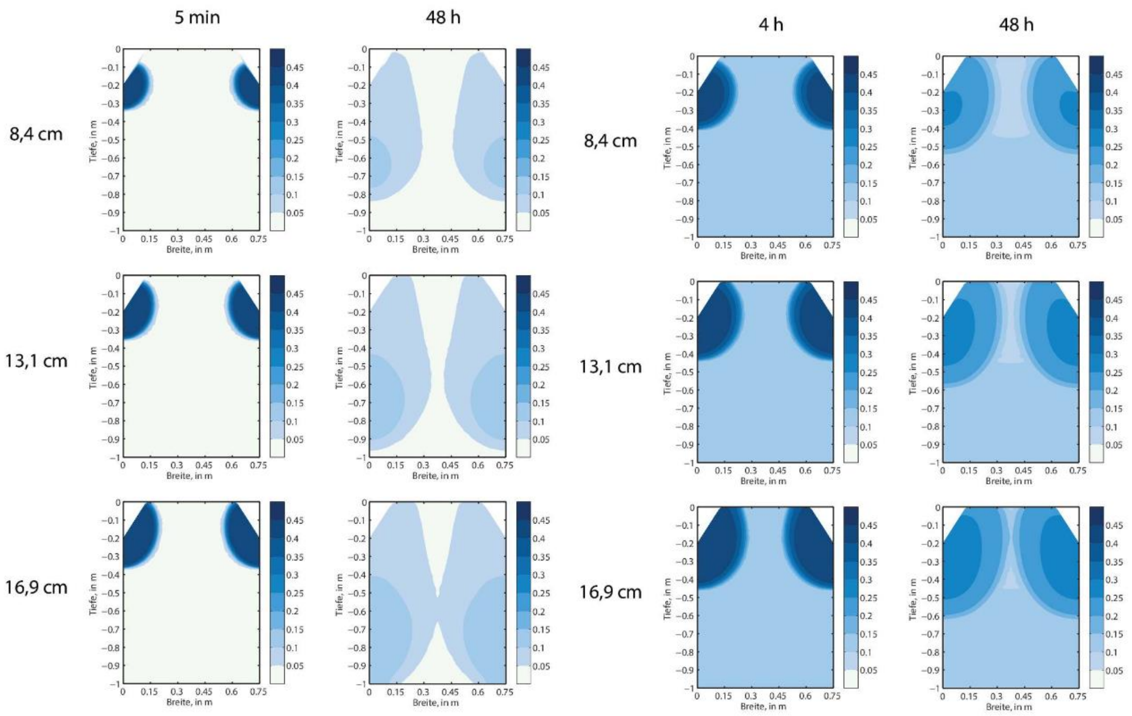


Figure 6: Left: Distribution-patterns of water in the soil at TRIANGULAR FURROWS IRRIGATION in dry SAND with a watering period of 5 minutes and three different irrigation heights (8,4 cm, 13,1 cm, 16,9 cm) directly after irrigation and after 48h [Saphir, 2014a]
Right: Distribution-patterns of water in the soil at triangular furrows irrigation in dry LOAM with a watering period of 4 hours and three different irrigation heights (8,4 cm, 13,1 cm, 16,9 cm) directly after irrigation and after 48h [Saphir, 2014a].

The following figure (Figure 6) shows an example from the atlas for furrow irrigation: it shows the distribution-patterns of water in the soil at triangular furrows irrigation in dry sand with a watering period of 5 minutes and three different irrigation heights (8,4 cm, 13,1 cm, 16,9 cm) directly after irrigation and after 48 hours, compared to the patterns in dry loam after an irrigation time of 4 hours.

As shown in the atlas for sprinkler irrigation [Saphir, 2014b], for sprinkler the overlapping effect of nearby sprinkles must be considered (see Figure 7).

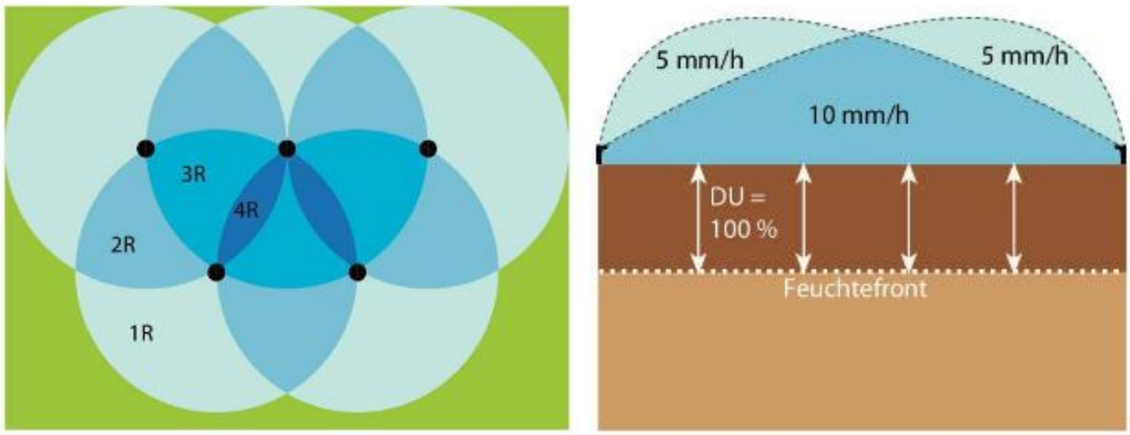


Figure 7: Illustration of effective irrigated area an overlapping irrigation arcs in sprinkler systems (R represents the precipitate of one sprinkler) [Saphir, 2014b].

For an area within a sprinkler network, a uniform is assumed, i. e. the moisture front resulting from irrigation spreads down parallel to the ground surface (see Figure 8).

