TOOLBOX ON SOLAR POWERED IRRIGATION SYSTEMS (SPIS)

POWERING AGRICULTURE:
AN ENERGY GRAND CHALLENGE FOR DEVELOPMENT

Module 8: Irrigate

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ABBREVIATIONS

Ah	Ampere hour
CWR	Crop Water Requirement
DC/AC	Direct Current / Alternating Current
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
Gd	Daily Global Irradiation
GIZ	Gesellschaft für Internationale Zusammenarbeit
GIWR	Gross Irrigation Water Requirement
GPFI	Global Partnership for Financial Inclusion
HERA	GIZ Program Poverty-oriented Basic Energy Services
H_T	Total Head
IEC	International Electrotechnical Commission
IFC	International Finance Corporation
IRR	Internal Rate of Return
IWR	Irrigation Water Requirement
MPPT	Maximum Power Point Tracking
NGO	Non-Governmental Organization
NIWR	Net Irrigation Water Requirement
NPV	Net Present Value
m^2	square meter
PV	photovoltaic
PVP	Photovoltaic Pump
SAT	Side Acceptance Test
SPIS	Solar Powered Irrigation System
STC	Standard Test Conditions
TC	Temperature Coefficient
UV	Ultraviolet
Vd	Daily crop water requirement
W	Watt
Wp	Watt peak

DEFINITIONS

Aquifer	Underground geological formation(s), containing usable amounts of groundwater that can supply wells or springs for domestic, industrial, and irrigation uses.
Chemigation	The process of applying chemicals (fertilizers, insecticides, herbicides, etc...) to crops or soil through an irrigation system with the water.
Conveyance loss	Loss of water from a channel or pipe during transport, including losses due to seepage, leakage, evaporation, and other losses.
Crop coefficient	Ratio of the actual crop evapotranspiration to its potential (or reference) evapotranspiration. It is different for each crop and changes over time with the crop's growth stage.
Crop Water Requirement (CWR)	The amount of water needed by a plant. It depends on the climate, the crop as well as management and environmental conditions. It is the same as crop evapotranspiration.
Current (I)	Current is the electrical flow when voltage is present across a conductor, or the rate at which charge is flowing, expressed in amperes [A].
Drainage	The natural or artificial removal of surplus ground and surface water and dissolved salt from the land in order to enhance agriculture production. In the case of natural drainage, the excess waters flow from the fields to lakes, swamps, streams and rivers. In an artificial system surplus ground or surface water is removed by means of sub surface or surface conduits.
Deep percolation	Movement of water downward through the soil profile below the root zone. This water is lost to the plants and eventually ends up in the groundwater. [mm, where 1 mm = 10 m3/ha)]
Drawdown	Lowering of level of water in a well due to pumping.
Drip irrigation	Water is applied to the soil surface at very low flow rates (drops or small streams) through emitters. Also known as trickle or micro-irrigation.
Emitter	Small micro-irrigation dispensing device designed to dissipate pressure and discharge a small uniform flow or trickle of water at a constant rate which does not vary significantly because of minor differences in pressure head. Also called a "dripper" or "trickler".
Evaporation (E)	Where liquid water is converted into water vapour and removed from the evaporating surface. This loss of water as vapor occurs from the surface of the soil or wet vegetation, [mm, where 1 mm = 10 m3/ha)]
Evapotranspiration (ET)	Combined water lost from evaporation and transpiration; evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. The crop ET (ETc) can be estimated by calculating the reference ET for a reference crop (ETo for clipped grass) from weather data and multiplying this by a crop coefficient.

	The ETc, or water lost, equals the CWR, or water needed by plant. [mm, where 1 mm = 10 m3/ha)]
GIWR	The Gross Irrigation Water Requirement (GIWR) is used to express the quantity of water that is required in the irrigation system [mm, where 1 mm = 10 m3/ha)].
Infiltration	The act of water entering the soil profile.
Fertigation	Application of fertilizers through the irrigation system. A form of chemigation.
Financial viability	The ability to generate sufficient income to meet operating expenditure, financing needs and, ideally, to allow profit generation. It is usually assessed using the Net Present Value (NPV) and Internal Rate of Return (IRR) approaches together with estimating the sensitivity of the cost and revenue elements (See Module INVEST).
Friction loss	The loss of pressure due to flow of water in a pipe. It depends on the pipe size (inside diameter), pipe roughness, fittings, flow rate, and length of pipe. It is determined by consulting a friction loss chart available in an engineering reference book or from a pipe supplier. [m]
Full Control Irrigation	A term referring to surface irrigation, sprinkler irrigation, and / or localized irrigation
Global solar radiation (G)	The energy carried by radiation on a surface over a certain time period. The global solar radiation is location specific as it is influenced by clouds, air humidity, climate, elevation and latitude, etc. The global solar radiation on a horizontal surface is measured by a network of meteorological stations all over the world and is expressed in kilowatt hours per square meter [kWh/m^2].
Gravity flow	The use of gravity to produce pressure and water flow, for example when a storage tank is elevated above the point of use, so that water will flow with no further pumping required.
Head	Value of atmospheric pressure at a specific location and condition. [m]: Head, total (dynamic) = Sum of static, pressure, friction, and velocity heads that a pump works against while pumping at a specific flow rate. [m]; Head loss = Energy loss in fluid flow. [m]
Insolation	The rate at which solar energy reaches a unit area at the earth measures in Watts per square meter [W/m^2]. Also called solar irradiance.
Irradiation	The integration or summation of insolation (=solar irradiance) over a time period expressed in Joules per square meter (J/m2) or watt-hours per square meter [Wh/m^2].
Irrigation	Irrigation is the controlled application of water to respond to crop needs.

Irrigation efficiency	Proportion of the irrigation water that is beneficially used to the irrigation water that is applied. [%]
Irrigation head	Header tank of water at an elevation above ground level to regulate water quantity, quality and pressure in an irrigation system. Usually accompanied and regulated by different types of valves, pressure regulators, filters and possibly a chemigation system.
Land Tenure	The relationship, whether legally or customarily defined between people, as individuals or groups, with respect to land (VGGT 2012).
Lateral	Pipe(s) that go from the control valves to the sprinklers or drip emitter tubes.
Latitude	Latitude specifies the north–south position of a point on the Earth's surface. It is an angle which ranges from 0° at the Equator to 90° (North or South) at the poles. Lines of constant latitude, or parallels, run east–west as circles parallel to the equator. Latitude is used together with longitude to specify the precise location of features on the surface of the Earth.
Leaching	Moving soluble materials down through the soil profile with the water.
Maximum Power Point Tracking (MPPT)	This allows solar panels to rotate automatically about a pivot to remain at the optimum angle to the solar irradiance. An important feature in many control boxes to draw the right amount of current in order to maintain a high voltage and achieve maximum system efficiency.
Net Irrigation Water Requirements (NIWR)	The sum of the individual crop water requirements (CWR) for each plant for a given period of time. The NIWR determines how much water should reach the crop to satisfy its demand for water in the soil. [mm, where 1 mm = 10 m3/ha)]
Power (P)	Power is the rate at which energy is transferred by an electrical circuit expressed in watts. Power depends on the amount of current and voltage in the system [W]
Photosynthesis	Photosynthesis is a process used by plants and other organisms to convert light energy into chemical energy.
Pressure	The measurement of force within a system. This is the force that moves water through pipes, sprinklers and emitters. Static pressure is measured when no water is flowing and dynamic pressure is measured when water is flowing. Pressure and flow are affected by each other. [bars, psi, kPa]
Priming	The process of hand-filling the suction pipe and intake of a surface pump. Priming is generally necessary when a pump must be located above the water source.
Pump	Converts mechanical energy into hydraulic energy (pressure and/or flow). Submersible Pump - A motor/pump combination designed to be placed entirely below the water surface. Surface Pump - A pump that is not submersible and placed not higher than about 7 meters above the surface of the water.

