ReWater MENA

ReWater MENA Project

MORE AND SAFER WATER REUSE IN THE MIDDLE EAST AND NORTH AFRICA

Training Handbook

Water Reuse Technologies

WATER REUSE TECHNOLOGIES

DEVELOPED BY

IWMI International Water Management Institute

CGIAR

RESEARCH PROGRAM ON Water, Land and Ecosystems

الجمعيـة العربيـة لمرافـق الميـاه

Arab Countries Water Utilities Association ACWUA

Sweden Sverige

This training material is developed by the Arab Countries Water Utilities Association (ACWUA), in collaboration with the International Water Management Institute (IWMI), under ReWater MENA, a project lead by IWMI and sponsored by Sida. It contains four training modules, covering a range of topics related to reuse of treated wastewater, with a focus on the MENA region.

The main content of the four training modules is provided and reviewed by leading experts in each field as follows:

• **Module 1: Assessing the Economic Feasibility for Integrated Wastewater Reuse (WWR) Projects: From Formulation to Reporting (ECON-WWR):**
Developed by: Dr. M. Ragy Darwish, Economic Expert and TOT.
Reviewed by: Solomie Gebrezgabher, Researcher- Economics, IWMI Ghana Office.
• **Module 2: Governance and Reuse Safety Plans:**
• Developed by: Dr. Maha Halalsheh, Wastewater Treatment Expert.
• Reviewed by: Javier Mateo-Sagasta, Senior Researcher and Coordinator- Water Quality, IWMI Headquarters in Sri Lanka
• **Module 3: Stakeholders' acceptance and gender integration in reuse interventions:**
Developed by: Dr. Noura Abdelwahab, Lead Gender Advisor.
Reviewed by: Everisto Mapedza, Senior Researcher- Social and Institutional Scientist, IWMI Ghana Office
• **Module 4: Water Reuse Technologies:**
Developed by: Dr. Mohammad Duqqa, Wastewater reuse Expert.
Reviewed by: Javier Mateo-Sagasta, Senior Researcher and Coordinator- Water Quality, IWMI Headquarters in Sri Lanka

A general review of the training modules was provided by Dr. Amgad Elmahdi, Head of IWMI MENA Office in Cairo and Eng. Khaldon Khashman, Secretary General, Arab Countries Utilities Association (ACWUA).

The Arabic translation of the training modules was provided by the experts who developed each training module, and was reviewed by Eng. Yasmeen Khashman, the Arab Countries Water Utilities Association (ACWUA) in Jordan, Dr. Mohamed Dawoud, Advisor at Water Resources, Environment Agency in Abu Dhabi and Dr. Nisreen Lahham, the Project Manager of ReWater MENA project at IWMI MENA Office in Cairo.

Table of Contents

Reuse Technologies Module-Learning Objectives and Outcomes

Upon the successful completion of this training, trainees will and should be able to:

- Be familiar with the standard that allow reuse of Wastewater in different sectors.
- Be familiar with the appropriate wastewater treatment technologies.
- Provide solutions to bottlenecks as a result of reusing treated wastewater in the region.
- Be familiar with the efficient Irrigation System Adapted.

1.1 Introduction

Wastewater is considered as a reliable resource when it comes to valuable water and nutrients. However, wastewater is associated with some health hazards including pathogenic microorganisms as well as some other chemical constituents. Risks associated with such hazards need to be minimized and/or well managed. Since wastewater is typically used for agricultural production at regional level, it should be noted that raw wastewater can still be utilized provided that risk management plans are well developed and implemented. Alternatively, wastewater can be collected and treated before agricultural valorization. This chapter is mainly providing a general and very basic description of some wastewater collection and treatment systems. In any case, treatment option shall be selected based on the required effluent quality as stated by legislations at each country without neglecting socio-economic considerations. It should be kept in mind, that the herein presented options do not cover all available treatment technologies due to the nature of the target group. Additionally, neither design considerations nor system modifications are presented in module one and two.

1.2 Wastewater collection systems

Wastewater collection systems convey wastewater from its generation source to the point where the wastewater is treated. A variety of collection systems are available and this section will only be oriented to gravity sewer systems. Selection of the most appropriate system will depend on the characteristics of the community to be served.

1.2.1 Conventional gravity sewers

This system consists of underground network pipes, which are provided with inspection and maintenance manholes. Moreover, the pipelines are usually installed beneath the surface of the roads (public property). The pipelines are installed with a certain slope in order to keep the minimum velocity required for solids flushing. Accordingly, deep excavations might be needed. In some cases, pumping stations might be required. Advantages and disadvantages of this system are presented in Table (1).

Table 1: Advantages and disadvantages of conventional gravity sewer networks

Advantages	Disadvantages
Convenient systems and no attention is needed by households or users	High investment costs
Abundant experience in such systems exist in the region	
System is mostly in line with existing national codes and standards	Minimum velocity is required to flush solids. Accordingly, minimum slope should be provided to maintain the minimum velocity
Requires less maintenance as compared to other gravity systems	Leakages may pose high risk for contamination as compared to other systems

1.2.2 Solids-free sewers

In such system, only liquid fraction of wastewater is received and therefore, solids are separated from wastewater using interceptor tank that is installed at each household upstream of the sewer network. The system is already applied in many countries including Australia, Nigeria, Zambia, USA and others. The main idea of the system is to prevent having deep excavations to maintain the slope required to flush the solids. Accordingly, shallow networks that are designed to flow under full flow conditions can be applied. This system is generally used in areas where water consumption and wastewater generation are limited. A main requirement for this system is to have a difference in elevation between the upstream and the downstream ends. In this case, a continuous downward slope is not required. Advantages and disadvantages of this system are presented in Table (2).

Table 2: Advantages and disadvantages of solids-free sewer system

Advantages	Disadvantages
Cost savings might be 30 to 50% as compared to conventional sewer system	Space has to be provided for the interceptor tank at each household. Additionally, access to the interceptor must also be provided
No need for continuous downward slope and accordingly the pipes might be installed at shallow depths	Regular de-sludging is crucial for the a well operated system
Inspection manholes are not required	Needs high public awareness as public are involved in the operation and maintenance of the system
Less environmental risks in case of leaks	In many cases in the region, codes and standards still need to be developed for such systems
Reduction on the treatment costs since solids are removed upstream	Lack of regional experience in such systems

1.2.3 Simplified sewer system

The main difference between the simplified sewer system and the solids-free sewer system is that in simplified systems, individual household interceptors are not required. Instead, a grit and a grease traps are used to prevent clogging of the sewer system. Additionally, a continuous downward slope is needed in simplified systems. Sufficient water supply and wastewater generation are also needed in order to provide self-cleaning of the network. However, manholes are not required in the simplified systems and pipes are usually laid within the property boundaries. Advantages and disadvantages of the system are presented in Table (3).

Table 3: Advantages and disadvantages of the simplified sewer system

Advantages	Disadvantages
Shallow depth and flatter gradients as compared to conventional systems	Toilets need to be flushed with sufficient amount of water to provide flushing for the system
Pipes are smaller and cheaper as compared to conventional sewer system	Grease and grit traps need to be installed at each household and regularly maintained. Accordingly, community involvement is crucial
	Higher maintenance requirements as compared to conventional system
	No sufficient experience exists so far in the region regarding such systems

2.1 Wastewater Treatment options

This section is intended to cover biological wastewater treatment technologies and to present some examples on the most popular technologies that are found in the region. However, and due to the very limited time provided for such section, wastewater characteristics and sludge management options are not covered, although they present a significant and a crucial element in full treatment scheme. Additional and detailed information can be found in Metcalf & Eddy (2014). The section also presents some selected options without differentiating between small-scale or large-scale systems or between different wastewater streams. Accordingly, the main purpose of this section is to give an overview of some treatment technologies for non "wastewater treatment" experts in order to reduce the gap between upstream and downstream experts when it comes to wastewater management.

2.1.1 Treatment phases

Wastewater treatment generally consists of four phases: preliminary treatment, primary treatment, secondary treatment and post-treatment (or polishing). In some cases, primary and secondary treatments are combined together and might be termed "main treatment". Each phase is important in the overall functioning of the treatment plant. A flow diagram of a regular wastewater treatment plant is shown in Figure (1), and the following is a brief description of the main phases/steps.

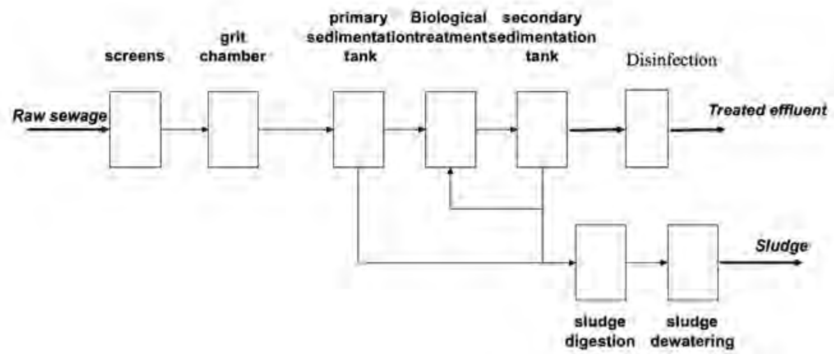

Figure 1: A flow diagram of typical municipal wastewater treatment plant

2.1.1.1 Preliminary treatment

Preliminary treatment usually consists of screens and a grit removal step. Large solids that enters the sewer network, such as plastics, textiles and paper are retained by screens to prevent clogging or damage mechanical parts downstream the treatment line. Grit is small inert material, mostly sand, that can accumulate in the treatment unit and reduce its effective volume. In stabilization ponds for instance, grit accumulates close to the inlet, possibly causing localized problems such as clogging or/and sludge build-up. Accordingly, the anaerobic pond(s) should be designed with extra depth at the inlet zone or they should be de-sludged more often, when no separate grit removal step is planned. The screens and grit chamber may be covered and equipped with air filters to avoid odor nuisances associated with raw wastewater. Costs and efforts for proper operation and maintenance of screens and grit remover worth the investment, since both steps are intended to prevent problems downstream. The preliminary step is not always located at the treatment plant and can be placed at household level, by installing small screens and/or septic tanks. Solids retainment at household levels makes it possible to apply a solids-free sewer, as discussed earlier. It is important to note that any intervention at household level requires alteration in operation and maintenance of sewer system practices as compared to the conventional systems. In solids-free sewer system, proper solids handling at the household level is crucial (e.g. desludging of tanks, etc.). Moreover, household's behavior might need to be changed.