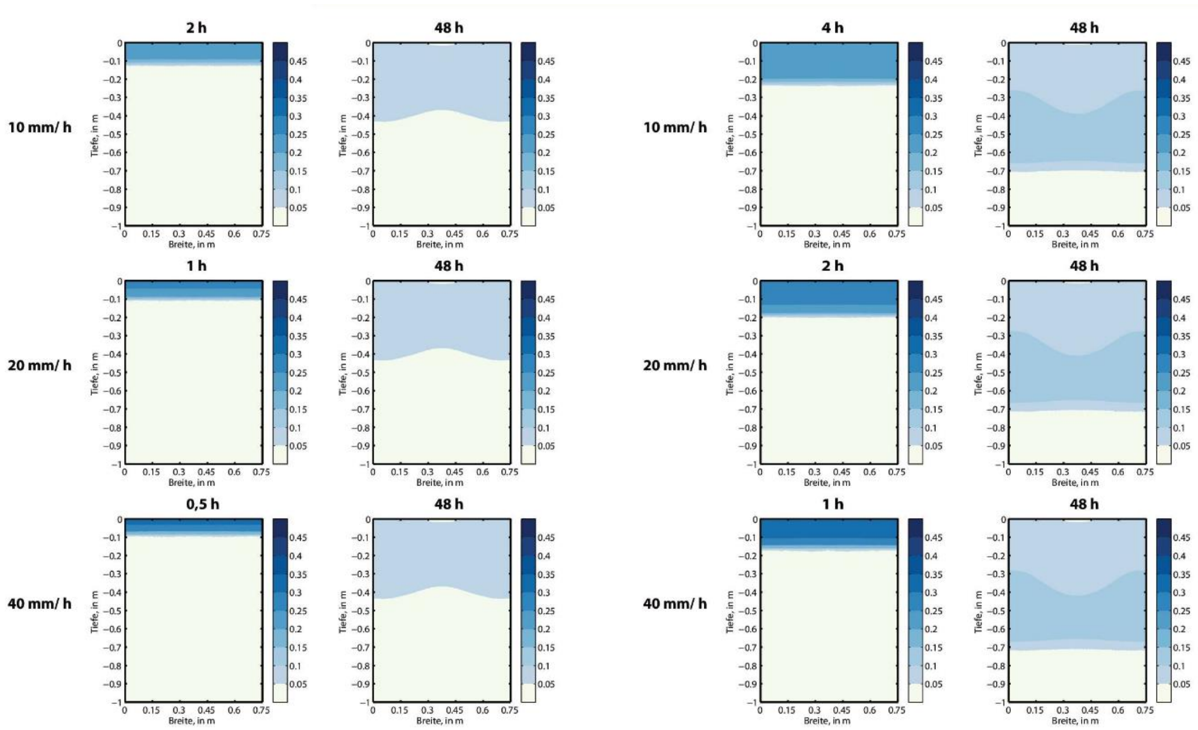


Figure 8: Distribution-patterns of water in the soil at SPRINKLER IRRIGATION in dry SAND with an irrigation rate of 10, 20 and 40 mm/h combined with different irrigation durations (4h, 2h, 1h, 0.5h) directly after irrigation and after 48h [Saphir, 2014b].

The following Figure 9 and Figure 10 are showing examples for distribution patterns for drip irrigation respectively for dry sand and dry loam and different irrigation scenarios (2h and 5 hours irrigation time and irrigation rates of 2 l/h, 4 l/h and 8 l/h) as contained in the Atlas for drip irrigation [Saphir, 2014c]. The same irrigation scenarios but for subsurface drip irrigation are used for the distribution patterns in Figure 11 and Figure 12.

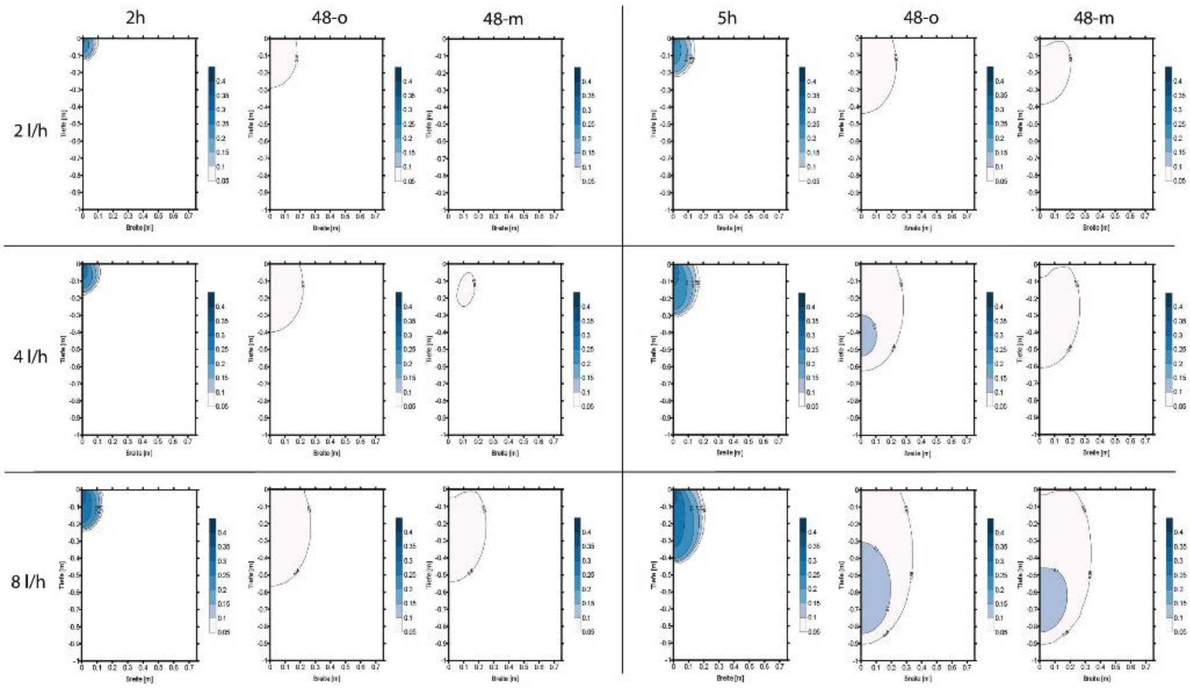


Figure 9: Distribution-patterns of water in the soil at DRIP IRRIGATION in dry SAND with an irrigation rate of 2, 4 and 8 l/h for 2- and 5-hours duration directly after irrigation and after 48h (whereas 48-o means no influence of evapotranspiration and 48-m with influence of evapotranspiration) [Saphir, 2014c].