Root Zone	The depth or volume of soil from which plants effectively extract water from. [m]
Salinity (Saline)	Salinity refers to the amount of salts dissolved in soil water.
Salinization	Occurs when surface water or groundwater containing mineral salts is used for irrigating crops, carrying salts out into the root zone. In the process of evapotranspiration, the salt is left behind in the soil, increasing its salt content.
Solar panel efficiency	Solar panel efficiency is the ratio of light shining on the panel, versus the amount of electricity produced. It is expressed as a percentage. Most systems are around 16% efficient, meaning 16% of the light energy is converted into electricity.
Suction lift	Vertical distance from the surface of the water to the pump. This distance is limited by physics to around 7 meters and should be minimized for best results. This applies only to surface pumps.
Surface irrigation	Irrigation method where the soil surface is used to transport the water via gravity flow from the source to the plants. Common surface irrigation methods are: Furrow irrigation- water is applied to row crops in small ditches or channels between the rows made by tillage implements; Basin irrigation- water is applied to a completely level area surrounded by dikes, and Flood irrigation- water is applied to the soil surface without flow controls, such as furrows or borders.
Transpiration (T)	Liquid water taken up by the plant's roots, contained in plant tissues, and vaporized or transpired into the atmosphere through small openings in the plant leaf, called stomata. [mm, where 1 mm = 10 m3/ha)]]
Voltage (U or V)	Voltage is the electric potential between two points, or the difference in charge between two points, expressed in Volts [V].
Waterlogging	Results primarily from inadequate drainage and over-irrigation and, to a lesser extent, from seepage from canals and ditches. Waterlogging concentrates salts, drawn up from lower in the soil profile, in the plants' rooting zone.
Water Tenure	Refers to the formal and informal arrangements that determine how people, communities and organizations gain access to, and use, water resources (FAO 2016b).

IRRIGATE

1. Introduction

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2. Understand Water Resources

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3. Assess Environmental and Socio-Economic Impacts

↓

4. Calculate Water Requirements

↓

5. Select Field Irrigation Method

↓

6. Plan Intake Structures, Conveyance And Distribution

↓

7. Irrigation Efficiency Tips

MODULE AIM & ORIENTATION

Irrigation is an important means to improving agricultural productivity, but in many developing countries, the potential for irrigated agriculture has not been realized. While irrigation bears obvious benefits, it is not without substantial impact on the environment (and by extension societies and economies dependent on this environment). Numerous technologies and approaches have therefore been developed to minimize the negative environmental and socio-economic effects.

This **IRRIGATE** Module provides an introduction to the complexities surrounding irrigation. It is part of the Toolbox on Solar Powered Irrigation Systems (SPIS) (GIZ FAO, 2017), which comprises further modules and complimentary tools relevant to informed decision making around SPIS.

Furthermore this module is supplemented by two Excel-based tools:

- **IRRIGATE – Soil Tool** for determining an appropriate irrigation schedule for selected crops and calculate water storage capacities

1 INTRODUCTION

IRRIGATION IS ESSENTIAL FOR FOOD SECURITY AND RURAL DEVELOPMENT

Globally, irrigated agriculture accounts for about 70 percent of water withdrawals, making it the largest water user. Irrigated agriculture provides approximately 40 percent of the world's food, including most of its horticultural output, from an estimated 20 percent of agricultural land, or about 300 million ha worldwide (FAO 2011). Most future growth in crop production in developing countries is likely to come from intensification with irrigation increasingly playing a strategic role (AQUASTAT).

In many countries around the world, irrigation has had direct benefits on productivity and food security, typically producing food at higher cropping intensities and at least twice the yields of nearby rain-fed crops (Faurès et al. 2007). It can reduce dependency on rainfed agriculture in drought-prone areas and increase cropping intensities in humid and tropical zones by 'extending' the wet season and introducing effective means of water control. As such, irrigation is often seen as the engine that drives rural development, producing food, providing job opportunities and generating income.

Nevertheless, irrigation has also been associated with negative environmental impacts, including a reduction in water flows, changes in downstream access to water, increased soil salinity or reduction of wetlands that provide important ecological functions for biodiversity, nutrient retention, and flood control. Related changes in land use and unsustainable resources management can lead to quality deterioration and depletion of water resources and associated ecosystems, upon which livelihoods depend.

Moreover, the water quality used for irrigation influences the yield and quantity of crops as well as soil permeability and productivity, and overall ecosystem health. Despite this, water scarcity and pollution levels are so significant in many parts of the world that millions of farmers are driven to irrigate with marginal quality water, such as urban wastewater or saline agricultural drainage water.

The impacts of climate change are already affecting irrigated agriculture as water demand is increasing, crop productivity is reducing, and water availability is becoming more limited in exactly those parts of the world where irrigation is most needed or has a clear comparative advantage.

WHAT MAKES A GOOD SOLAR-POWERED IRRIGATION SYSTEM?

Solar-powered irrigation is typically introduced as a new system, or when an already existing system is being modernised. In the latter case, solar energy replaces conventional forms of energy with photovoltaics (PV). Pumps powered by solar energy may be used to withdraw surface or groundwater resources.

When designing a Solar-Powered Irrigation System (SPIS), it is crucial that the full cycle of the water supply system is taken into account (Figure 1). This includes the water resources, water intake, conveyance and distribution, field irrigation methods, crop water supply, and drainage. Energy in the water supply system stems from the intake, conveyance, and distribution sections via pumping, lifting, and transporting.

Examining these elements, this module provides guidance on some of the key issues around planning and managing a solar powered irrigation system for agriculture.

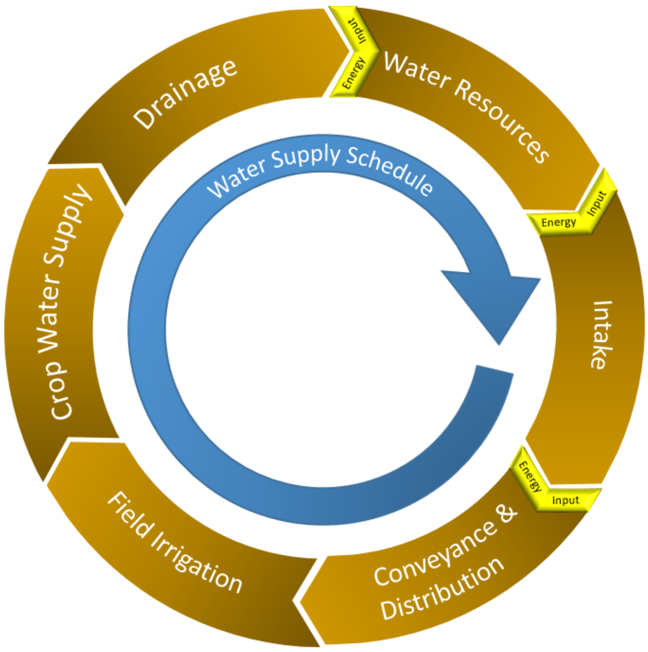


Figure 1: Schematic analysis of agricultural water supply system, adapted from "Irrigation Techniques for Small-scale Farmers" (FAO 2014)

DATA REQUIREMENTS

- Site data, including climate forecasts, farm location, topography, crop rotations desired, area of land to be irrigated, soil type
- Water data, including water quality, quantity, flow, depth and variability
- Information on the design/ layout of the irrigation system

PEOPLE / STAKEHOLDER

- Irrigation system designers & managers, water user groups or farmer organization
- Project managers
- Policy-makers

IMPORTANT ISSUES

- Understand the linkage of the water and energy supply cycle
- Assess climate risks and understand the limitations that exist for the water supply system

OUTCOME / PRODUCT

- General introduction of the role of irrigation in agriculture and potential environmental impacts
- Overview of agricultural water supply system and energy inputs

2 UNDERSTAND WATER RESOURCES

The type of water source, the elevation or depth, the water quantity, resource responsibility, and quality all have a significant influence on establishing boundaries within which crop choices and decisions on the irrigation method can be made. The understanding of these aspects should be a first step in any SPIS planning or implementation project

Sources of water can be surface water, groundwater and non-conventional water. Typically, water for irrigation is extracted from rivers, lakes and aquifers. About 61 percent of the irrigated area worldwide uses surface water, and 38 percent groundwater. In Asia, Northern Africa and the Middle East, groundwater use has grown rapidly in recent years following the introduction of tubewell technology, accompanied by improved energy access and low energy prices (data from 2013, AQUASTAT 2016). Non-conventional sources, such as treated wastewater and desalinated water, provide a minor source of irrigation water globally (about 1 percent). The use of this water for irrigation is focussed in the Mediterranean, Middle East, and Andes regions.

The **elevation** difference between the water source and the field determines whether water can be delivered under pressure. This is particularly relevant for surface water for which it is important to understand whether gravity alone can support pressurised irrigation systems or whether it needs to be supported through pumps. For groundwater, the depth of the water table is decisive for the size of pump and the associated costs. Nowadays, pumps powered by solar energy can lift up water up to 200m (and increasing). However, these pumps are more expensive and less commonly available.

The available discharge from the source (the **quantity of water**) and variability is also important. Understanding what water resources are available, under what conditions, helps in deciding which irrigation method is most appropriate in the given environmental (climate, soils, and landscape) and agricultural context. When and how much does it rain during the year? What are the available surface and groundwater resources? What is the variability of these water resources throughout the year in terms of flow, quantity and quality? How variable is the water availability in the context of climate change? What are the requirements of other users? What are the environmental flow requirements?