2.1.1.2 Primary treatment

Primary treatment basically targets removal of solids by sedimentation and is achieved using a clarifier (sedimentation tank). The solids retained by primary sedimentation tank originate from fresh wastewater, and are thus by nature untreated and non-stabilized. Accordingly, primary sludge has a high risk of creating odor problems. This is especially unwanted at small scale treatment plants that are close to settlements. Primary clarifiers can be excluded from the wastewater treatment plant in small scale systems or when wastewater does not contain high concentrations of settleable solids. Moreover, anaerobic reactors (as will be explained latter) are often function as primary treatment as it combines both solids physical removal and secondary treatment (conversion of solid and soluble organics).

2.1.1.3 Secondary treatment

Secondary treatment aims at conversion of the biodegradable organic material found in wastewater. When anaerobic treatment processes are applied, the organic compounds are converted into CH_4, CO_2 (and a limited amount of sludge), whereas in aerobic treatment systems (mainly activated sludge plants), only CO_2 is formed in addition to a large amount of sludge. Natural treatment systems such as constructed wetlands (CWL) produce CO_2 and biomass in the form of plant material. Both aerobic and anaerobic processes take place in natural treatment systems as will be described latter.

2.1.1.4 Post treatment

Post treatment is sometimes termed tertiary treatment and consists of the technology which renders the effluent suitable for use or discharge. Such technology aims at pathogens removal. In some cases, it also includes nitrogen and phosphorus removal. Pathogens removal can be achieved by disinfection using a variety of options. In small-scale WWTPs the most used disinfection technical solutions are chlorination and UV-light exposure. Natural die-off in maturation ponds (natural systems) is another alternative. The benefit of not requiring additional equipment and/or chemicals should be balanced against the substantially higher footprint needed for maturation ponds.

2.1.2 Description of the main biological treatment systems

2.1.2.1 Anaerobic treatment

Anaerobic wastewater treatment has many different advantages: firstly, organic matter can be removed in a compact system; secondly, biogas -as an energy source- can be generated; thirdly, no energy consumption (apart from pumping) is required; and fourthly, minimal sludge production is expected as compared to aerobic systems. From purely technological perspective, anaerobic systems are the preferred main treatment option for highly concentrated wastewater such as is found in many areas in the region. For instance, options might include the Upflow Anaerobic Sludge Blanket reactor (UASB), and the Anaerobic Baffled Reactor (ABR). Anaerobic filters (AF) are another type of anaerobic reactor making use of a fixed filter material for attached growth of active biomass in the form of biofilms. This option is not preferable for treatment of raw domestic wastewater, because of clogging risks. However, sometimes the AF is located at the last compartment of an ABR and accordingly, functions as a polishing step.

UASB reactors are an established technology for wastewater treatment that can be applied at any scale. Wastewater enters the reactor from the bottom and flows upward. Sludge that is kept in suspension with high concentrations in the reactor provide a kind of a filter that captures organic matter and further biodegrade it using anaerobic bacteria that breaks down organic matter by anaerobic digestion. The resultant biogas is collected at the top of the system using gas collector as can be shown in Figure (2). Applied research activities on the application of UASB reactors for treating Jordanian wastewater have shown that this is a technologically viable option. A single-stage UASB reactor was successfully operated at loading rates in the range of 1.5-1.8 kg $COD/m^3.d$ (average HRT = 24 h), resulting in a maximum COD removal efficiency of around 90% (Halalsheh et. al.2005).

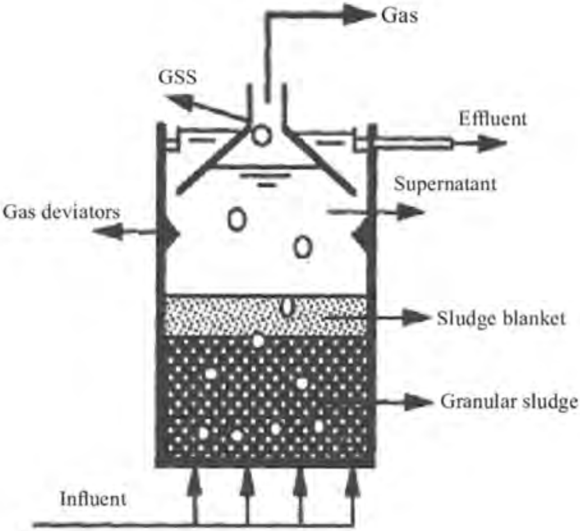

Figure 2: Schematic diagram of UASB reactor (Ali et. al., 2012)

ABRs are improved septic tanks with a series of baffles in which wastewater flows under and above the baffles from the inlet to the outlet of the reactor as shown in Figure (3). Sludge is also kept at the system and the increased contact with the active biomass allows for the treatment of wastewater. The system is robust and applied successfully under a range of conditions and on any scale (Stuckey, 2010). Both UASB and ABR are technologically very interesting, however, there are currently limited practical applications of high-rate anaerobic reactors for wastewater treatment in the region. This can present problems in acceptance by both the public and by the future operating body.

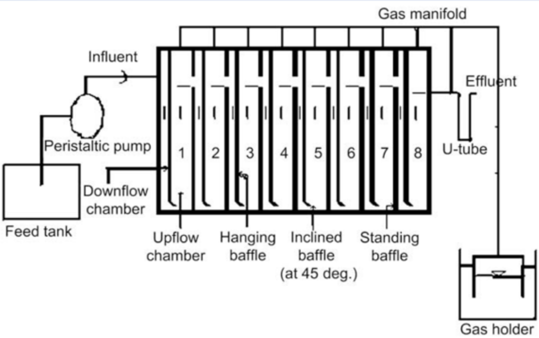

Figure 3: Schematic diagram of the ABR (Krishna et. al., 2009)

The previous systems are considered high rate anaerobic treatment systems since high organic loading rates are applied. One of the great benefits of high rate anaerobic reactors is the possible collection of biogas as an energy source. Gas lamps for lighting the treatment plant at night could be a relatively simple way to put the biogas into use. If no useful application is found (in case wastewater is diluted), the biogas would need to be flared to prevent greenhouse gas emissions. It should be noted that anaerobic treatment presents only limited removal of nitrogen and phosphorous. Both are partially incorporated into the sludge, and the remaining part is almost fully converted into NH_4 and PO_4. In cases where these compounds should be removed, post treatment should be designed for that specific purpose.
Perhaps the simplest anaerobic treatment technology can be represented by the Septic tanks (ST). The system consists of one or two chambers that are commonly constructed underground and used as a simple house onsite sewage facility without biogas collection. UASB-septic tanks (UASB-ST) is a cross-over between septic tanks and UASB reactors, combining improved solids retention by functioning in an upflow mode with a larger reactor volume to allow for sludge storage. In such system, sludge is not frequently discharged as the case in a conventional UASB reactor.

2.1.2.2 Aerobic treatment

Aerobic technologies such as activated sludge systems, trickling filters and rotating biological contactors are commonly used for wastewater treatment and for post treatment of effluent from anaerobic reactors. Organic matter is converted into CO_2 and, if designed for it, activated sludge systems can remove nitrogen and phosphorous almost completely.
Compared to natural systems, aerobic reactor systems are much more compact, while compared to anaerobic systems they produce a much cleaner effluent. However, energy consumption and sludge production are larger compared to other options. The key to aerobic treatment is aeration, brought about by the use of aerators in activated sludge systems and the rotating arm spraying wastewater on an open structure in the case of trickling filters. Aerobic micro-organisms cannot live without oxygen, and consequently aerobic reactor systems depend on a continuous energy supply. At the same time, sufficient concentration of viable biomass has to be maintained in the system in order to perform degradation. In activated sludge systems (AS), wastewater is introduced to the aeration tank as shown in Figure (4). The activation of the process is based on providing sufficient amount of oxygen in order to increase the amount of active biomass. Maintaining sufficient amount of biomass is critical to the process and is performed using recirculation from a secondary clarifier. Due to extracellular polymers, flocks with good settling properties are formed and removed using the secondary clarifier. Excess sludge needs to be further processed before final disposal or final use.

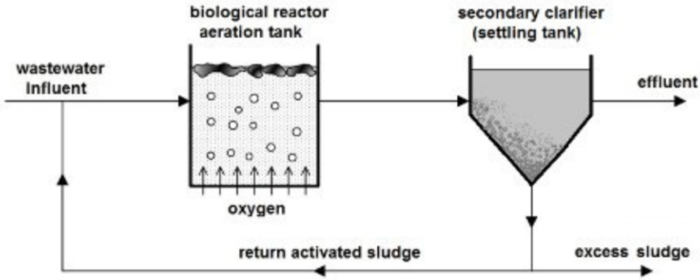

Figure 4: Schematic presentation of activated sludge systems (Fracz, 2016)

Trickling filters are aerobic attached growth systems in which aerobic bacteria is attached to a media (rock, polyurethane foam, plastic, etc.). Wastewater is typically distributed at the top of the reactor and trickles downward where it is collected using underdrain system as shown in Figure (5). The biofilm layer that grows on the media is called the slime layer. Historically, trickling filters have been designed with natural draft aeration that depends on air movement due to difference between water and air temperatures. In these systems sludge is not recirculated as in AS systems, while recirculation of effluent might take place in order to maintain wetting of the media particularly at low flows and because it enhances the supply of oxygen and treatment performance.