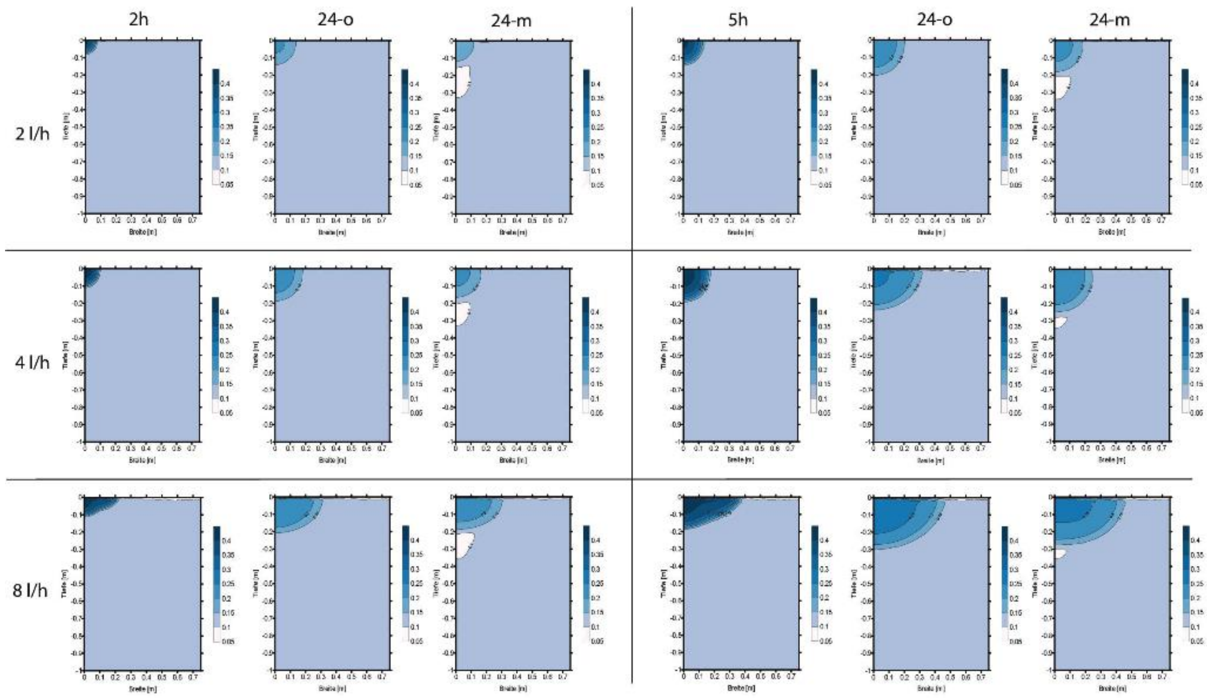


Figure 10: Distribution-patterns of water in the soil at DRIP IRRIGATION in dry LOAM with an irrigation rate of 2, 4 and 8 l/h for 2- and 5-hours duration directly after irrigation and after 24h (whereas 24-o means no influence of evapotranspiration and 24-m with influence of evapotranspiration) [Saphir, 2014c].

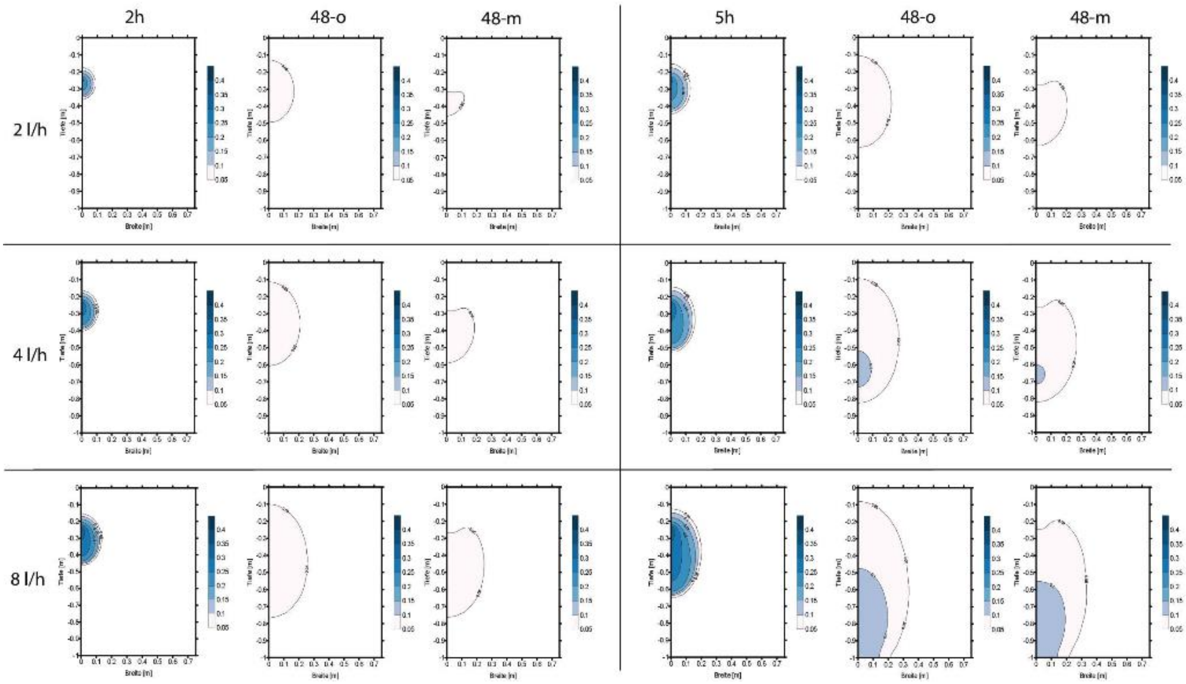


Figure 11: Distribution-patterns of water in the soil at SUBSURFACE DRIP IRRIGATION in dry SAND with an irrigation rate of 2, 4 and 8 l/h for 2- and 5-hours duration directly after irrigation and after 48h (whereas 48-o means no influence of evapotranspiration and 48-m with influence of evapotranspiration) [Saphir, 2014c].