The **SAFEGUARD WATER – Water Resource Management Checklist** tool helps to get a rough idea of the availability of water resources. In existing water scarce regions and regions predicted to experience water scarcity over the coming 20 years (See WRI predictions), it is advisable to run a more in-depth water balance analysis and feasibility study with tangible data before installing a SPIS.

A study should be conducted on the aquifer to establish sustainable abstraction rates. The **responsibility** of carrying out this analysis depends on the allocation of resource ownership within the watershed. In most cases it is prudent to establish a basin committee that engages the relevant stakeholders and takes responsibility for the aquifer analysis, as well as permitting, monitoring, and enforcement of abstraction. If resources are managed in a more fractured manner, then the permitting authorities should consider the impacts of their actions on the wider basin, other stakeholders, and the ecosystem. In either arrangement the resilience to future climate scenarios is key to the longevity of agricultural production.

The **quality of water** also needs to be taken into account as it affects the choice of irrigation method and the kinds of crops that can be grown. Both the chemical composition of water and the sediment load can influence this choice. The presence of certain elements, like sodium (Na), chlorine (Cl) and Boron (B), beyond a certain threshold, can cause leaf burn and defoliation under sprinkler irrigation. Similarly, the total concentration of salts in water affects leaching requirements, which makes saline water not very suitable for furrow irrigation. The sediment load of water determines the filtration requirement for drip irrigation and the selection and maintenance program of drippers, hence, its applicability under certain conditions. Similarly, sediments increase the wear of pumps and other components of sprinkler irrigation.

OUTCOME / PRODUCT

- Identification of key factors determining irrigation method
- General overview of how water quantity, quality and variability
- Awareness of environmental hazards that need of specific attention
- Establishment of basin committee or structured means of assessing sustainable abstraction
- Understanding the need for governance of water resources
- Awareness of the risks posed by climate change and the need to be resilient

DATA REQUIREMENTS

- Information on the source of water (surface, groundwater, non-conventional water) and its behaviour (recharge rates, drawdown rates, etc.)
- Information on the elevation between water source and field
- Information on water availability, quality and flows.
- Information on future water availability scenarios
- Information on other user requirements upstream and downstream

PEOPLE / STAKEHOLDER

- Water Resources Management and Licensing Authority
- Hydrological services
- Irrigation managers, water user groups or farmer organization
- Farmers
- Downstream water users
- Environmental protection agencies or similar, environmental NGOs

IMPORTANT ISSUES

- No irrigation development can take place without a legal water abstraction permit or similar.
- Water abstraction quotas are binding and constitute the maximum water availability for peak demand.
- Assess climate risks and understand the limitations that exist for water supply system.
- Regular review of the permits is necessary to ensure resilience and fair allocation of water resources as the climate and water availability change.
- Aquifer and watershed analysis are necessary to understand the hydrological system, foresee impacts of the SPIS, and mitigate negative outcomes.

3 ASSESS ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS

Irrigation and drainage projects invariably result in many far-reaching environmental and socio-economic changes. Some of these benefit human population, while others threaten the long- term productivity of the irrigation and drainage projects themselves as well as the natural resource base. Negative changes are not limited to increasing pollution or loss of habitat for native plants and animals; they cover the entire range of environmental components, such as soil, water, air, energy, and the socio-economic system.

IRRIGATION AND THE ENVIRONMENT

Irrigation makes possible the expansion and intensification of agriculture. Yet, without appropriate management, irrigation development can have significant negative environmental impacts.

At basin level, irrigation schemes can negatively affect the hydrology. Large irrigation projects which store or divert river water have the potential to cause major environmental disturbances, resulting from changes in the hydrology and limnology of river basins. Reducing the river flow changes flood plain land use and ecology and can cause salt water intrusion in the river and into the groundwater of adjacent lands. Diversion of water through irrigation further reduces the water supply for downstream users, including municipalities, industries and agriculture. A reduction in river base flow also decreases the dilution of municipal and industrial wastes added downstream, posing pollution and health hazards.

Groundwater irrigation can increase the risk of over-abstraction, resulting in groundwater depletion, land subsidence, decreased water quality, and saltwater intrusion in coastal areas.

Moreover, it is important to understand how water quality is affected through irrigation development. The quality of water entering the irrigation area is influenced by upstream land uses, particularly when it comes to the sediment content (for example from agriculture-induced erosion) and chemical composition (for example from agricultural and industrial pollutants). The use of river water with a large sediment load may result in canal clogging. Polluted return flows, containing harmful concentrations of salts, organic wastes, agrochemical residues or other substances, lead to the degradation of downstream ecosystems. Increased nutrient levels in the irrigation and drainage water can result in algal blooms, proliferation of aquatic weeds, and eutrophication in irrigation canals and downstream waterways.

At field level, there is a great risk of waterlogging and salinization. Irrigation-induced salinity can arise as a result of the use of saline water, irrigation of saline soils, and rising levels of saline groundwater combined with inadequate leaching. Salinity reduces plant growth and soil productivity. Salt-affected soils are more fragile and prone to erosion. In the case of sodic soils, the loss of organic matter leads to weakened soil structures, increased carbon dioxide emissions, and decreases water infiltration due to surface sealing. This inevitably affects agricultural productivity, yields, and farmers' incomes.

Irrigated lands, especially areas with high water tables, typically require drainage to avoid waterlogging. Because groundwater drainage is a complex and expensive operation (often more expensive than the initial development of irrigation itself), there is a temptation to start new irrigation projects while ignoring the need for drainage or delaying its installation until it is urgently needed. However, by the time the need for drainage becomes inescapable, the cost of implementing it may be prohibitive.

Monitoring water tables by means of observation wells (piezometers) as well as groundwater quality is crucial. This can provide an early warning of the danger of salinization and groundwater depletion.

Table 1 Potential Negative impacts of irrigation schemes

Increased evaporation in the scheme
Degradation of irrigated land
• Salinization
• Alkalisation
• Increased groundwater recharge, waterlogging and drainage problems
• Soil acidification
• Soil compaction
• Soil erosion
Poor water quality
• Reduction in irrigation water quality and leaching
• Water quality problems for downstream users cause by irrigation return flow quality
Groundwater depletion
• Drying up of drinking and irrigation wells
• Saltwater intrusion along coasts
• Reduced base flow
Reduced downstream river discharge
Ecological degradation
• Reduced biodiversity in irrigated and surrounding area
• Damage to downstream ecosystems due to reduced water quantity and quality
Negative impacts on human health
• Increased incidence of water-related diseases

CAN SOLAR-POWERED IRRIGATION HELP IMPROVE WATER USE EFFICIENCY?

The introduction of solar technology can be coupled with more water efficient irrigation methods that can help improve the water application efficiency in the field. Nevertheless, there is a risk that instead of saving water, this may actually lead to increased water consumption in situations where no barrier exists to encourage or incentivize efficient water use. Farmers may (i) apply more water in the field overall (for example, when shifting from deficit to optimal irrigation), (ii) expand the area of land under irrigation, (iii) shift to higher value, but often more water-intensive crops, (iv) sell water to neighbouring farmers and communities. This is particularly an issue in areas where groundwater resources are already overexploited and recharge rates are slow.

It may be important to distinguish between the following concepts:

Water Use Efficiency represents the ratio between effective water use and actual water withdrawal. It characterizes, in a specific process, how effective the use of water is. Efficiency is scale and process dependent.

Irrigation Efficiency: The ratio or percentage of the irrigation water requirements of crops on an irrigated farm, field or project to the water diverted from the source of supply.

Scheme Irrigation Efficiency: The scheme irrigation efficiency (in %) refers to the water pumped or diverted through the scheme inlet, which is effectively consumed by the plants.

The scheme irrigation efficiency can be sub-divided into:

- The **conveyance efficiency**, which represents the efficiency of water transport in canals. It mainly depends on the length of the canals, the soil type or permeability of the canal banks, and the condition of the canals.

- The **field application efficiency,** which represents the efficiency of water application in the field

UNINTENDED CONSEQUENCES OF EFFICIENCY

It is often argued that SPIS in combination with drip irrigation will ensure that water is efficiently used at field level. Drip and sprinkler systems allow farmers to improve the timing and distribution uniformity of irrigation, which can enhance crop yields, such that transpiration per hectare increases. The prospect of higher returns per hectare, however, will encourage some farmers to expand planted area or to switch to higher-value, more water-intensive crops (Berbel and Mateos, 2014). Assuming drip irrigation will automatically lead to water savings at the farm level is a fallacy.