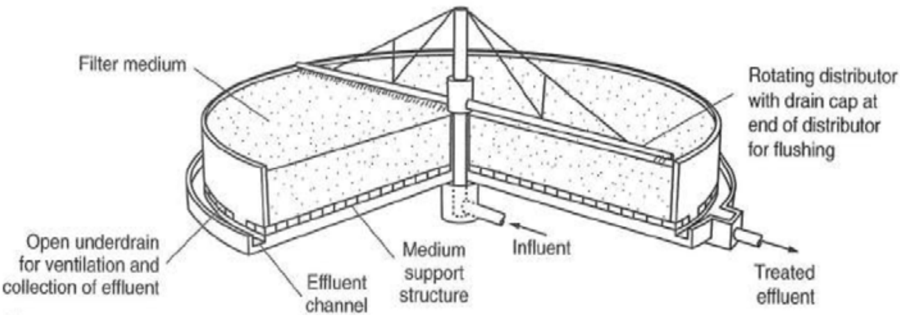

Figure 5: Cutaway view of a rock trickling filter (Metcalf & Eddy, 2014)

Rotating biological contactors are other types of attached growth aerobic systems and consist of a number of circular plastic disks which are mounted on a central draft as shown in Figure (6). The disks are submerged and rotated in a tank containing wastewater to be treated (Crites and Tchobanoglous, 1998). Oxygen is obtained by adsorption from the air as the slime layer is rotated out of the liquid. Operationally, the bio-disk process is similar to the trickling filter process with a high rate of recirculation.

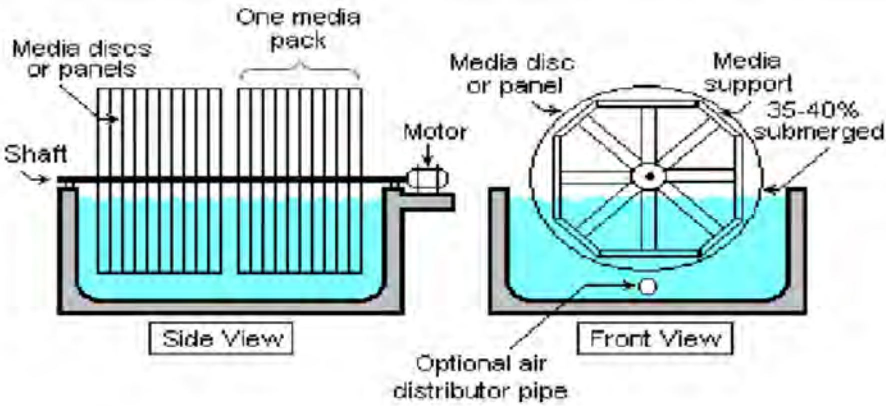

Figure 6: A two-stage rotating biological contactors (Stalin, 2014)

2.1.2.3 Natural treatment systems

Apparently, all biological treatment systems make use of natural processes, however, natural treatment systems such as waste stabilization ponds and constructed wetlands are seen as the most "natural" systems because they look like landscape features. When correctly designed, built and operated, these systems produce high quality effluent (Tchobanoglous et, al., 2002). Both ponds and wetlands require very large footprints compared to reactor systems, which limit their application for wastewater treatment due to lack of space. These systems can also be used as a post-treatment treatment step to remove nitrogen, phosphorus, and to perform disinfection.

Waste stabilization ponds (WSP) system for wastewater treatment consists of a series of anaerobic, facultative and aerobic ponds as shown in Figure (7). The system is applied in many different places worldwide. If properly designed, constructed and operated, the system is robust and produce high quality effluent. If the purpose of application is post treatment, anaerobic pond is usually excluded (Mara, 2003). Generally speaking, Public acceptance of WSPs is low, mainly because of the odor problem associated with anaerobic ponds. System operation is very simple as compared to technologically more complex systems, however, the emphasis on simplicity has led to many cases in which O&M efforts were underestimated or not well planned. Overloading of the system or failure to timely planned de-sludging had led to cases of in-creased odor problems.

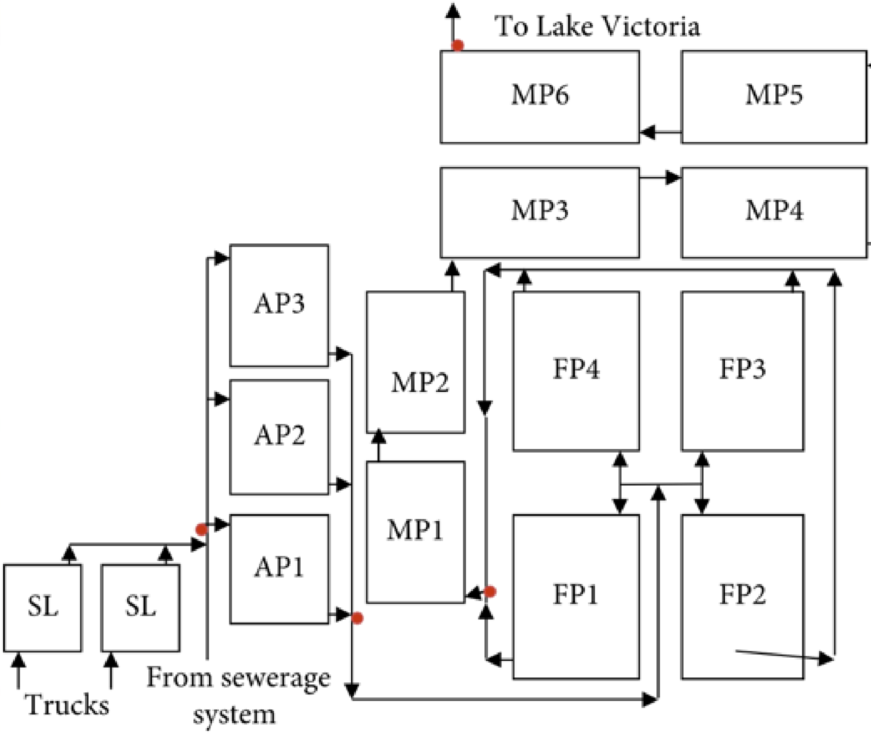

Figure 7: Example layout of WSP (Zacharia et. al., 2019)

Constructed wetlands (CWL) exist in different varieties (Tilley et. al., 2014), with horizontal subsurface flow and vertical subsurface flow being the most commonly applied as shown in Figure (8). CWLs are sometimes preceded by a settling tank, to prevent blockage of influent feeding system. An alternative to the standard vertical flow CW is the so-called "French-type" CWL, which consists of a staged system. Raw wastewater is applied on the surface of a first bed, after which a second bed is fed with first stage effluent. Constructed wetlands produce high-quality effluent and have quite a good public acceptance, as odor problems are not an issue and the system can be nicely integrated in the landscape.

Vertical CWLs distribute the influent over the entire surface area and just beneath the surface of the wetland. Feeding is intermittent and influent infiltrates the CWL bed and moves down with the entrapped air, thus creating mostly aerobic conditions. Intermittent feeding can be achieved by pumps or syphon systems. On the other hand, horizontal CWLs have the advantage to be technically less complex, as they do not require pulse feeding. However, there is a higher risk of clogging of the filter bed, especially in the inlet zone. Nitrogen removal is better in horizontal systems, as aerobic zones are only present near the surface and near plant roots. In the anaerobic zones denitrification can take place. Effluent recirculation can be applied to further increase N-removal, as formed nitrate can then be denitrified.

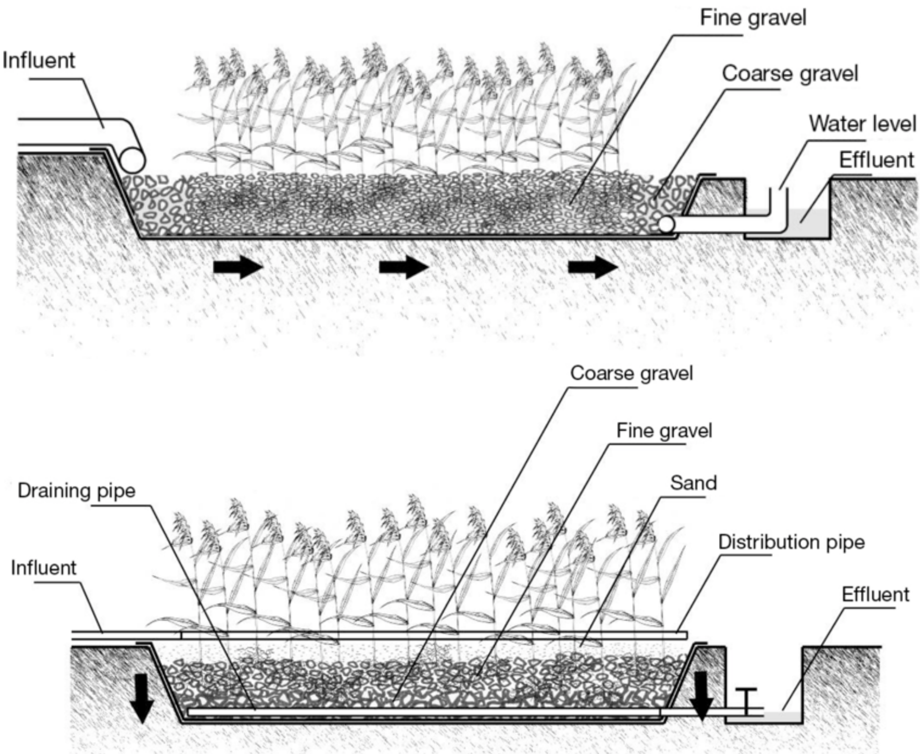

Figure 8: Schematic presentation of horizontal flow (upper) and vertical flow (lower) constructed wetlands, (Martin, 2013)

2.2 Criteria to be used for systems comparison

One of the tools that can be used for deciding the best sustainable system to be implemented is called sustainability criteria that basically utilizes four main weighed aspects in comparisons. Namely, technical, environmental, social, and economical aspects (Seghezzo, 2004). Each basic criterion is divided into 20 operational indicators that are adapted to the local conditions. Basic four aspects are shown in table (4). Assessment and selection procedure can be divided into four steps:

- Step 1: Assigning criteria importance.
- Step 2: Assigning importance to indicators under each criterion.
- Step 3: Assigning performance to each indicator under each concept.