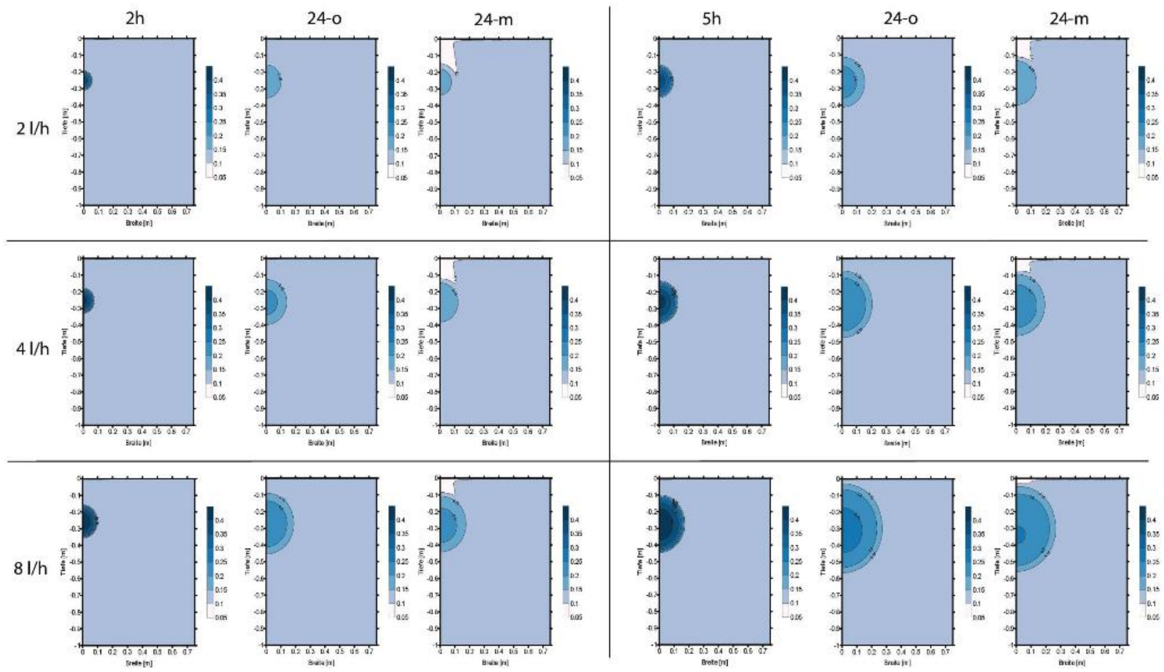


Figure 12: : Distribution-patterns of water in the soil at SUBSURFACE DRIP IRRIGATION in dry LOAM with an irrigation rate of 2, 4 and 8 l/h for 2- and 5-hours duration directly after irrigation and after 24h (whereas 24-o means no influence of evapotranspiration and 24-m with influence of evapotranspiration) [Saphir, 2014c].

Salinization and Leaching

An increasing salt content in the soil, called salinization, harms the most crops. Salinization can mainly be caused by four different kinds:

1. Natural processes (mineral weathering)
2. Ocean Water (gradual withdrawal of an ocean)
3. Capillary rise from the groundwater
4. Irrigation

The last point refers to the following fact: Since plants transpire pure water and all irrigation waters contain some dissolved salts, the salt concentration in the soil increases gradually. Dependent on the salt content in the irrigation water and the salt tolerance of the crop, excessive salts must be leached from the root zone more or less often. This means that in certain intervals more irrigation water is necessary for leaching. [Letey, 2007]

Nitrogen Use Efficiency in Crop Production

Nitrogen is one of the most important nutrient fertilizer [Sepaskhah et al., 2006], as most plants need it in a relatively large amount compared to other plant nutrients [Seidel, 2012]. Exceptions are legumes which are able to fix atmospheric nitrogen.

Agriculture is already one of the main sources of greenhouse gas emissions [Seidel, 2012]. There are huge losses by volatilization, leaching, surface runoff, and denitrification, which cause higher cost of crop production, but more important grave environmental pollution [Tilman et al., 2002; Fageria and Baligar, 2005]. Thereby leaching, or more precisely surface water runoff and deep percolation, seems to be the main loss of nitrogen in the soil-plant system [Seidel, 2012]. As a consequence, 20% of European aquifer show to high nitrogen concentrations [Casa et al., 2011] and there are serious problems with eutrophication and low-oxygen conditions in surface water. But volatilization of agricultural soils, also causes 14% of annual nitrogen emissions. Only 30-50% of nitrogen is recovered in plants [Tilman et al., 2002; Fageria and Baligar, 2005].

This means there is a great need to increase the Nitrogen Use Efficiency (NUE) and it is indispensable to reduce nitrogen leaching, which implies a link between Water Productivity (WP), Irrigation and Nitrogen Use Efficiency (NUE).

Nitrogen Use Efficiency (NUE)

The Nitrogen Use Efficiency (NUE) relates the yield to the available nitrogen:

$$NUE = \frac{Y}{N + \Delta N_{soil}} \quad in \left[{}^{kg}/_{kg}\right]$$

With Y actual grain yield

N amount of N fertilizer applied

ΔN_{soil} N depletion from the root zone during the growing season

NUE-values become small, when there is a large amount of nitrogen available. In addition to similarities in the equations for Nitrogen Use Efficiency and Water Productivity (WP), the shapes of the two functions also show similar behavior. Equivalent to the WP, a high NUE means either achieving more yield per kg nitrogen, or less nitrogen losses (nitrogen savings). Despite the similarities between WP and NUE, there is still a lack of understanding of the interactions between crop water use and nitrogen application rates [Hatfield and Prueger, 2001].