Water efficiency at field or farm level can also have implications at basin level. Water resource systems are highly integrated, and apparent gains (in terms of water use efficiency) in one part of the system can be offset by real losses in other parts of the system. Rainfall, surface water, groundwater, soil moisture and rates, and processes of evaporation from different land uses are all part of the same hydrological cycle and cannot be regarded as separate. Changes in water use in one domain may lead to unintended or undesirable consequences locally or downstream.

SOCIO-ECONOMIC IMPACTS

The main objective of irrigated agriculture is to increase agricultural production and consequently improve the economic and social well-being of the people using it. However, changing land use patterns due to irrigation may have other socio-economic impacts too such as land tenure, water tenure, and changes in labour inputs for construction, operation, and maintenance.

Small plots, communal land use rights, and conflicting traditional and legal land rights all create difficulties when land is converted to irrigate agriculture. Traditional land tenure arrangements are likely to be disrupted by major development and rehabilitation works (e.g. building of dams, reservoirs, and canals). The most significant impact would be the resettlement of people. This can be particularly disruptive to communities and requires sensitive project development and adequate compensation. Land use change such as new irrigation development can also negatively affect those using the land for other purposes as well as the local biodiversity. Other uses of land such as hunting, grazing, collecting fuel wood, charcoal making, or growing vegetables are negatively impacted if the same land is then used for irrigated mono-cropping agriculture. Women, migrant groups and poorer social classes have often lost access to resources and gained increased workloads. Conversely, the increased income and improved nutrition from irrigated agriculture may benefit women and children in particular.

Similar problems can arise as a result of changes to water access and infrastructure. Such developments often increase inequity in opportunity. For example, land owners benefit in a greater proportion than tenants or those with communal rights to land.

These socio-economic impacts need to be assessed and taken into account in the planning processes of irrigation schemes or their modernization. This may be less relevant for individual pumping units or projects using community-led design, planning and management. It should ensure that the needs of local communities and users are met and potential challenges are foreseen with mitigation measures in place should they arise.

POTENTIAL HEALTH IMPACTS OF IRRIGATION

The risks of water-borne or water-related disease increase in areas that lack adequate drainage of canals and soil, have unlined canals and unchecked vegetation growth, or are left with stagnant water (e.g. pits, but also on rice or sugar cane fields). For diseases, such as malaria, bilharzia (schistosomiasis) and river blindness (onchocerciasis), vectors proliferate in the irrigation waters.

Other irrigation-related health risks include those associated with increased use of agrochemicals, deterioration of water quality, and increased population pressure in the area. The reuse of wastewater for irrigation has the potential, depending on the extent of treatment, to transmit communicable diseases. The population groups at risk include agricultural workers, consumers of crops and meat from the wastewater-irrigated fields, and people living nearby.

ENVIRONMENTAL ASSESSMENT TOOLS

Wise management of the environment requires an ability to forecast, monitor, measure and analyse environmental trends and assess the capabilities of land and water at different levels, ranging from a small irrigated plot to a catchment. Adoption of environmental impact assessments (EIAs) will enable countries to plan water and land use in an integrated manner, avoiding irreversible environmental damage.

The **PROMOTE & INITIATE – Impact Assessment Tool**, based on the ICID Environmental Check-List to Identify Environmental Effects of Irrigation, Drainage and Flood Control Projects" (Mock and Bolton, 1993) can serve as a starting point.

WATER ACCOUNTING

It is important to systematically study the current status and trends in water supply, demand, accessibility and use (FAO 2012). This is called water accounting. By evaluating return flows, measuring both basin and field efficiencies, and distinguishing between consumptive and non-consumptive savings, water accounting helps to address questions, such as: What are the underlying causes of imbalances in water supply (quantity and quality) and demand of different water users and uses? Is the current level of consumptive water use sustainable? What opportunities exist for making water use more equitable or sustainable (FAO 2016)? This assessment should be made prior to the SPIS, to establish a baseline, as well as periodically after implementation to measure the changes due to irrigation.

When assessing the impacts of solar-powered irrigation on water use efficiency, it is important to distinguish between these different levels of analysis (field/ farm/ scheme/ basin) and to carry out systematic water accounting to understand what options there are for optimising water use overall.

These efforts need to be complemented by appropriate regulation and policies. Subsidies may follow specific criteria (e.g. only in areas where groundwater is not overexploited) or provide incentives to use water, tenders may set standards (e.g. a groundwater metering system will be integrated in the solar pump), regulation may restrict SPIS use at certain times or places. If all this is considered, SPIS has the potential to fundamentally improve the lives of many people. For more information on this please refer to the 2017 FAO report "*The Benefits and Risks of Solar Powered Irrigation – A Global Overview*".

ENVIRONMENTAL MANAGEMENT TOOLS

Many of these negative environmental impacts can be addressed through effective planning and implementing of environmental protection and conservation measures.

Not only can negative impacts be reversed, but with an integrated management approach, further benefits can be reaped. Irrigation, for instance, can play a positive role in land use management. By intensifying food and forage production in the most favourable lands, for example, pressure on marginal lands can be reduced, using them for rain-fed agricultural production or grazing. Dams and reservoirs offer ways to mitigate the potential negative impacts of changes to flood flows but require care in planning to not disrupt the flow to downstream users and environments. Planning irrigation systems with designated flood plains and provisions for natural infrastructure, like wetlands, can improve groundwater recharge and attenuate peak discharge flows.

Further information on sustainable land, soil and water management practices can be found here:

http://www.fao.org/land-water/land/sustainable-land-management/slm-practices/en/

SOIL SALINITY ASSESSMENT

Soil Salinity Assessment. FAO Irrigation and Drainage Paper 57. www.fao.org/docrep/019/x2002e/x2002e.pdf

Visual Soil Assessment Field Guides by FAO http://www.fao.org/3/a-i0007e.pdf

LAND DEGRADATION ASSESSMENT

Land Degradation Assessment in Dry Lands by FAO www.fao.org/fileadmin/templates/nr/kagera/Documents/LADA_manuals/MANUAL2_final_draft.pdf

WATER QUALITY

USGS *Water Quality Assessment – Field Methods and Techniques*: https://water.usgs.gov/owq/methods.html

SOCIO ECONOMIC CHECKLIST

PROMOTE & INITIATE – IMPACT ASSESSMENT TOOL

OUTCOME / PRODUCT

- Understanding of the links between irrigation, the environment, and society
- Understanding of the risks SPIS poses to environmental flows and the options for risk mitigation
- Awareness of efficiencies in solar powered irrigation systems
- Awareness of the impacts on and roles of water rights, land rights, and gender equality in the socio-economic ecosystem
- Awareness of health impacts and delayed costs posed by poorly planned irrigation schemes and lack of adequate drainage
- Understanding of water accounting and the potential policies, subsidies, and governance systems that can produce responsible irrigation systems
- Awareness of tools available for environmental management

DATA REQUIREMENTS

- Data necessary for environmental management tools
- Baseline data to monitor the socio-economic and environmental impacts of irrigation (gender data, income data, biodiversity data, employment data, water use, water quality, health data, behavioural data from government interventions, land use change, soil data, etc.)

PEOPLE / STAKEHOLDER

- Irrigation planners/ system managers
- Policy makers
- Water Resources Management and Licensing Authority
- Irrigation managers, water user groups or farmer organization
- Environmental protection agencies or similar, environmental NGOs

IMPORTANT ISSUES

- The far-reaching impacts, both positive and negative, of solar powered irrigation schemes
- The importance of upfront planning for drainage, public health, and inclusive basin wide development
- The need to engage in baseline data collection

- Understand the different efficiencies in SPIS and recognize the potential negative consequences
- Use nature-based solutions as measure to understand the impact of irrigation on land use, biodiversity, and potential climate change mitigation, adaptation, and resilience
- Understand that land rights, water rights, and gender issues interact with land use and agricultural productivity

4 CALCULATE WATER REQUIREMENTS

Understanding when, where, and how much water is needed for agricultural production and other uses is crucial for efficient water management.

CROP WATER REQUIREMENTS

Crop water requirements are defined as the total amount of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally.

The crop water requirement always refers to a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and favourable soil conditions (including fertility and water). The crop thus reaches its full production potential under the given environment.

The crop water need mainly depends on:

- *Climate*: in a sunny and hot climate crops need more water per day than in a cloudy and cool climate
- *Crop type*: crops like maize or sugarcane need more water than crops like millet or sorghum
- *Growth stage of the crop*: fully grown crops need more water than crops that have just been planted.