• Step 4: Calculating sustainability index for different concepts.
In the first step, criteria can be weighted according to their relative contribution to the whole environmental and social system within the local context. In the second step, assignment of importance to each indicator can be done independently of the technologies compared as exemplified in table (5). Both step 1 and step 2 can be done by experts who can assign weights to criteria and indicators. In step 3, relative scores are assigned to each technological option in relation to each indicator. Finally, a sustainability index (SI) can be calculated as the importance of the indicator multiplied by the performance given to the technology for this particular indicator and divided by the maximum possible performance (100). Individual scores can then be summed up by row to obtain a sustainability index (SI) for each technological option. The technology that achieve the highest score is then selected.

Table 4: Criteria and indicators used to assess the sustainability of sewage treatment technologies. (Seghezzo, 2004)

Criteria	Indicators	Short description
Technical aspects	Effectiveness Removal efficiency Reliability System manageability	Compliance with discharge standards Removal of pollutants (when not in standards, or beyond them Robustness, vulnerability and risks associated with errors, disasters Operation and maintenance, personnel requirements
Environmental aspects	Conservation External inputs Land use and impact Emissions Reduce, reuse, recycle	Protection of the ecosystem and conservation of biodiversity Need of materials, equipment, electricity, fossil fuels, self-sufficiency Footprint (area occupied), impact on the landscape Substances released into the environment, pollution prevention Sludge, biogas, treated water for irrigation, nutrients
Social aspects	Institutions and policies Management capacity Community participation and involvement Change of routines Social acceptability Scientific support Regulatory framework	Basic institutions, awareness of policy makers/pubic about sanitation Governmental and private proficiency to manage sanitation systems Changes by practitioners to adopt sanitation technologies, lobbies Cultural aspects, user's adaptation, poverty alleviation, minorities The role of universities and research centers (monitoring, innovation) Local legislation that promotes or hinders the use of different options
Economic aspects	Investment costs Running costs Life time externalities	Construction costs, equipment required, land cost Operation and maintenance, reparations, availability of spare parts Lifetime of construction items and electromechanical equipment Changes in natural capital, excavations, social disruptions

Table 5: Example of weights of Criteria and indicators

Assessment parameters		Importance (0-100)				
Criteria	Indicators	Mean	Ratio	Total	Value	Check
Technical aspects		88	100		31	
Environmental aspects		67	76		23	
Social aspects		59	67		20	
Economic aspects		74	84		26	100
Technical aspects	Effectiveness	71	84		4.67	
	Removal efficiency	74	89		4.87	
	Reliability	83	99		5.46	
	Expansion potentials	73	87		4.80	
	Management scale	71	84		4.67	
	System manageability	84	100	543	5.52	31
Environmental aspects	Conservation	80	100		5.84	
	External inputs	75	94		5.49	
	Land use and impact	50	63		3.68	
	Reuse, reduce and recycle	60	75		4.38	
	Emissions	50	63	394	3.68	23
Social aspects	Management capacity	81	92		3.38	
	Change in routines	54	61		2.25	
	Social acceptability	88	100		3.67	
	Scientific support	47	53		1.96	
	Community participation and	81	92		3.38	
	involvement	64	73		2.67	
	Institutions and policies	64	73	544	2.67	20
	Regulatory framework					
Economic aspects	CAPEX	84	95		6.28	
	OPEX	88	100		7.48	
	Life time	68	77		5.78	
	Externalities	66	74	347	5.61	26

3.1 Wastewater Reuse Applications

As shown in Table (6), wastewater reuse maybe applied in agriculture, industry, groundwater recharge, and urban usage, including landscape irrigation and fire protection. Wastewater reuse can be adopted to meet the water demand in different fields and contribute to the conservation of freshwater resources.

Practices of wastewater reuse vary among countries, as target applications and technology options differ significantly depending on socio-economic circumstances, industrial structure, climate, culture, religious preference, as well as policy readiness. Various application areas and examples for wastewater reuse are introduced in the following sections.

Table 6: Categories of wastewater reuse

Category of reuse	Examples of applications
• Urban use	
○ Unrestricted	Landscape irrigation of parks, playgrounds, school yards, golf courses, cemeteries, residential, green belts, snow melting
○ Restricted	Irrigation of areas with infrequent and controlled access
○ Other	Fire protection, disaster preparedness, construction
• Agricultural	
○ Food crops	Irrigation for crops grown for human consumption
○ Non-food crops and crops consumed after processing	Irrigation for fodder, fiber, flowers, seed crops, pastures, commercial nurseries, sod farms
• Recreational use	
○ Unrestricted	No limitation on body contact: lakes and ponds used for swimming, snowmaking
○ Restricted	Fishing, boating, and other non-contact recreational activities
• Environmental enhancement	Artificial wetlands creation, natural wetland enhancement, stream flow
• Groundwater recharge	Groundwater replenishment for potable water, saltwater intrusion control, subsidence control
• Industrial reuse	Cooling system water, process water, boiler feed water, toilets, laundry, construction wash-down water, air conditioning
• Residential use	Cleaning, laundry, toilet, air conditioning
• Potable reuse	Blending with municipal water supply, pipe to pipe supply

Source: Asano, T., F.L. Burton, and G. Tchobanoglous (2006) Water Reuse: Issues, Technologies and Applications, Metcalf & Eddy, Inc., McGraw-Hill Book Co., New York, NY.

3.2 Treatment and Technology Needs

An important determinant of the potential applications and treatment requirements for water reuse is the quality of water resulting from various municipal uses. Water treatment technologies are applied to source water such as surface water, groundwater, or seawater to produce drinking water that meets applicable drinking water regulations and guidelines. Conversely, municipal water uses degrade water quality by absorbing and accumulating chemical or biological contaminants and other constituents. The quality changes necessary to upgrade the resulting wastewater then become the basis for wastewater treatment. In practice, treatment is carried out to the point required by regulatory agencies for protection of the environment, including aquatic ecosystems and preservation of beneficial uses of receiving waters.

As the quality of treated water approaches that of unpolluted natural water, the practical benefits of water reclamation and reuse become evident. The levels of treatment and the resultant water quality endow the water with economic value as a water resource.

As more advanced technologies are applied for water reclamation, such as carbon adsorption, advanced oxidation, and membrane technologies, the quality of reclaimed water can meet or exceed the conventional drinking water quality standards by all measurable parameters. Today, technically proven water reclamation or water purification processes exist to provide water of almost any quality desired, including ultrapure water for precision industries and medical uses.

3.3 Types of Technology

With advancements in water reclamation technologies, it is technically possible to produce reclaimed water of virtually any quality. The question then is what level of treatment is necessary and satisfactory for a specific water reuse application? Reclaimed water quality requirements depend not only on the relevant regulations and guidelines, but also on specific applications for which reclaimed water is to be used. Demand and supply balance and need for infrastructure also vary with various applications. Infrastructure must have a capacity to supply reclaimed water safely, sufficiently, and reliably. Thus, a water reuse project cannot be planned without identifying primary and potential users of the reclaimed water and understanding how reclaimed water is to be used in each application.

Technologies that follow secondary treatment which are suitable for most water reuse applications include depth and surface filters, membrane filtration (pressure or vacuum), carbon adsorption, reverse osmosis, disinfection with ultraviolet radiation, and advanced oxidation.

Membrane bioreactors maybe used in place of secondary treatment and membrane filtration. Membranes represent the most significant development as several new products are now available for a number of water and wastewater treatment and water reuse applications. Membranes had been limited previously to water softening and desalination, but they are now being used increasingly for wastewater applications to produce high quality reclaimed water suitable for reuse. Treatment trains that incorporate membrane filtration are capable of producing several grades of product water that can serve a range of water reuse applications. Reclaimed water may also be demineralized by means of reverse osmosis and electrodialysis.

Increased levels of contaminant removal not only enhance the product water for reuse, but also lessen health risks. Further, the cost of producing high-quality reclaimed water has decreased considerably, largely due to the development of low-pressure membranes and the entrance of a number of suppliers in the competitive marketplace.

Chlorination remains as the most widely used disinfection technology and its effectiveness is vastly improved by improved reclaimed water quality. Increased removal of particulate matter and the development of ultraviolet disinfection technology also improve the applicability of reclaimed water for many more applications. Advanced oxidation is also an important technology for reducing or removing trace constituents and emerging contaminants to safe levels, especially for indirect potable water reuse applications.