N Fertilization Management and Scheduling

Equivalent to Irrigation Scheduling, fertilization schedules can be determined in three different ways:

- Empirically (N Balance Method)
- Sensor based
- Simulation based (crop growth or Soil-Vegetation-Atmosphere-Transport (SVAT) Models)

Since the risk of environmental pollution as well as the cost of crop production depends on the applied amount of nitrogen, it is important to determine the correct quantity of nitrogen needed for fertilization. There are different methods for determination of the required Nitrogen amount, for example the N Balance Method. According to Wallach [2006] this method can be defined as:

$$d = (P_f - P_i) - (M_n - R_i - L - R_f)$$

With d recommended dose of nitrogen

P_f total N requirement of the crop

P_i amount of N absorbed up to time of fertilization

M_n total mineralization of soil during the growth period

R_i initial soil mineral N

L amount of mineral N lost to deep percolation

R_f final soil mineral N

But more potential to decrease nitrogen losses provides the so-called precision agriculture, also named as precision farming or site-specific management [Van Alphen and Stroovogel, 2000]. The principle of precision agriculture is to restrict the application of fertilizers and pesticides to periods of greatest crop demand, to position the application at or near the plant roots and to reduce the amount or use more frequent applications [Bongiovanni and Lowenberg-Deboer, 2004]. The higher effort and required investment of these management strategies can be compensated by the saving costs for fertilizer and phytosanitary effort, as well as the potential for improving agronomic, economic and environmental efficiency [Casa et al., 2011].

There are different methods for precision N fertilization management for example:

- “On the go” methods, in which the crop status, for example detected by sensors on the tractor, are used to determine the required amount of nitrogen instantaneously
- “Nitrogen prescription maps”, which are based on spatial information layers [Casa et al., 2011]

Another important support for fertilizing management is the simulation modelling. Similar to irrigation management computer models, and especially Soil-Vegetation-Atmosphere-Transport

(SVAT) Models can help to determine the crop demand for nitrogen and to put this demand into relationship to the spatial and temporal distribution of nitrogen application.

Combination of Irrigation and N Fertilization Scheduling

Since leaching, or more precisely surface water runoff and deep percolation is the main loss of nitrogen in agricultural systems, which causes grave environmental pollution [Tilman et al., 2002; Fageria and Baligar, 2005], it is very important to consider irrigation and fertilization management decisions not separated from each other [Seidel, 2012]. Furthermore, an improvement of Water Productivity (WP) can achieved by adequate nitrogen management, as a proper soil nutrient status can promote plant growth and increase yield [Hatfield et al., 2001].

Similar to the Crop Water Production Functions (CWPF) the relationship between total water amount and nitrogen applied referring to the achieved yield can be called Crop Water Nitrogen Production Function (CWNPF) [Walser and Schütze, 2010]. This Functions are three-dimensional and were for example determined by Sepaskhah et al. [2006]. They show, that limited water and nitrogen supply can reach better results for yield achievement, than full irrigation and full nitrogen fertilization. Since there is a large diversity of results in studies regarding Water Productivity related to soil nutrient management, it seems to be a great challenge to understand the water nutrient interactions [Hatfield et al., 2001]. To improve management strategies, there should be a closer link in the evaluation of nitrogen management strategies to WP [Seidel, 2012].

Soil-Vegetation-Atmosphere-Transport (SVAT) Models

SVAT models simulate energy and mass transfers between the soil, the vegetation, and the atmosphere using descriptions of turbulent, radiative and water exchanges, as well as a description of stomatal control in relation with water vapor transfers and photosynthesis [Olioso et al., 1999].

There are many different SVAT models and their complexity varies in a wide range. Equivalent to their complexity in representing the processes, the required information / input data for the use of these models also vary. Usually information about vegetation structure (LAI, height), optical properties of soil and vegetation, physiological properties of vegetation (stomatal conductance description, water transfer from soil to plants), thermal and hydraulic properties of the soil, and atmospheric conditions (air temperature and humidity, wind speed, incident radiations) are required [Olioso et al., 1999]. Since there are a lot of feedback and interactions between the processes that drive the fluxes of water, energy and carbon in the soil-vegetation-atmosphere system, it should be seen and treated as a continuum [Wöhling et al., 2013]. Figure 13 shows schematically the main processes in SVAT models and their interactions.

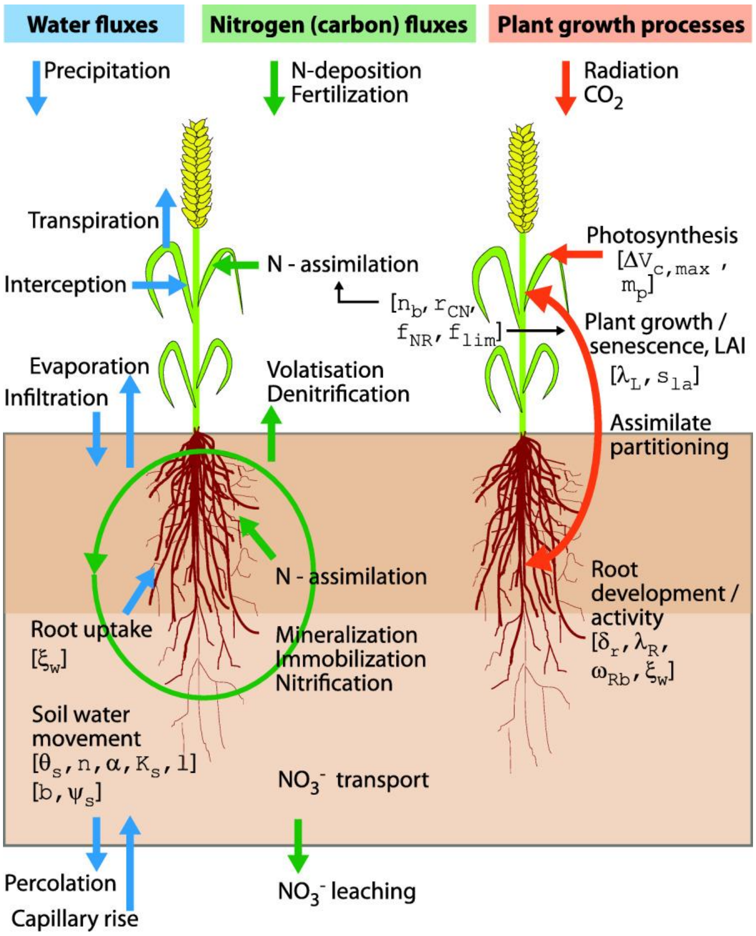


Figure 13: Schematic illustration of the main processes in SVAT models [Wöhling et al., 2013]