Table 2 Impact of climate conditions on crop water needs (Source: FAO 1989)

Climatic Factor	Crop water need	
	High	Low
Temperature	hot	cool
Humidity	low (dry)	high (humid)
Windspeed	windy	little wind
Sunshine	sunny (no clouds)	cloudy (no sun)

Nevertheless, real-life conditions are rarely optimal and there are many other factors that also influence evapotranspiration rates. Factors such as soil salinity, poor land fertility, limited use of fertilizers and chemicals, lack of pest and disease control, poor soil management and limited water availability at the root zone may limit crop development and reduce evapotranspiration.

Other factors that affect evapotranspiration are groundcover and plant density. Cultivation practices and the type of irrigation system can alter the microclimate, affect the crop characteristics, and affect the wetting of the soil and crop surface.

IRRIGATION WATER REQUIREMENTS

Irrigation water requirements refer to the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements. If irrigation is the sole source of water supply for the plant, the irrigation requirement will always be greater than the crop water requirement to allow for inefficiencies in the irrigation system. If the crop receives some of its water from other sources (rainfall, water stored in the ground, underground seepage, etc.), then the irrigation requirement can be considerably less than the crop water requirement.

In humid climates, precipitation and soil moisture can be sufficient for to ensure satisfactory growth in rainfed agriculture. In arid climates or during extended dry seasons, however, irrigation is necessary to compensate for the evapotranspiration (crop transpiration and soil evaporation) deficit due to insufficient or erratic precipitation.

In order to understand how much irrigation water is required, an analysis of the water balance is needed. There are three levels to such an analysis.

The first is the balance of agricultural and other demands within a watershed. This helps establish the safe yield of water from various sources and thereby how much irrigation is possible within sustainable margins see module **SAFEGUARD WATER**.

Another water balance perspective is at farm (or command area) level. Fields are often not irrigated individually, but they share the water delivered through a canal or well. They also often share drainage channels. A water balance at the farm looks at the access to water, priority uses, timing and duration of irrigation. This is the basis for efficient design of the system and delivery of services.

A third perspective looks at the water requirements of crops in a field. Providing the crop with irrigation at the appropriate time and in the appropriate quantity requires experience and will depend on climate, rainfall, soil and crops stage, as well as the field irrigation system and irrigation technology used.

Special computerized irrigation programmes, such as the FAO CROPWAT programme, may be used to advise farmers on water supply and irrigation schedules for the given climatic conditions, crop, soil and field irrigation method.

The **SAFEGUARD WATER – Water Requirement Tools** and the **IRRIGATE– Soil Tool** may be useful in roughly assessing the crop water supply needed.

IRRIGATION SCHEDULING

Once the crop water and irrigation requirements have been calculated, the next step is the preparation of field irrigation schedules. Three parameters have to be considered in preparing an irrigation schedule:

- The daily crop water requirements
- The soil, particularly its total available moisture or water-holding capacity
- The effective root zone depth

Plant response to irrigation is influenced by the physical condition, fertility and biological status of the soil. Soil condition, texture, structure, depth, organic matter, bulk density, salinity, sodicity, acidity, drainage, topography, fertility and chemical characteristics all affect the extent to which a plant root system penetrates into and uses available moisture and nutrients in the soil. Many of these factors influence the water movement in the soil, the water-holding capacity of the soil, and the ability of the plants to use the water. The irrigation system used should be able to function under all or most of these conditions.

In the field, the actual value may vary from site to site, season to season and even within the season. Within the season, it varies depending on the type of farm and tillage equipment, number of tillage operations, residue management, type of crop, and water quality.

Soils to be irrigated must also have adequate surface and subsurface drainage, especially in the case of surface irrigation. Internal drainage within the crop root zone can either be natural or from an installed subsurface drainage system.

WHAT CROPS ARE BEST SUITED FOR SOLAR-POWERED IRRIGATION?

There are no crops that are particularly suitable (or unsuitable) for solar-powered irrigation as long as the irrigation method can meet crop water requirements and is compatible with farming practices, climate, water resources, and other agronomic aspects.

The cropping pattern should be such that the selected crop can be successfully grown under the prevailing climate and soil conditions, and the irrigation system should be compatible with crops and agricultural practices. Furthermore, adequate attention should be given to the selection of the crops and cropping calendar. Crops should be marketable at economic prices.

SELECTION OF SUITABLE CROPS FOR IRRIGATION

Specific agronomic aspects to be considered include the following:

- Cropping calendar of present common crops grown in the area during the wet and dry seasons, indication of seasonal hazards (drought, floods, pests and diseases)
- New crops with good potential to be introduced under irrigation
- Crops for self-sufficiency and (household/ national) food security
- Crops destined for the market
- Experience, motivation and priorities given by farmers in selection of the crops.

The use of crops or varieties with greater resilience to dry spells is preferable. This can also help farmers to adapt to changing temperatures and rainfall patterns. Increased agricultural diversification, including better integration of trees, crops, fish and livestock can reduce risk and increase the resilience of farming systems.

Some crops are sensitive to the way water is applied to them. Systems, which wet the whole crop, such as sprinkler irrigation, may have undesirable consequences, such as leaf burn, fruit spotting and deformation, crown rot, and other. These considerations would influence the choice of the irrigation method (Savva and Frenken 2004).

As a rule, most vegetable (and other row) crops have shallow effective root zone depth and respond better to low moisture depletion levels. They are therefore well suited for localized, drip irrigation, which is often linked to PV powered pumps.

It is important to note that plant breeding and biotechnology can help by increasing the harvestable parts of the biomass, reducing biomass losses through increased resistance to pests and diseases, reducing soil evaporation through vigorous early growth for fast ground cover, and reduced susceptibility to drought (FAO 2012).

In selecting suitable crops, farmers need to ensure that they have access to agricultural inputs, such as quality seeds, fertilizers, pesticides and tools, as well as credit to buy the necessary inputs.

SUITABLE AGRICULTURAL PRACTICES AND INPUTS

- Present agricultural practices of common crops grown in terms of inputs, labour and tools;
- New or improved agricultural practices to be introduced for the irrigated crops to ensure optimum production levels
- Assessment of inputs required for optimal production in terms of quality seed, organic and inorganic fertilizers, tools, availability of inputs, and access to credit.

OUTCOME / PRODUCT

- Understanding of what affects crop water requirements
- Recognizing the difference between crop water requirements and irrigation water requirements
- Incorporating the different perspectives of water requirements into the irrigation plan
- Incorporating the necessary parameters in irrigation scheduling and drainage design

DATA REQUIREMENTS

- Crop rotations planned
- Schedule of planting and harvesting
- Consumption requirements of other water users in the basin
- Future climate scenarios for the area

PEOPLE / STAKEHOLDER

- SPIS advisors
- Farmers

- Irrigation managers, water user groups or farmer organization

IMPORTANT ISSUES

- The CWR and IWR need to be resilient to future climate scenarios
- Irrigation schemes require planning at multiple scales, from basin to farm to individual crop
- The soil health and type are key to calculating the water requirements
- Boundaries on seasonal water availability should influence the crop choice balancing CWR, other user requirements, and water availability
- Soil drainage should be an upfront concern and consideration
- Choice of crops should also factor in other availability of other inputs such as labour, fertilizer, tools, herbicides, etc.

5 SELECT FIELD IRRIGATION METHOD

The vast majority of the total global irrigated area is equipped for full control irrigation. Full control irrigation methods differ in the way water is distributed (AQUASTAT)

Once the crop requirements, water resources, and impacts of implementing a SPIS are understood, the appropriate irrigation methods can be selected.

WHAT IRRIGATION METHODS ARE THERE?

Surface irrigation uses gravity to move water over land. This category can be subdivided into small channels (furrows), strips of land (borders) and basin irrigation (including submersion irrigation of rice).

Surface irrigation is widely utilised and therefore a well-known system, which can be operated without any high-tech applications. In general, it is more labour intensive than other irrigation methods. When designing a surface irrigation system, the soil type (texture and infiltration rate), slope and levelness of the field, stream size and length of run should be taken into account. It is generally more difficult to obtain a high uniformity of water distribution in long fields on coarse textured soil (gravels and sand) than on fine textured soils (loams to clay). Levelling the field and building water ditches and reservoirs may be expensive, but once this is done, costs are low and the farmer has greater capacity to respond to changing demand for irrigation.

Sprinkler irrigation consists of a pipe network, through which water moves under pressure before being delivered to the crop via sprinkler nozzles. The system basically simulates rainfall in that water is applied through overhead spraying.