3.4 New Treatment Technologies

As a result of the developments and improvements in treatment technology, many of the economic and environmental barriers to water reuse have been reduced significantly and several new opportunities for water reuse applications are possible. Many of these opportunities are associated with membrane treatment and UV disinfection. Health and environmental concerns associated with the use of treated wastewater effluent can be mitigated significantly, thus improving the acceptability of reclaimed water for defined uses such as landscape irrigation and groundwater recharge.

As more membrane facilities are installed and operated, and their ability to produce consistently high-quality water becomes more widely known, public acceptance of reclaimed water increases significantly. Removal of total dissolved solids provides another level of quality for reclaimed water as the suitability for irrigation, industrial use, and aquifer recharge is enhanced significantly. Control of total dissolved solids is the key component, especially in closed loop systems.

3.5 Wastewater Reuse for Agriculture

Agricultural irrigation is crucial for improving the quality and quantity of production. Worldwide, agriculture is the largest user of water. Agriculture receives 67% of total water withdrawal and accounts for 86% of consumption in 2000 (UNESCO, 2000). In Africa and Asia, an estimated 85 to 90% of all the freshwater use is for agriculture.

Thus, more efficient use of agricultural water through wastewater reuse is essential for sustainable water management.

Benefits

Potential benefits of wastewater reuse for agriculture include the following:

• Conservation and more rational allocation of freshwater resources, particularly in areas under water stress.

• Avoidance of surface water pollution.

• Reduced requirements for artificial fertilizers and associated reduction in industrial discharge and energy expenditure.

• Soil conservation through humus build-up and prevention of land erosion.

• Contribution to better nutrition and food security for many households.

Potential concerns

While wastewater reuse for agriculture has many benefits, it should be carried out using good management practices to reduce negative human health impacts. The WHO initially published Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture in 1989 and later revised it as "Guidelines for the safe use of wastewater, excreta and grey water, volume 2: wastewater use in agriculture" (WHO, 2006).

The Guidelines, presented in Table (7), include recommendations for crops to be consumed uncooked, and crops to be cooked or used as feed, as well as for parks and localized irrigation. The Guidelines are set to minimize exposure to workers, crop handlers, field workers and consumers, and recommend treatment options to meet the guideline values (WHO, 2006).

The Guidelines are focused on health-based targets and provide procedures to calculate the risks and related guideline values for wastewater reuse in agriculture.

Table 7: WHO guidelines for using treated wastewater in agriculture

Type of irrigation	Health-based target for helminth eggs	Required pathogen reduction by treatment (log units)	Verification monitoring level (E. coli per 100 ml)	Notes
Unrestricted:	≤1 per liter (arithmetic mean)[b,c]	4	$\leq 10^3$	Root crops.
		3	$\leq 10^4$	Leaf crops.
	High-growing crops: [d,e] No recommendation	2	$\leq 10^5$	Drip irrigation of high-growing crops.
	Low-growing crops: [d] ≤1 per liter (arithmetic mean)	4	$\leq 10^3$	Drip irrigation of low-growing crops.
	E	6 or 7	$\leq 10^1$ or $\leq 10^0$	Verification level depends on the requirements of the local regulatory agency.[a]
Restricted:	F	3	$\leq 10^4$	Labour-intensive agriculture (protective of adults and children under 15).
	G	2	$\leq 10^5$	Highly mechanized agriculture.
	H	0.5	$\leq 10^6$	Pathogen removal in a septic tank.

[a] for example, for secondary treatment, filtration and disinfection: BOD_5, <10 mg/l; turbidity, <2 NTU; Cl_2 residual, 1 mg/l; pH, 6–9; and faecal coliforms, not detectable in 100 ml (State of California, 2001).

[b] When children under 15 are exposed additional health-protection measures should be used (see Sections 4.2.1 and 4.2.2 for details).

[c] A rolling arithmetic mean should be determined throughout the irrigation season. The mean value of ≤1 egg per liter should be obtained for at least 95 per cent of samples in order to allow for the occasional high-value sample (i.e. with >10 eggs per liter). With some wastewater treatment processes (e.g. waste stabilization ponds) the hydraulic retention time can be used as a surrogate to assure compliance with ≤1 egg per liter, as explained in Section 5.7.1 and Box 5.1.

[d] See Section 4.2.3.

[e] No crops to be picked up from the soil.

Source: based on WHO, 2006

The Guidelines state that 'local epidemiological, socio-cultural and environmental factors should be taken into account and the guidelines modified accordingly' (WHO, 2006). The microbiological quality guidelines have been

used as the basis for standard setting in several countries and regional administrations. In other situations, the quality guideline levels have been adopted with specifications of additional management practices and restrictions. Standard setting in other countries has been influenced by the WHO guidelines, but often with some modification of the microbiological guidelines before adoption as standards (WHO, 2001).
Wastewater use, whether treated, untreated, raw or diluted, can be found in humid and arid climates. However, even treated effluent should not be assumed to be pathogen free. It should only be applied to land when the risk to workers and the wider community is well assessed and managed through multiple barriers adopted along the sanitation chain (Drechsel et. al., 2010).
Where effluent is used for irrigation water, a multi- barrier may include the application of treatment processes, selecting crops that are high growing and/or not eaten raw, low contact irrigation methods (e.g. drip irrigation), the use of Personnel Protected Equipment (PPE), and the disinfection, washing and cooking of produce. The WHO Guidelines for the Safe use of Wastewater, Excreta and Greywater (WHO, 2006) provide further guidance. It should be noted that different interventions (barriers) will have different costs, capacity to reduce risks and requirements in terms of behavior change.
A multi-barrier approach should be used to manage health risks associated with end use and disposal (for further details see WHO, 2006 and WHO, 2003).
To reduce the risk, end use/disposal technologies should be:
• Designed for the local context taking into consideration the characteristics of the effluent or faecal sludge; local climate and seasonal variations; and the available energy sources and human resource capacity.
• Compatible with the preceding treatment technology and treatment product.

Adopting the following additional control measures reduces the risk to workers especially those whose work involves handling treatment products:
• Wearing of PPE, particularly where using/disposing of wastewater and, faecal sludge.
• Training on the risks of handling effluents or faecal sludges and on standard operating procedures.
• Regular health checks and preventive treatment such as deworming and vaccination.

Examples of additional control measures to reduce the risk to the local community and wider community where wastewater and faecal sludge are used in agriculture and aquaculture (WHO, 2006) are:
• Selection of crops that grow high above ground level (such as fruit trees) or crops not eaten raw.
• Low contact irrigation methods (e.g. drip irrigation).

• Withholding periods between application of treated faecal sludge (e.g. compost) or wastewater and crop harvesting.

In contrast, end use/disposal technologies that do not adequately reduce the risk are those which result in untreated effluent and/or faecal sludge being left in the open, disposed in recreational waters, or used for food production therefore exposing the local community to pathogens. For instance, in densely populated urban areas where space is limited, and the soil is compacted and/or saturated, soak pits, leach fields or cover and fill approaches are not applicable as the adsorption process will fail.
Wastewater intended for reuse should be treated adequately and monitored to ensure that it is suitable for the projected applications. If wastewater streams come from industrial sources and urban run-off, toxic chemicals, salts, or heavy metals in the wastewater may restrict agricultural reuse. Such materials may change soil properties, interfere with crop growth, and cause bioaccumulation of toxic materials in food crops. While separating household wastewater and run-off from industrial effluent is preferable, this may not be feasible. Thus, proper treatment and monitoring should be practiced.
Wastewater reuse for agriculture needs to be planned with attention to target crops and existing water delivery methods. Nutrients in reclaimed water that are important to agriculture include nitrogen, potassium, zinc, boron and sulphur. However, excess nitrogen may cause overgrowth, delayed maturity, and poor quality of crops. While boron is an essential element for plant growth, excess boron becomes toxic. Furthermore, proper care should be taken to control the saline problems cause by wastewater reuse.

3.6 Wastewater Reuse for Industry

Industrial water use accounts for approximately 20% of global freshwater withdrawals. Power generation constitutes a large share of this water usage, with up to 70% of total industrial water used for hydropower, nuclear, and thermal power generation, and 30 to 40% used for other, non-power generation processes. Industrial water reuse has the potential for significant applications, as industrial water demand is expected to increase by 1.5 times by 2025.

Benefits

Industrial water reuse has the following specific benefits, in addition to the general environmental benefits discussed in earlier sections:
• Potential reduction in production costs from the recovery of raw materials in the wastewater and reduced water usage.
• Heat recovery.
• Potential reduction in costs associated with wastewater treatment and discharge.

Water reuse and recycling for industrial applications have many potential applications, ranging from simple housekeeping options to advanced technology implementation. Wastewater reuse for industry can be implemented through the reuse of municipal wastewater in industrial processes, internal recycling and cascading use of industrial process water, and non-industrial reuse of industrial plant effluent, as summarized in Table (8) below.

Table 8: Types and examples of industrial water reuse

Types of water reuse	Examples
Reuse of municipal wastewater	Cooling tower make-up water Once-through cooling Process applications
Internal recycling and cascading use of process water	Cooling tower make-up water Once-through cooling and its reuse Laundry reuse (water, heat, and detergent recovery) Reuse of rinse water Cleaning of premises
Non-industrial use of effluent	Heating water for pools and spas Agricultural applications

Source: Asano, T., F.L. Burton, and G. Tchobanoglous (2006) Water Reuse: Issues, Technologies and Applications, Metcalf & Eddy, Inc., McGraw-Hill Book Co., New York, NY.