Software Examples

There is a wide range of different SVAT-, soil- or crop models. The International Soil Modeling Consortium has built up a homepage which catalogues and describes those models to a large extent:
https://soil-modeling.org/resources-links/model-portal

In the following, only a few examples will be given:

Hydrus 1D:

https://soil-modeling.org/resources-links/model-portal/hydrus-1d

http://www.pc-progress.com/en/Default.aspx?hydrus-1d

Hydrus 1D contains equations for saturated-unsaturated water flow, as well as for heat and solute transport (advection and dispersion). The equation for water flow contains a sink term to account for water uptake by plant roots. The equation for heat transport considers conduction and convection with flowing water and in the solute transport, advective-dispersive transport in the liquid Phase, and diffusion in the gaseous phase are taken into account. The program may be used to analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. Hydrus contains a parameter estimation technique, which allows several unknown parameters to be estimated from observed water contents, pressure heads, concentrations, and/or instantaneous or cumulative boundary fluxes (e.g., infiltration or outflow data).

Hydrus 2D-3D:

https://soil-modeling.org/resources-links/model-portal/hydrus-2d-3d

http://www.pc-progress.com/en/Default.aspx?hydrus-3d

Hydrus 2D-3D is, just like Hydrus 1D, a modeling environment for the analysis of water flow and solute transport in variably saturated porous media. But in contrast to Hydrus 1D it simulates the two- and three-dimensional movement of water, heat and solutes in the soil.

AgroC:

https://soil-modeling.org/resources-links/model-portal/agroc

AgroC is a numerical model for simulating the 1-dimensional fluxes of soil heat, soil water and carbon in agricultural systems. It provides hourly or daily time series of the carbon balance of cropped ecosystems and accounts for soil carbon turnover, soil CO2 flux, plant water stress and organ-specific carbon allocation. Furthermore, root exudation and root death and the effect of both processes on soil respiration are considered. An existing soil carbon dioxide model (SoilCO_2/RothC [Herbst et al., 2008; Šimůnek et al., 1993]) was extended with the dynamic plant growth module SUCROS [Spitters et al., 1988]. It contains standard input parameters for cereals, sugar beet, maize, potato and grassland, if no other data is available.

WAVE:

https://soil-modeling.org/resources-links/model-portal/wave

http://www.uclouvain.be/208891.html

WAVE stand for Water and Agrochemicals in the soil, crop and Vadose Environment. This deterministic, numerical and integrated model simulates the vertical transport and transformation processes of matter (water, agrochemicals) and energy (heat) in the soil, crop and the vadose zone (means the unsaturated soil between surface and groundwater). It was composed of different existing models such as SWATRER (water module), SOILN (nitrogen module), LEACHN (heat and solute modules) and SUCROS (crop growth module).

DAISY:

https://soil-modeling.org/resources-links/model-portal/daisy

http://www.daisy-model.org

Daisy is a mechanistic model, which simulates physical and biological processes in an agricultural system, more precisely, the transport and turnover of water, energy, carbon, nitrogen, and pesticides, both above and below ground. The model is able to predict production, environmental impact in the form of leaching, and change in soil (carbon) quality over time. The input to Daisy is through text files of daily or hourly weather data (at least precipitation, global radiation, and temperature, much more can be used if available), management information (sow/harvest, tillage operations, as well as data and amounts of irrigation, fertilizer and pesticide applications), and finally soil quality (texture, humus content). The default Daisy model is 1-dimensional and assumes homogenous fields, with no significant horizontal transport. A 2-dimensional model is included and can be chosen, for example to simulate row crops and drain pipes.

Expert-N:

https://soil-modeling.org/resources-links/model-portal/expert-n

http://www.helmholtz-muenchen.de/en/iboe/expertn/

Expert- N is a modular model system, which contains components for soil water flow, soil heat and N transport and for crop growth. These components are built up of different standardized model units representing each a single process for the component as N mineralization for N transport or root water uptake for crop growth. The modular structure allows an easy exchange of model units to compare different submodels or model algorithms describing the same process or to adapt the model to the actual simulation purpose including management or research, to the specific site conditions involving crop, soil and agricultural practice and to the quality and availability of data.

CropWat:

http://www.fao.org/land-water/databases-and-software/cropwat/en/

CropWat is a decision support tool developed by the FAO (Food and Agriculture Organization of the United Nations), which is used to calculate crop water and irrigation requirements. It allows the development of irrigation schedules for different management conditions, to evaluate current irrigation practices and to estimate crop performance under rainfed or irrigated conditions. As input soil, climate and crop data are required. If these are not available, CropWat contains standard crop and soil data. Climate data can be obtained from CLIMWAT, the climatic data base which is also provided by FAO.

Optimization of Irrigation

The main goal of optimizing Irrigation in agricultural systems is to improve the Water Productivity (WP). This means on the one hand, to improve yield (see chapter Increase crop yield), on the other to reduce the amount of necessary irrigation water. The latter includes the need to reduce losses due to transpiration, deep percolation or in the supply pipe system of the irrigation systems, as well as new management methods (for example Controlled deficit irrigation (CDI)). Since some of these points are related or influence each other (applicability of management strategies depends on the irrigation system, and both can affect as well the achieved crop yield as the used amount of water (see Controlled deficit irrigation (CDI))), there is no sharp boundary between the different means and goals mentioned above. Therefor the Optimization of irrigation can involve different aspects of irrigation which can improve as well the increasing of crop yield as the reduction of irrigation water:

- Optimization of irrigation systems (see chapter Irrigation Methods)
- Optimization of Irrigation Scheduling
- Optimization of Irrigation Control

According to Playán and Mateos [2006] the improvement of irrigation management shows much better economic return than the improvement of the irrigation structures. The goals of irrigation optimization depend amongst others on the region and the associated water supply. Especially in regions where water scarcity prevails it can be more profitable to maximize crop water productivity instead of maximizing the harvest [Seidel, 2012].