The pump is usually a centrifugal pump, which takes water from the source and provides adequate pressure for delivery in the pipe system. Mainline and sub-mainline pipes deliver water from the pump to lateral pipes. The laterals then deliver water to the sprinklers. They can be permanent, but more often they are portable and made of light material (e.g. aluminium) that is easy to carry.

Rotor-type sprinklers operate by rotating streams of water over an area of land. This includes impact and gear-drive sprinklers, producing streams of water, and spray nozzles that discharge water in patterns.

Due to the high-capital investment costs, the more elaborate systems (e.g. centre pivots, side roll systems etc.) are typically used for high-value crops, such as vegetables. A higher-level of expert knowledge is needed to operate the systems, even though the overall labour requirement is low due to the high level of automation. Motors, pipes and other mechanical components all need to be systematically maintained to avoid damage and high repair or replacement costs.

Sprinkler irrigation is suited for most row, field and tree crops, and water can be sprayed over or under the crop canopy. However, large sprinklers are not recommended for delicate crops, such as lettuce, because the large water drops produced by the sprinkler may damage the crop.

Localized irrigation consists of "water being distributed under low pressure through a piped network, in a pre-determined pattern, and applied as a small discharge to each plant or adjacent to it" (AQUASTAT 2016).

A typical **drip irrigation** system has a pump unit, a control head, mainlines and sub-mainlines, lateral lines and emitters or drippers. It may also feature reservoir tanks, filters and fertigation devices.

With drip irrigation, water is applied more frequently (usually 1-3 times a day) than with other methods, providing a favourable high level of soil moisture. As long as the water application rate is below the soil's infiltration capacity, the soil remains unsaturated and no free water stands or runs over the surface. This way water resources can be used very efficiently and water losses can be reduced to a minimum.

Moreover, fertiliser and nutrients can be used with high efficiency as water is applied locally and leaching is reduced. Weed growth is reduced as water and nutrients are supplied only to the cultivated plant.

Nevertheless, drip irrigation has a high initial investment cost as well as it requires a high-level of technical knowledge and regular investments to replace equipment, which is vulnerable to clogging and dysfunction, especially when water quality is not optimal. There also is a risk of rising soil salinity.

The method is suitable for most soils. On clay soils, water must be applied slowly to avoid surface water ponding and run-off. On sandy soils, higher emitter discharge rates will be needed to ensure adequate lateral wetting of the soil.

Drip irrigation is most suitable for row crops, such as vegetables and fruits, tree and vine crops. Given the high investment, drip irrigation tends to be used for high-value crops.

Other types of irrigation include:

Equipped lowland areas, such as (i) cultivated wetland and inland valley bottoms that have been equipped with water control structures for irrigation and drainage; (ii) areas along rivers where cultivation occurs making use of structures built to retain receding flood water; (iii) developed mangroves and equipped delta areas.

Spate irrigation, using floodwaters of ephemeral streams and channelling it through short steep canals to where cropping takes place. Dams are often built in the streams to be able to store the water whenever it arrives.

WHAT IRRIGATION METHOD IS BEST SUITED FOR SOLAR-POWERED SYSTEMS?

PV water pumping systems have shown significant advancements in the last decade. The limitations in the design of solar pumps from the 1970s – such as terminals that did not readily provide good electrical connection or overheated electronic circuitry - have been overcome, and solar pumps are now much more efficient and reliable.

Nowadays, they can support drip, sprinkler, pivot or flood irrigation technologies. Systems range from sophisticated computer controlled setups with high start-up costs to moderate-cost systems that include bubblers, mini-sprinklers and drip irrigation.

Generally, the size – and cost – of the solar pumping system is determined by the water and pressure requirements of the irrigation system. Methods working at comparably low operating pressures are often the preferred option in combination with PV pumps.

Sprinkler irrigation requires relatively high water pressure to operate, which demands a specific SPIS composed of high capacity solar modules and an integrated energy storage capacity (battery). In contrast, drip irrigation requires low pressure and have the potential to apply water more efficiently.

Drip irrigation – also known as micro-, localised, or trickle irrigation – uses networks of pipes and tubes to apply water directly to the soil surface or root zone of plants. It has the potential to reduce the ‘drop per crop’ water consumption through minimising non-productive evaporative losses (e.g. Narayanamoorthy, 2004; Rijsberman, 2006). Another advantage is that moderately saline water may be used for irrigation. Marginal plots of land may be used productively as drip irrigation techniques can deliver required water and nutrients directly to the plants.

Drip irrigation is ideal for high-value crop production such as vegetables and fruits, tree and vine crops, and due to its high efficiency, the solar pump can be quite conservatively sized.

Nevertheless, drip irrigation comes at a high initial capital cost and requires sufficiently good quality water (to avoid clogging of the emitters) or a pre-treatment system. Moreover, good irrigation management is needed to operate the system effectively, apply fertigation and maintain equipment.

Table 3 Suitability of irrigation methods for solar pumps, adapted from “Manual and Tools for promoting SPIS – Stocktaking and Analysis Report” (2015).

Irrigation method	Typical application efficiency	Suitability for use with solar pump
Flood	40-50%	Depends on local conditions
Open channels	50-60%	Depends on local conditions
Sprinkler	70-80%	Yes
Drip	85-95%	Yes

Beyond these technical considerations, there are other factors determining the suitability of irrigation methods regardless of the source of energy powering the pumps. These include natural conditions such as:

- *Soil type*, determining water storage capacity and infiltration rate;
- *Slope of land*, influencing water drainage and whether land needs levelling;
- *Climate*, including winds (e.g. that may disturb spray from sprinklers), sun radiation and precipitation patterns, and temperature;
- *Water availability,* see Section 2
- *Water quality,* see Section 2
- *Resilience* requirements, see Section 2

It is also important to consider the type of crop grown both from an economic as well as from an agronomic point of view. Due to the higher capital investment costs per hectare, sprinkler and drip irrigation are commonly used for high-value cash crops, such as vegetables, fruit trees and spices. Drip irrigation is better suited for individual plants, trees or row crops.

There are also other socio-economic aspects to consider when selecting the irrigation method. Labour input is one such factor. The construction, operation and maintenance of surface irrigation often requires higher labour input than sprinkler or drip. Surface irrigation requires accurate land levelling, regular maintenance and a high level of farmers’ organisation to operate the system. Another aspect to consider are unexpected complications when introducing new irrigation methods. Getting farmers to change practices and servicing the equipment may be challenging.

When selecting an irrigation method, these aspects needs to be weighted and a cost/benefit analysis of the available options needs to be made. Costs include the capital investment, construction and installation as well as operation and maintenance, including energy. These costs should be compared to the expected benefits, including yields, market prices, avoided operational costs, and labour savings. This cost benefit analysis is explained in further detail in the SPIS Toolbox section on financing.

OUTCOME / PRODUCT

- Understanding the different irrigation methods and their respective advantages / disadvantages
- Ability to incorporate the natural conditions that affect irrigation into the choice of irrigation method
- Appropriate application of the cost benefit analysis
- Understanding the trade-offs involved in different irrigation methods regarding capital and operational costs, water efficiency, and increased agricultural production and income.

DATA REQUIREMENTS

- Water pressure
- Seasonal water availability (sustainable abstraction allowance)
- Water quality
- Soil type
- Slope of land
- Capital, operational, and maintenance costs
- PV efficiency and power available
- Power requirement of different irrigation methods

PEOPLE / STAKEHOLDER

- Policy makers
- Irrigation advisors/ planners
- Irrigation managers, water user groups or farmer organization
- Farmers

IMPORTANT ISSUES

- Different irrigation methods exist that provide different benefits and drawbacks
- The ultimate decision of which irrigation method to use should be a balance of the financial and environmental costs / benefits over the life of the asset

6 PLAN INTAKE STRUCTURES, CONVEYANCE AND DISTRIBUTION

The principal engineering challenge of any irrigation system consists in withdrawing water from a source, delivering it to land in due time and in the required amount, distributing it among individual farms and crop-rotation fields, and providing soil moisture needed for plants on fields. All this requires energy to move water, maintain pressure and ensure quality.

The operation of the system should offer enough flexibility to supply water to the crop in variable amounts and schedules that allow the irrigator some scope to manage soil moisture for maximum yields as well as water, labour and energy conservation.

Water may be supplied on a continuous or a rotational basis in which the flow rate and duration may be relatively fixed. In those cases, the flexibility in scheduling irrigation is limited to what each farmer or group of farmers can mutually agree upon within their command areas. At the preliminary design stage, the limits of the water supply in satisfying an optimal irrigation schedule should be evaluated (see Section 1).