Water quality requirements for industry reuse differ according to application types. Obtaining the necessary quality may require secondary treatment, tertiary treatment, or specific methods to meet individual needs. For example, rinsing and cleaning for semiconductor wafer manufacturing requires ultra-pure water, which can be supplied from municipal wastewater that has undergone reverse osmosis and ultraviolet treatment. Almost all well-managed cooling towers use a water treatment scheme such as sulphuric acid treatment, side stream filtration and Ozonation to inhibit corrosion and scaling. The cascading of process water of non-potable quality without treatment may be sufficient for general office cleaning and rinse water. In the steel industry, the effluent from wet scrubbers of blast furnaces can be recycled after treatment to remove iron oxide, silica, carbon lime and magnesium by coagulation or high-gradient magnetic separation. In the pulp and paper industry, water reuse is an important strategy for recovering fibers, chemicals and heat from process effluent, as well as for reducing freshwater consumption and wastewater production.

Potential concerns

Potential concerns for industrial water reuse include scaling, corrosion, biological growth, and fouling, which may impact industrial process integrity and efficacy, as well as product quality. These concerns are often interrelated and may be addressed by the options summarized in Table (9).

Table 9: Industrial water reuse: concerns, causes, and treatment options

Concerns	Causes	Treatment options
Scaling	inorganic compounds, salts	scaling inhibitor, carbon adsorption, filtration, ion exchange, blowdown rate control
Corrosion	dissolved and suspended solids pH imbalance	corrosion inhibitor, reverse osmosis
Biological growth	residual organics, ammonia, phosphorous	biocides, dispersants, filtration
Fouling	microbial growth, phosphates, dissolved and suspended solids	control of scaling, corrosion, microbial growth, filtration chemical and physical dispersants

Salt concentrations can be affected by various factors, including process operating temperatures, sources of wastewater, and areas from which wastewater is collected (e.g. coastal areas may have higher concentrations).
Occupational health concerns include exposure to aerosols that contain toxic volatile organic compounds and bacteria, such as Legionella, which causes Legionnaire's disease.

Some of the important and practical aspects for industrial wastewater reuse are:

• Usually, the industry itself decides the needs and extent of wastewater treatment for its reuse. The government does not decide how to reuse/recycle water in the industry, it only motivates industry through incentives such as the price of water or subsidies for the technology.

• Most industries select types of wastewater treatment processes that have a great level of reliability. This differs from wastewater reuse projects in municipalities, where the cost is a crucial factor to decide both the type of reuse and the type of treatment.

3.7 Wastewater Reuse for Urban Applications

In urban areas, the potential for introducing wastewater reuse is quite high, and reuse options may play a significant role in controlling water consumption and reducing its pollutant load on the environment. A large percentage of water used for urban activities does not need quality as high as that of drinking water. Dual distribution systems (one for drinking water and the other for reclaimed water) have been utilized widely in various countries, especially in highly concentrated cities of the developed countries. This system makes treated wastewater usable for various urban activities as an alternative water source in the area and contributes to the conservation of limited water resources. In most cases, secondarily treated domestic wastewater followed by sand filtration and disinfection is used for non-potable purposes, such as toilet flushing in business or commercial premises, car washing, garden watering, park or other open space planting, and firefighting.

Benefits

The benefits of wastewater reuse for urban applications include the following:

• High volume of wastewater generation, and a large number of potential applications and volume for water reuse, which may benefit from the economy of scale.

• Reduction in the wastewater volume to be treated by municipal wastewater treatment plants, which are over-extended and in need of expansion in many developing countries' mega-cities.

There is also a small-scale on-site system where the grey water is recycled as an in-building water resource, with a dual distribution system. Reclaimed water can be used for toilet flushing, car washing, stream augmentation or landscape purposes.

Potential concerns

One of the key concerns for wastewater reuse in urban applications is the protection of public health, as urban reuse has the potential to expose a large number of people to disease-causing microorganisms. Care should be taken to avoid contamination of drinking water by misconnection (cross connection) between potable water pipes and reclaimed water pipes, and also to disinfect reclaimed wastewater properly.

In addition, the following problems have also been identified in wastewater reuse for toilet flushing:

• Corrosion of pipe.

• Blockage of pipe and strainer.

• Biofilm (slime) formation in reservoir tank due to reduction of residual chlorine in reclaimed water.

These problems, some of which are similar to concerns associated with industrial reuse, tend to occur because reclaimed water contains more salts and organics than drinking water.

Furthermore, an insufficient amount of residual chlorine in reclaimed water allows bacteria growth and biofilm formation in the reservoir tank. The reduction of residual chlorine occurs as the consumed chlorine reacts with salts and organics in reclaimed water. Therefore, the chlorine injection rate must be monitored carefully and should be kept at an appropriate level.

3.8 Wastewater Reuse for Environmental Water Enhancement

Another area where wastewater reuse is being applied is in environmental enhancement, such as the augmentation of natural/artificial streams, fountains, and ponds. In metropolitan areas, urbanization, and the resulting increase in surface area coverage by buildings and pavements, has resulted in decreased water retention capacity. In addition, storm water is rapidly drained and discharged to a river and/or sea to prevent flooding, often leaving little water for environmental water usage.

Benefits

The key benefit for environmental enhancement is the increased availability and quality of water sources, which provide public benefits such as aesthetic enjoyment and support ecosystem recovery. The restoration of streams or ponds with reclaimed water has been practiced in many cities, contributing to the revival of aquatic life, such as fish, insects, crawfish and shellfish, and creating comfortable urban spaces and scenery. The recovery of water channels has great significance for creating 'ecological corridors' in urban areas.

Potential concerns

As with urban applications, public health concerns must be adequately addressed for environmental enhancement applications in order to avoid negative human health impacts. When treated wastewater is used for water augmentation in a water channel, proper water quality guidelines must be considered on the assumption that there will be human contact with the reused water, and sufficient disinfection must be carried out. Disinfection options may include chlorination or UV irradiation. In addition to the public health considerations, the removal of nutrients including nitrogen or phosphorus should be implemented since they may cause algal blooming, which spoils the appearance of streams, lakes and reservoirs.
Care must also be taken to facilitate ecosystem recovery. In the case of the restoration of aquatic flora and fauna in a stream, ozone or UV disinfection is more preferable than chlorination, since it generates fewer disinfection by-products with smaller residual effects to the flora and fauna.

3.9 Wastewater Reuse for Groundwater Recharge

A groundwater aquifer is important for freshwater storage and water transmission. It provides water resources that can be withdrawn for various purposes. Three common methods for aquifer recharge are illustrated in Figure (9).

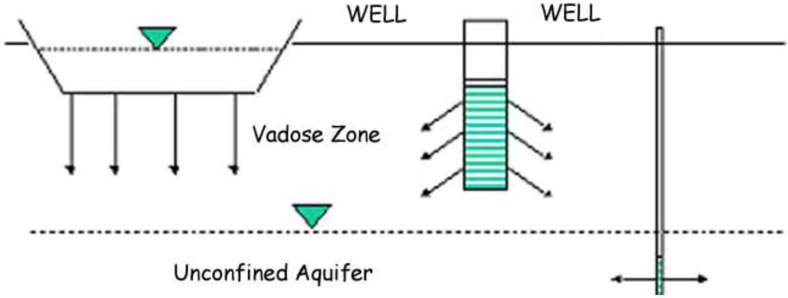

Figure 9: Method for aquifer recharge

The use of a recharge basin requires a wide area with permeable soil, an unconfined aquifer with transmissivity, and an unsaturated (or vadose) zone without restricting layers. With this system, the vadose zone and aquifer work as natural filters and remove suspended solids, organic substances, bacteria, viruses and other microorganisms. In addition, reduction of nitrogen, phosphorus and heavy metals can also be achieved. This process is called soil aquifer treatment.

Direct injection of treated wastewater can access deeper aquifers through an injection well. Direct injection is utilized when aquifers are deep or separated from the surface by an impermeable layer. This method requires less land than the recharge basin methods, but it costs more to construct and maintain the injection well. A well wall is susceptible to clogging by suspended solids, biological activity or chemical impurities. In this method, the soil aquifer treatment effect is not observed. The method requires advanced pretreatment of applied water, including sufficient disinfection. Without treatment, the injected wastewater may pollute the aquifer, causing health concerns.

Vadose zone injection is an emerging technology that provides some of the advantages of both recharge basins and direct injection wells. This method is used when a permeable layer is not available at a shallow depth, and a recharge well has a relatively large diameter.

Benefits

Groundwater recharge has been used to prevent the decline in groundwater level and to preserve the groundwater resource for future use. Compared to conventional surface water storage, aquifer recharge has many advantages, such as negligible evaporation, little secondary contamination by animals, and no algal blooming. It is also less costly because no pipeline construction is required. Furthermore, it protects groundwater from saltwater intrusion by barrier formation in coastal regions, and controls or prevents land subsidence.

Potential concerns

In any of the methods described above, groundwater recharge with reclaimed water presents various health concerns when water is extracted from a collection well and used for irrigation or other purposes. As the performance of soil aquifer treatment is uneven depending on hydraulic loading, each project should be carefully designed, and adequate attention paid to reducing pathogens.

4.1 Introduction

The technical advances in irrigation materials and methods from the end of the twentieth century are becoming part of usual agricultural practice.

Selection of irrigation method should be done taking into account these developments, which include computer models on water use optimization, developed for golf course irrigation. In addition to advanced irrigation technologies, low-cost and simple-to-use methods have been developed and implemented in emerging countries.

4.2 Criteria for Selection of an Appropriate Irrigation Method

The common irrigation methods could be classified in 3 main groups depending on the location of water application on the soil surface, which can be on all, part of, or under the surface.

Further distinction between irrigation methods comes from the type of water, which can be applied with low or high velocity or as spraying water.

The most common and widely used classification of irrigation methods is based on the practical experience, taking into account mostly the application of water Table (10):

- Surface irrigation, where water is applied directly on the soil surface by gravity.
- Overhead or sprinkler irrigation, where water is distributed over the soil surface under high pressure as small drops similar to rainfall.