For the optimization of the irrigation systems and control the pattern of the moisture soil around the water source is important (see section Infiltration). This pattern can be determined by direct measurements of the soil wetting fronts or by simulation modelling [Elmaloglou and Diamantopoulos, 2009]. It is highly dependent of soil properties as well as the irrigation control. As explained in chapters Crop Water Production Functions (CWPF) and Revenue Functions the respective functions are useful means for irrigation scheduling and optimization.

Furthermore, simulation-based modelling and so called Soil-Vegetation-Atmosphere-Transport (SVAT) Models are important tools for optimizing irrigation and fertilizing management strategies. These models can help to determine the crop demand for irrigation or nitrogen and to put this demand into relationship to the spatial and temporal distribution of irrigation or nitrogen application. Combined with optimization algorithms (e.g. evolutionary or gradient based methods, see chapter Optimization Algorithms), those or similar models (crop models, root models) can be used for a simulation-based optimization of irrigation.

Although Crop Water Production Functions (CWPF) and other methods mentioned above provide the scientific and economic basis for optimizing irrigation, they are often not practicable or affordable for farmers in full complexity. However, the principles can be applied in a reduced form. Letey, [2007] defined irrigation as "the practice of recharging the storage capacity that has been depleted by ET (Evapotranspiration) when natural precipitation is not adequate to meet the ET demands". Numerous studies showed that total dry matter production in plants is linearly related to ET. So, if the farmers do not have complete detailed information available, the knowledge of ET can be most helpful. Alternatively, time series of soil water contents can be used to determine the irrigation demand of a field. Therefore, a method of monitoring either ET or the change in soil water content is required for optimized irrigation scheduling. [Letey, 2007]

Multi Objective Optimization (MOO) Algorithms

Multi objective optimization methods can be classified in two main groups (see Figure 14):

1. Pareto Methods
2. Scalarization Methods

and a small group that cannot be assigned to either one type or the other type of methods. Scalarization methods transform multi objective optimization problems into single objectives one. For that, information about the preferences regarding the objective functions must be available. [Gambier and Badreddin, 2007]. This group of methods in turn can be divided in

- Evolutionary Algorithms
- Non-evolutionary Algorithms.

Whereby, the evolutionary search methods have proven to be useful for the consideration of several conflicting objective functions [Vrugt/Robinson, 2007].

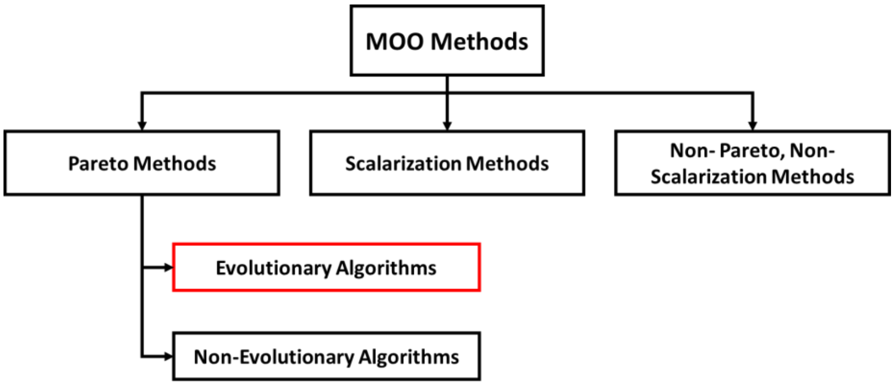


Figure 14: General classification of MOO solving methods [modified according to Gambier and Badreddin, 2007]

An evolutionary algorithm (EA) is a heuristic optimization algorithm using techniques inspired by mechanisms from organic evolution such as mutation. Heuristic means that information currently gathered by the algorithm is used to decide which solution candidate should be tested next [Weise, 2009]. In EA a population is evaluated and according to the principal surviving of the fittest, a next generation is generated by mutation and recombination of the best parent population.

Irrigation in Israel

In the following some statistical information about Israel in context of water supply, water use and irrigation from the FAO WATER REPORT 34 [Frenken, 2008] are summarized:

Israel has a total area of about 20,770 km² of which in 2004 428,000 ha were used for agriculture. Israel has a Mediterranean climate characterized by long, hot, dry summers and short, cool, rainy winters, whereas the rain is unevenly distributed and decreases sharply to the south (less than 100 millimetres annually). The main sources of fresh water in Israel are:

- Lake Kinneret or Lake Tiberias (the Sea of Galilee) (710 million m³ volume)
- The Coastal Aquifer (mean annual recharge of 250 million m³ in addition to 50 million m³ of agricultural drainage water → naturally recharged by precipitation and artificially recharged by water from the National Water Carrier)
- The Mountain Aquifer (Yarkon-Taninim), divided in Western Basin, known as the Yarkon Taninim Aquifer (350 million m³ annual renewable recharges), and the Northeastern and Eastern Basins
- Relatively smaller aquifers are located in Western Galilee, Eastern Galilee, the Jordan Rift, and the Arava valley

The total renewable water resources in Israel are estimated at 1 780 million m³/year, of which 92 percent is considered to be exploitable. (The total internal renewable water resources in Israel are estimated at 750 million m³/year, whereas 250 million m³ is surface water and 500 million m³ groundwater. It is estimated that 305 million m³ surface Water and 725 million m³ groundwater is entering Israel per year.)

As a result of Israel's growing water scarcity, desalination (mainly from brackish water) becomes more significant and Israel's goal is to produce 750 million m^3/year of desalinated water in 2020 [MAE, 2005 according to Frenken, 2008]. Also, to increase the wastewater treatment is a main goal of Israel. In the FAO WATER REPORT 34 [Frenken, 2008] it is stated, that from the total amount of 450 million m^3 wastewater, 283 million m^3 are adequately treated and the goal is to increase the treated wastewater to 100 percent. The percentages of water sources in 2004 are shown in Figure 15.