INTAKE STRUCTURE

The *intake structure* is used for water withdrawal from an irrigation source and delivery to an irrigation network. These can be gravity and water-lifting types.

Pumps powered by solar energy can be used both for surface water and groundwater withdrawal. There are two main types of pumps: centrifugal pumps and positive displacement pumps. Both can be used for SPIS.

Solar-powered pumps have to be oversized to meet peak demand, which means they tend to be underutilised during the off-season. To a certain extent, this seasonal variability in water demand can be balanced by adapted crop rotations (including permanent crops) and irrigation management.

The performance of solar-powered pumps depends on the crop water requirements, size of water storage, head (m) by which water has to be lifted, volume of water to be pumped (m^3), PV array virtual energy (kWh), energy at pump (kWh), unused PV energy (kWh), pump efficiency (%), system efficiency (%), and diurnal variation in pump pressure due to change in irradiance and pressure compensation. All this needs to be considered when designing the SPIS and is best done by an expert.

The fluctuations in solar irradiance, the accumulation of dust on PV modules and high air temperatures affect the performance of the PV systems and hence the pump. Spraying clean water on the PV modules results in cleaning the dust as well as cooling of modules improves the module efficiency and hence the water flow rate. Therefore, PV modules should be easily accessible for maintenance purposes.

The **DESIGN – Pump Sizing Tool** can be helpful in ensuring that the pumping system is designed to purpose and to avoid unnecessary pressure loss.

CONVEYANCE AND DISTRIBUTION

Once the water has entered through the intake structure, it needs to be delivered through *conveyance and distribution systems*. Typical conveyance and distribution systems are diversion dams, lined or partially lined canals and ditches, pipelines, hydrants and other means.

A distinction can be made between water provision for lands of a single (on-farm irrigation system) or several (inter-farm irrigation system) farms, associations of farms and agricultural enterprises, and even several administrative centres.

A badly planned conveyance and distribution system can lead to high water losses, poor irrigation efficiency and much smaller areas than planned being irrigated.

Design software is available for irrigation system planning. For example, GESTAR is a software developed by the Faculty of Fluid Mechanics at the University of Zaragoza and can be used to size medium to large-scale irrigation schemes. GESTAR tools and methods are specifically designed for pressurized irrigation (such as sprinkler and drip irrigation). Planning tools specific to an irrigation method also exist.

WHAT ARE THE IMPLICATIONS OF SOLAR-POWERED IRRIGATION FOR ENERGY?

SPIS can provide a reliable and affordable source of energy in rural areas, potentially reducing energy costs for irrigation and reducing greenhouse gas emissions associated with fossil fuel pumping systems.

Irrigation systems use energy to lift water from a well or reservoir, to pressurize water to overcome friction losses in pipes and to distribute water evenly over the soil. Pumps are typically powered by diesel or electrical energy, with the latter supplied from the grid, or by decentralized energy sources.

- **Energy efficiency**: How efficiently irrigation systems use water and energy is determined primarily by the type of system and the way it is operated, maintained, and managed. When specifying pump size and designing water distribution systems, engineers consider the distance the water has to be lifted and transferred, the depth from which water needs to be transported, and the friction caused within pipes and channels as determined by layout, diameter and operating pressures. They should also consider the system resilience to future climate scenarios and changes in groundwater levels that may occur through widespread implementation of SPIS.

  Energy savings can be made through efficient design (e.g. pipe layout), appropriately sized pumps, and optimised equipment (e.g. variable speed drives). A further consideration is the trade-off between water application efficiency and energy efficiency. For instance, forcing water through a drip irrigation network will use more energy than running it through channels and furrows, but this type of system will apply water more efficiently than a more energy-efficient centre pivot irrigation system.

- **Energy costs**: Pressurised systems tend to be more efficient, but have higher energy requirements and thus higher energy costs. These costs depend on the source of energy, energy price per unit as well as other factors, such as the depth of the aquifer from where the water is pumped. As such, the energy costs can potentially undo any cost savings that were anticipated when investing in making irrigation systems more efficient. It leaves scope for interventions at technical and management level to improve both water and energy use efficiency and to reduce operating costs.

  Solar-powered photovoltaic systems can provide an economically viable alternative source of energy without emitting greenhouse gas emissions. They also have the advantage of not depending on the availability and costs of fossil fuels.

  Nevertheless, it requires some prior knowledge of how to set-up and use solar pumps optimally. In contrast to motor-driven pumps, the dimensioning of PV irrigation systems is a critical strategic decision for farmers, given the initially higher investment costs and the complexity in designing, operating and maintaining the system. Usually this is done by technical experts. Training of farmers is necessary to operate the PV system for maximum benefits.

Although costs have decreased significantly in recent years, the economic viability of PV systems varies, especially for small-holder farmers for whom a solar pump represents a substantial investment. Thus, the economic viability of such an investment needs to be assessed to understand whether the introduction of PV pumps is economically viable.

The **INVEST – Payback Tool** can be useful in assessing the costs of solar systems vs. other types of energy systems for irrigation.

OUTCOME / PRODUCT

- Understanding of the different aspects of an irrigation system
- Overview of how to size pumps and other parts of a SPIS
- Recognition of the long-term cost savings from installing a SPIS
- Understanding of the need to design in resilience and adaptability to the system

DATA REQUIREMENTS

- Water volume and pressure required
- Pump size, pump cost, electricity requirements
- PV system size requirement and cost
- Ancillary structures and systems, sizes, and costs

PEOPLE / STAKEHOLDER

- Irrigation system planners
- Irrigation managers, water user groups or farmer organization
- Farmers
- Financers

IMPORTANT ISSUES

- Careful life-cycle cost-benefit analysis should be carried out
- Resilience and adaptability should be built into the system by design
- A poorly designed system can be damaging to the environment and other watershed users
- Technical expertise are required for the sizing, installation, and maintenance of such systems

7 IRRIGATION EFFICIENCY TIPS

Irrigation water is a precious resource. This not only applies directly to agricultural production, but also indirectly to the ecosystem at large. The wise use and conservation of irrigation water is hence essential. A number of best practices and tips can reduce overall water consumption, improve plant growth and lead to higher yields.

MAP IT OUT

Review the layout of the land and map the optimal placement of irrigation piping, with attention to reducing the number of fittings used (prone to leakages). Keep in mind that slopes would cause an uneven distribution of water and could result in run-off. Hence levelling and terracing is advised when using flood or sprinkler irrigation (drip lines should run horizontal to the slope). Sprinkler irrigation disperses water in a circle around the central nozzle. Determine the radius and place sprinklers in such a fashion that overlaps are kept to a minimum, while still ensuring that a maximum area is covered (i.e. few dry areas remain).

PRESERVE TREES

Ideally, large trees should remain in the crop area. Not only do they provide moving shade, but certain species (e.g. acacias) support nitrogen-fixing bacteria which enhance soil fertility.

ACROECOLOGICAL APPROACH

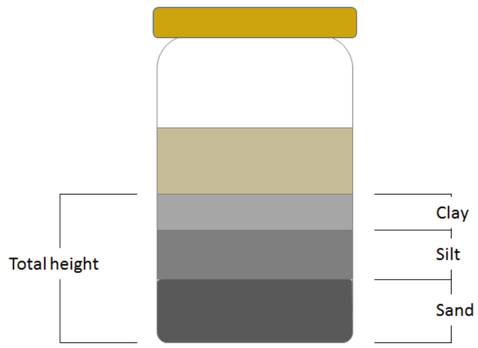
The [ten agro-ecological principles] outlined by the FAO highlight aspects that relate to water resources, use, reuse, governance, and rights. These principles also provide a means to look beyond the farm level intervention to impacts in the wider community and food system.

The **PROMOTE & INITIATE – Impact Assessment Tool** incorporates, to some extent, these principles.

SOIL TESTING

Soil moisture available to plant roots is depended on soil type. The soil type can be determined in the laboratory using a particle size analysis. Sand, silt and clay have different diameters, by sieving them their distribution delivers information about the soil type. Another way to determine the soil type is the "Jar Test":

1. Remove soil from the zone to be irrigated
2. Place the soil sample into the jar (halfway) and fill it with water (until two-thirds full)
3. Shake the jar and let it sit for two hours, the particles will settle to the bottom, in their different layers
4. Measure the total height of all layers, then the height of each layer.
5. Divide the height of each layer by the total height which gives you the percentage of clay, silt and sand.