- Localized or micro irrigation, where small quantities of water is applied near the roots of crops as drops, tiny streams or mini spray including a number of methods such as bubbler, trickle, micro-spray or subsurface drip irrigation.

Table 10: Basic Features of Selected Irrigation Systems

Irrigation method	Topography	Crops	Comments and recommendations
Surface (flood) irrigation Widely spaced borders	Land slopes capable of being graded to less than 1% slope and preferably 0.2%	Alfalfa and other deep-rooted close growing crops and orchards	The most desirable surface method for irrigating close-growing crops where topographical conditions are favorable. Even grade in the direction of irrigation is required on flat land and is desirable but not essential on slopes of more than 0.5%. Not suitable for sandy soils. Can be useful for salinity control purposes. Water application efficiency 45–60%.
Graded contour furrows	Variable land slopes of 2–25%, but preferably Less	Row crops and fruit	Especially adapted to row crops on steep land, though hazardous due to possible erosion from heavy rainfall. Unsuitable for rodent infested fields or soils that crack excessively. Actual grade in the direction of irrigation 0.5–1.5%. Ensure better health protection than border irrigation and can be useful for salinity control. Water application efficiency 50–65%. Rectangular checks (levees) Land slopes capable of being graded so single or multiple tree basins will be leveled within 6cm Orchards Especially adapted to soils that have either a relatively high or low water intake rate. May require considerable grading. Water application efficiency 30–60%.
Rectangular checks (levees)	Land slopes capable of being graded so single or multiple tree basins will be leveled within 6cm	Orchards	Especially adapted to soils that have either a relatively high or low water intake rate. May require considerable grading. Water application efficiency 30–60%.
Sub irrigation	Smooth-flat	Shallow-rooted (potatoes or grass) or hydrophilic (sugar cane, date palm) crops	Requires a water table, very permeable subsoil conditions, and precise leveling. Very few areas adapted to this method. For use of recycled water should be replaced by subsurface irrigation. Water application efficiency 50–70%.
Sprinkler irrigation Center pivot Lateral move Hand-move Solid set, etc.	Undulating 1_>35% Slope	All crops, well suited for turf grass	Allows uniform, efficient and frequent application, as well as addition of chemicals and fertilizers. Good for rough or very sandy lands in areas of high production and good markets. Good method where power costs are low. May be the only practical method in areas of steep or rough topography. Good for high rainfall areas where only a small supplementary water supply is needed. High degree of

			automation. Capital costs typically 50 to 100% higher than surface irrigation, as well as operation and maintenance (O&M) costs. Affected by wind. High evaporation losses. Water application efficiency 60–85%.
Localized or micro-irrigation **Mini sprinklers**	Wide range of terrain Conditions	All crops	Point source application by a small spray on the soil surface, usually without overlapping. High efficiency and possibility of addition of chemicals. Especially suited for irrigation with recycled water enabling high-frequency and low-volume irrigation with easy scale up for small units. Capital costs typically over 100% higher than sprinkler irrigation, as well as O&M costs (50%). Water application efficiency 70–90%.
Drip/trickle	Any topographic condition suitable for row crop farming	Row crops, fruits or vineyards	Perforated pipe on the soil surface drips water at base of individual vegetable plants or around fruit trees. High efficiency and possibility of addition of chemicals. Has been successfully used with saline irrigation water. Capital costs similar to mini-sprinkler irrigation and typically over 300–400% higher than surface irrigation. Water application efficiency 70–95%.
Subsurface	Field slope is limiting, in particular undulating terrain	Fruit trees, perennial row crops	Application of water below the soil surface through emitters or porous tube with discharge rates similar to drip irrigation. This system provides the highest health protection when using recycled water for irrigation. The main constraints are the high capital costs and needs of good design, operation and maintenance. Water application efficiency 70–98%.

Under normal conditions, the type of irrigation method selected will depend on water supply conditions, climate, soil, crops to be grown, cost of irrigation method, available irrigation material, and the ability of the farmer to manage the system Table (10). However, when using recycled water as the source of irrigation, other factors such as contamination of plants and harvested product, farm workers or the environment, as well as salinity and toxicity hazards need to be considered. There is considerable scope for reducing the undesirable effects of wastewater use in irrigation through the selection of appropriate irrigation methods.

The choice of irrigation method using recycled water is governed by the following technical factors:
- Choice of crops.
- Wetting of foliage, fruits, and aerial parts.
- Distribution of water, salts, and contaminants in the soil.

• Ability to maintain high soil water potential.
• Efficiency of water application.
• Complexity of irrigation equipment.
• Potential of farm workers to suffer health problems derived from exposure to water components.
• Potential to contaminate the environment.
• Capital (installation) and operation costs, including energy requirements, labor availability, and maintenance costs.

Table (11) presents an analysis of these factors in relation to four widely practiced irrigation methods: border, furrow, sprinkler, and drip irrigation. Common irrigation methods could be classified in three main groups, depending on the location of water application on the soil surface.

Water application efficiency becomes especially important in areas with water scarcity and high evaporation rates. In these conditions, mini-sprinklers and drip irrigation ensure the most effective water use. Moreover, these systems provide the best health protection by lowering the probability of direct contact with recycled water.

From the health aspect point of view, the following points should be considered during the selection of the most appropriate irrigation method:

• All irrigation methods are appropriate to be used for recycled water, which is in compliance with water reuse guidelines or regulations for unrestricted irrigation, provided that agronomic criteria are also met.
• A number of existing regulations require higher water quality for sprinkler irrigation because of the possible disease transmission with aerosols.
• Sprinkler irrigation with recycled water that does not meet the health criteria is possible in conditions of implementation of specific management practices such as crop selection (industrial crops and fodder), irrigation scheduling (irrigation during night), and other restrictions (no irrigation during windy conditions).

In addition to the technical and health considerations, socioeconomic conditions should also be taken into account.

In this context, an irrigation system considered most appropriate in one country or region may not be so in another.

Table 11: Evaluation of Common Irrigation Methods in Relation to Use of Recycled Water

Parameter of evaluation	Furrow irrigation	Border irrigation	Sprinkler irrigation	Drip irrigation
Foliar wetting and consequent leaf damage resulting in poor yield	No foliar injury as crop is planted on ridge [a]	Some bottom leaves may be affected, but damage is not so serious as to reduce yield [a]	Severe leaf damage can occur, resulting in significant yield loss [b]	No foliar injury under this method of irrigation [a]
Salt accumulation in the root zone with repeated applications	Salts tend to accumulate in ridge, which could harm crop [b]	Salts move vertically downwards and are not likely to accumulate in the root zone [a]	Salt movement is downwards and root zone is not likely to accumulate salts [a]	Salt movement is radial along the direction of water movement; a salt wedge is formed between drip points [c]
Ability to maintain high soil water potential	Plants may be subject to water stress between irrigations [c]	Plants may be subject to water stress between irrigations [c]	Not possible to maintain high soil water potential throughout growing season [b]	Possible to maintain high soil water potential throughout the growing season and minimize the effect of salinity [a]
Suitability to handle brackish wastewater without significant yield loss	Fair to medium; with good management and drainage, acceptable yields are possible [c]	Fair to medium; good irrigation and drainage practices can produce acceptable levels of yield [c]	Poor to fair; most crops suffer from leaf damage and yield is low [b]	Excellent to good; almost all crops can be grown with very little reduction in yield [a]
Cost of equipment, operation and maintenance	Low costs; land preparation of furrows, 30–450m long, 20–30 cm deep	Low costs; land preparation of field areas with downslope 0.1–0.4%	Very high cost of equipment, significant O & M costs, and need for periodic maintenance	High cost of equipment, moderate O&M costs, and need for maintenance

a Irrigation method is recommended.
b Irrigation system is not advisable.
c Irrigation method may cause problems.
Source: Lazarova V., and Bahri A. (2004). Water reuse for irrigation: agriculture, landscapes, and turf grass.

4.3 Comparison of Irrigation Methods

4.3.1 Surface Irrigation Methods

Surface or flood irrigation methods account for about 95% of the world's irrigated area because of the low cost and simplicity of use and implementation. In this case, irrigation water is simply flowing by gravity across the irrigated area. This method involves complete coverage of the soil surface with treated effluent, Figure (10) and is normally not an efficient method of irrigation.

Figure 10: Flood irrigation the entire root zone is wetted to saturation.

Flood irrigation is not suitable on steep slopes, on soils with high hydraulic conductivity (sandy soils with too rapid infiltration), for shallow-rooted crop species, and at sites where it is critical to minimize deep drainage. As surface irrigation systems normally result in the discharge of a portion of the irrigation water from the site, some methods of tailwater return or pump-back may be required in areas where discharge is not permitted. To avoid surface ponding of stagnant effluent, land leveling should be carried out carefully and appropriate land gradients should be provided.

The efficiency of surface irrigation methods in general (borders, furrows) is not greatly affected by water quality, although the health risk inherent to these systems is most certainly of concern. Some problems might arise if the effluent contains large quantities of suspended solids, which settle out and restrict flow in transporting channels, gates, pipes, and appurtenances. The possibility of biofilm growth on the transport pipeline systems could be a concern.

- **Border Irrigation**

In border irrigation systems, the irrigated land is divided into wide long bays bordered by earth mounds, also called strips or borders. Recycled water flows into each bay through a pipe or gate valve from the distribution channel. As a rule, this method is used on land of flat topography.

This system can lead to contamination of vegetable crops growing near the ground and root crops and will expose farm workers to the effluent more than any other method. Thus, from both health and water conservation points of view, border irrigation with recycled water is not very satisfactory, although it can occasionally be useful for salinity-control purposes.