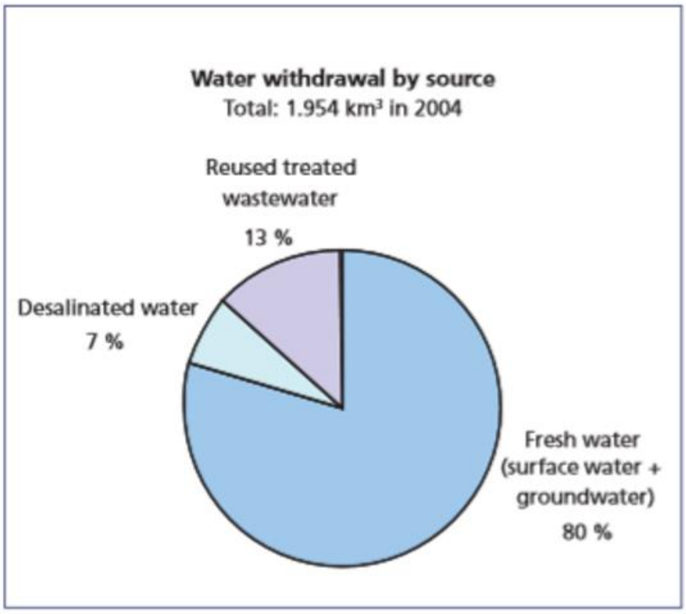


Figure 15: Water withdrawal by sources [Frenken, 2008].

Figure 16 shows the water use by sector in 2004. As it can be seen agriculture uses the majority of the total water consumption. But according to Frenken [2008], agricultural water consumption decreased 13 % since 1993.

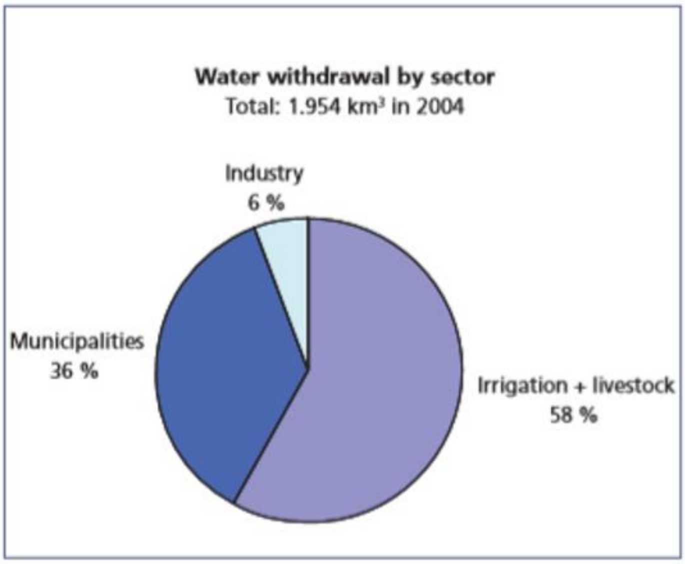


Figure 16: Water withdrawal by sector [Frenken, 2008].

Irrigation has always played a big role in Israel and intensive efforts have been invested in irrigation research. Some innovative technologies such as drip irrigation have been developed by the local irrigation equipment industry. In 2004, 225000 ha land were equipped for irrigation.

And already up to 75% of all irrigation was performed with localized irrigation, mostly drip irrigation (see Figure 17). The remaining 25% was applied with sprinkler technology or with flood and furrow irrigation. Those last 25% have the potential to be converted to more efficient irrigation systems, as drip irrigation (if not already done). But the economic legitimacy of this measure is very case-specific and needs to be reviewed by experts on a case-by-case basis.

Due to the major improve in irrigation efficiency the average annual water application per hectare could be decreased from 8000 m^3 to 5000 m^3, while agriculture has increased.

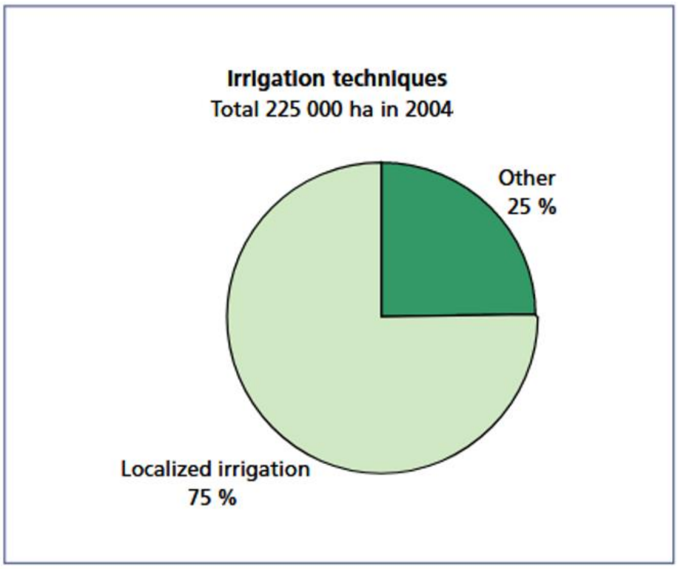


Figure 17: Irrigation techniques in Israel 2004 [Frenken, 2008].

Literature Recommendations

General introduction in the topic irrigation and irrigation optimization:

FIGARO, (Flexible and Precision Irrigation Platform to Improve Farm Scale Water Productivity) is a European wide research project, which aims to increase water productivity in major water-demanding crops and develop a cost-effective precision irrigation platform:

http://www.figaro-irrigation.net/

Wiki platform for collaborative knowledge exchange on renewable energy, energy access, and energy efficiency topics in developing countries (contains some very good articles about irrigation too):

https://energypedia.info/wiki

Software:

https://soil-modeling.org/resources-links/model-portal

Irrigation atlases:

https://tu-dresden.de/bu/umwelt/hydro/ihm/hydrologie/forschung/projekte/saphir/atlanten-der-bewaesserung

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