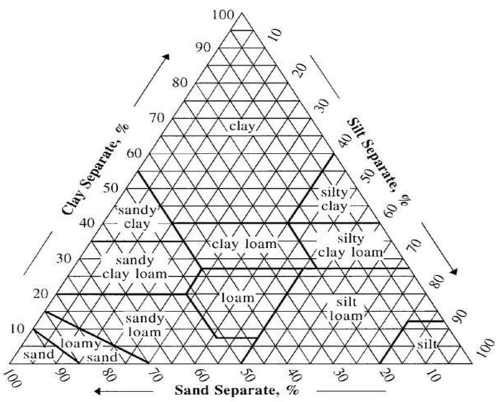


Sedimentation layers in the soil jar test

(Source: K Blumenthal)

Putting in the obtained percentages of clay, silt and sand, a soil texture triangle, as seen in the figure below, shows the type of soil present.

Soil Texture Triangle



The Soil Texture Triangle

(Source: United States Department of Agriculture)

The **IRRIGATE– Soil Tool** describes the different soil type properties and allows for establishing a soil-based irrigation schedule according to different crops.

IRRIGATION SCHEDULING

Scheduling irrigation based on soil-plant or atmosphere measurements can decrease water use while improving yields. Software programs can collect weather data including local temperature, rainfall, humidity, and crop evapotransporation to provide recommendations for optimal irrigation scheduling (see FAO Irrigation and Drainage Paper 56). The **IRRIGATE– Soil Tool** allows for establishing a soil-based irrigation schedule according to different crops.

MULCH

Mulching is an effective technique to reduce evaporation of soil moisture, insulate against cold weather and gradually enhance the organic composition of soils. It helps to prevent soil compaction, acts as a soil conditioner, and encourages the presence of natural aerators, like earthworms. It adds nutrients by contributing to the availability of potassium and can add nitrogen, phosphorus, and trace elements to the soil. Furthermore it is an ideal way to make use of recycled crop waste.

Mulching comprises the layering of organic (straw, wood bark, leaf litter, maize stalks) or inorganic (PVC sheeting) materials over the crop area, through which the crops can grow. Mulching can also be achieved through intercropping, by for instance planting ground creepers (water melon, pumpkin) between rows of maize. Important considerations regarding mulching include:

- Once you begin mulching stay with it. Removing a layer of mulch will dry out the soil and potentially injure the roots below.
- Mulching against a tree’s trunk can lead to bark rot, disease, and insect problems. Thus leave several centimeters of space between the base of the tree and the mulch layer.
- Avoid over applying mulch. Spreading mulch too thickly can cause roots to grow shallow and make them more susceptible to dying during extended dry periods. As a general rule the mulch layer should not exceed 5 cm.
- Use woody or bark mulches in areas where little digging is required, e.g., around trees and in flower beds. Lighter mulch materials such as straw, which is easily worked into the soil, is better suited for seasonal crops and vegetable gardens where replanting is regular.
- Before applying a new layer of mulch, rake through and mix the older mulch layer. Mulch, especially from woody materials, can compact over time and thus prevent soil aeration and water penetration.

INTERCROPPING

Intercropping is a multiple cropping practice involving growing two or more crops in proximity. The most common goal of intercropping is to produce a greater yield on a given piece of land by making use of resources or ecological processes that would otherwise not be utilized by a single crop (*Ouma, George; Jeruto, P (2010)*). The elements of intercropping (*Wikipedia, "Intercropping", January 2018*) include:

- **Resource partitioning**: Careful planning is required, taking into account the soil, climate, crops, and varieties. It is particularly important not to have crops competing with each other for physical space, nutrients, water, or sunlight. Examples of intercropping strategies are planting a deep-rooted crop with a shallow-rooted crop, or planting a tall crop with a shorter crop that requires partial shade.

- **Mutualism**: Planting two crops in close proximity can especially be beneficial when the two plants interact in a way that increases one or both of the plant's fitness (and therefore yield). For example, plants that are prone to tip over in wind or heavy rain (lodging-prone plants), may be given structural support by their companion crop. Climbing plants can also benefit from structural support. Some plants are used to suppress weeds or provide nutrients. Delicate or light-sensitive plants may be given shade or protection, or otherwise wasted space can be utilized. An example is the tropical multi-tier system where coconut occupies the upper tier, banana the middle tier, and pineapple, ginger, or leguminous fodder, medicinal or aromatic plants occupy the lowest tier. Intercropping of compatible plants can also encourage biodiversity, by providing a habitat for a variety of insects and soil organisms that would not be present in a single-crop environment. These organisms may provide crops valuable nutrients, such as through nitrogen fixation.

- **Pest management**: There are several ways in which increasing crop diversity may help improve pest management. For example, such practices may limit outbreaks of crop pests by increasing predator biodiversity. Additionally, reducing the homogeneity of the crop can potentially increase the barriers against biological dispersal of pest organisms through the crop.
  There are several ways pests can be controlled through intercropping:

  - Trap cropping involves planting a crop nearby that is more attractive for pests compared to the production crop, the pests will target this crop and not the production crop.
  - Repellant intercrops have a repellent effect to certain pests. This system involved the repellant crop masking the smell of the production crop in order to keep pests away from it.
  - Push-pull cropping, this is a mixture of trap cropping and repellant intercropping. An attractant crop attracts the pest and a repellant crop is also used to repel the pest away.

Agricultural extension officers and advisors should be able to give guidance regarding intercropping and companion planting.

RAINWATER CATCHMENT

Ensuring that rainwater does not run-off, but percolates into deeper soil layers avoids top soil erosion and can improve groundwater recharge, while improving soil moisture at depth. Strategically placed furrows can trap rainwater and divert it to crop areas (or the pump well), while roof gutters leading to water storage tanks can build up reserves for the dry season.

MONITORING

Monitoring water consumption and soil moisture levels regularly, ensures a deeper understanding of the water resources necessary for healthy crops. Water flow meters and hand-held soil moisture meters are important devices through which data is collected and recorded for analysis.

IMPROVED FURROWS

Numerous techniques exist to optimize water flow through furrows. These may include covering furrows with plastic PVC sheeting or rock slabs to reduce evaporation, lining or firming main furrows to reduce water infiltration rate at the head end of the field (then additional water is available to advance further down the furrow. The result is faster advance time to the end of the field and improved water distribution) or optimizing slope angles to ensure efficient water flow.

EVAPORATION AVOIDANCE

Evaporation from uncovered water storage and water conveyance systems implies a direct loss of water resources to the atmosphere. This loss has financial implications where costs were incurred to pump the water from a well or procure it from a service provider. Stopping evaporation is a question of restricting the solar energy available to the water (to energise water molecules) and lowering its exposure to dry air. When water evaporates it forms a moist layer of air over the surface, lowering the capacity of the air to accept more water molecules from the liquid. Moving air draws water vapor away from the area over the surface of the water and replaces it with drier air, increasing evaporation. Using sealed tanks or covering open storage tanks and canals is advisable. For larger irrigation reservoirs or dams floating covers can be considered, along with wind breaks (e.g. hedges and trees) around the perimeter. The latter might also contribute towards shading the water surface, thus reducing the kinetic energy available to water molecules.

IRRIGATION TIMING

In principle it is best to irrigate during the morning hours starting just before sunrise. Cooler air and lower wind speeds reduce evaporation losses, while crops are assured an adequate water supply at the root zone in preparation for higher daytime temperatures. Watering in the late afternoons and evenings is not advised, as crops cannot absorb the available water and stagnant water offers a breeding ground for pests and fungi.

OUTCOME / PRODUCT

- Understand some practical approaches towards reducing irrigation water demand

DATA REQUIREMENTS

- Information on intercropping and companion planting
- Soil properties in crop areas

PEOPLE / STAKEHOLDER

- Agricultural extension officers and advisors
- Irrigation planners and service providers
- Horticulture and permaculture specialists

IMPORTANT ISSUES

- Irrigation efficiency can only be ensured through active and regular monitoring. Any improvement measure should be scrutinized carefully before implementation and baseline information captured (e.g. amount of water consumed, amount of fertilizer added). Comparing the baseline information with the new post-measure data, allows to assess the success or failure of the improvement. This deepens understanding.

FURTHER READING, LINKS AND TOOLS

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Water Accounting: http://wateraccounting.org/

WOCAT *Global Database on Sustainable Land Management*: https://qcat.wocat.net/en/wocat/

SPIS tools

PROMOTE & INITIATE – Impact Assessment

IRRIGATE – Soil Tool

DESIGN – Pump Sizing Tool

The following tools that are assigned to other Modules are also relevant:

SAFEGUARD WATER – Water Requirement Tool

INVEST – Payback Tool

INVEST – Farm Analysis Tool

Tool

DESIGN – Site Data Collection Tool