• **Furrow Irrigation**

Furrow irrigation does not wet the entire soil surface Figure (11), because the irrigation water is distributed through shallow, narrow, gently sloping furrows (narrow ditches dug between the rows of crops). Typically, water is supplied to the furrows from gated pipes or siphons Figure (12). This method can reduce crop contamination, since plants are grown on ridges. However, complete health protection cannot be guaranteed. Contamination of farm workers is potentially medium to high, depending on automation. If the effluent is transported through pipes and delivered into individual furrows by means of gated pipes, risk to irrigation workers is minimal.

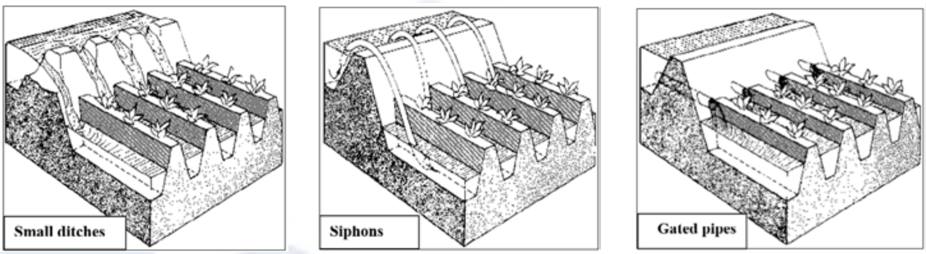

Figure 11: Furrow irrigation

Figure 12: Furrow irrigation of crops

• **Sub-irrigation**

This method, which has a limited application, consists in supplying water to the root zone of crops by artificially regulating the groundwater table. Open ditches are usually dug to a depth below the water table, and the level of the water is controlled by check dams or gates. In this manner, the ditches can serve either to drain excess water and thereby lower the water table during wet periods or to raise the water table during dry periods and thereby wet the root zone from below. Sub-irrigation may be used for field crops and pasture, as well as orchards. It is best suited to hydrophilic crops such as sugar cane and dates.

This system is applicable only where the water table is naturally high, as it frequently is along river valleys. Reduced risk of crop contamination is expected with such a system. The disadvantage of open ditches is that they interrupt the field and interfere with tillage, planting, and harvesting as well as take a significant fraction of the land out of cultivation. An alternative is to place porous or perforated pipes below the water table, with controllable outlets (subsurface irrigation).

4.3.2 Sprinkler Irrigation Methods

Sprinkler or overhead irrigation methods create artificial rainfall, and, thus, they are generally more efficient in terms of water use since greater uniformity of application can be achieved Figure (13). Sprinklers are mounted on riser pipes and scattered throughout the irrigation area by blocks with overlap of 25–50% to achieve uniform wetting. The spraying is accomplished by using several rotating sprinkler heads or spray nozzles or a single gun-type sprinkler. In general, sprinkler systems are the most expensive and are less suitable for plantations harvested in short rotation, because of their vulnerability to damage by heavy machinery. Table (12) summarizes the most important advantages and disadvantages of sprinkler systems. Sprinkler irrigation is especially suitable for continuous low vegetation (such as ground cover turf grass, decorative estates, some fodder crops), plants with shallow root systems, as well as any vegetation that benefits from overhead water and high humidity.

Figure 13: The wetting pattern of sprinkler irrigation.

Table 12: Advantages and Disadvantages of Sprinkler Irrigation Systems Relative to Surface Irrigation

Advantages	Disadvantages
Suitable to use on porous and variable soils	Initial cost can be high
Suitable to use on shallow soil profiles	Energy costs higher than for surface systems
Suitable to use on rolling terrain	Higher humidity levels can increase disease potential for some crops
Suitable to use on easily eroded soils	Sprinkler application of highly saline water can cause leaf burn
Suitable to use with small flows	Water droplets can cause blossom damage to fruit crops or reduce quality of some fruit and vegetable crops
Suitable to use where high water tables exist	Portable or moving systems can get stuck in some clay soils
Can be used for light, frequent applications	Higher levels of pre-application treatment generally required for sprinkler systems than for surface systems to prevent operating problems (clogging)
Control and measurement of applied water is easier	Distribution subject to wind distortion
Tailwater control and reapplication is minimized	Wind drift of sprays increases potential for public exposure to wastewater
	Vulnerability to damage by logging machinery during harvesting

It is important to stress that sprinkler irrigation should not be used at sites where spray drift is undesirable for health or environmental reasons. These overhead irrigation methods may contaminate ground crops, fruit trees, farm workers, and other people not related to the facility. In addition, pathogens contained in aerosols may be transported downwind and create a health risk to nearby residents. Therefore, buffer zones or devices (tree barriers) should be established around irrigated areas. In some systems (i.e., center pivot), the sprinkler nozzles may be dropped closer to the ground to reduce aerosol drift and thus minimize the buffer requirements. In all cases, wind must be considered as a limiting factor.

Labor requirements are usually low, with the exception of maintenance. As a rule, sprinklers and plastic risers need to be replaced about every 10 years. Generally, mechanized or automated systems have relatively high capital costs and low labor costs compared with manually moved sprinkler systems. Rough land leveling is necessary for sprinkler systems to prevent excessive head losses and achieve uniformity of wetting. Sprinkler systems are more affected by water quality than surface irrigation systems, primarily as a result of the clogging of orifices in sprinkler heads, potential leaf burn, and phytotoxicity, in particular when water is saline and contains excessive toxic elements. In-

adequate treatment, especially filtration, leads to clogging of sprinklers. The micro-spray systems are the most vulnerable to clogging. Sediment accumulation in pipes, valves, and distribution systems should also be taken into account. Secondary wastewater treatment has generally been found to produce an effluent suitable for distribution through sprinklers. Nevertheless, further precautionary measures are often adopted, such as additional treatment with granular filters or micro strainers and use of nozzle orifice diameters not less than 5 mm.
Homogeneous water distribution can be also disrupted by weeds, in particular with low-pressure systems. Recommended measures to avoid such constraints are periodic weed control by herbicides or by mounting the sprinklers on taller risers.

4.3.3 Micro-sprayer Irrigation

Micro-spray irrigation is a part of localized or micro-irrigation systems. Micro-sprayers, also called mini-sprinklers or spitters, ensure the greatest uniformity in effluent distribution and are similar in principle to drip systems, where water is applied only to a part of the ground surface Figure (14). These systems eject fine water jets from a series of nozzles, mounted on moving spindles or fixed sprinkler arms. Compared to drip emitters, micro-sprayers can water a larger area of several square meters. In addition, clogging problems are reduced thanks to the larger nozzle orifices. The discharge rate is also greater, ranging from 20 to 300 L/h.

Figure 14: The wetting pattern of micro-spray irrigation.

The pressure requirement is lower compared to conventional sprinklers, more than 2 atm, which still requires pumping or reservoir elevation of over 20 m. Another disadvantage relative to drip irrigation is the evaporation loss and wetting of foliage that can be damaged by brackish water.

It is important to stress that these systems, which are commonly used for trees, are especially suited for irrigation with recycled water because of their benefits, similar to drip irrigation, enabling high-frequency and low-volume irrigation with easy scale-up for small irrigation units.

4.3.4 Drip Irrigation

Drip irrigation is another micro-irrigation system, which often is considered as synonymous of trickle irrigation. The principle is the same, but the discharge rates of trickle systems could be higher than the upper limit of drip emitters, which is 12 L/h. In drip irrigation methods, water is applied through a network of small emitters placed on the ground surface Figures (15) and (16).

Figure 15: The wetting pattern of drip irrigation

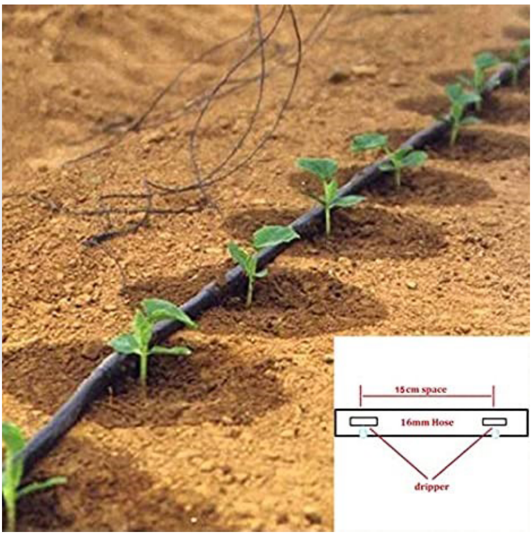

Figure 16: View of drip irrigation of crops

At regular intervals of the distribution network, near the plants or trees, a hole is made in the tube and equipped with an emitter to supply water to the plants slowly, drop by drop. The saturated zone is usually less than 50% and depends on the density of the wetting points, the rate of application, and the soil properties. As a rule, drip emitters are designed to supply controlled water rate of 1–10 L/h. The operating pressure is in the range of 0.5–2.5 atm, preferably 1 atm at the dripper, which is dissipated to atmospheric pressure by the head loss of the emitters.

The most important advantage is that these systems can be used with all types of soils and topography without special land preparation, provided that pressure regulators or regulated dripper nozzles are used in slopping lands. Moreover, these systems provide numerous other benefits, including more efficient use of recycled water, higher crop yields, and the greatest degree of health protection for farm workers and consumers, particularly when the soil surface is covered with plastic sheeting or other mulch.

Drip irrigation is particularly suited to sites with water scarcity where a low irrigation rate is desirable. To achieve a given rate of irrigation, the required volume for drip systems is about -4, -10 and -50 fold lower than conventional sprinkler, furrow, and border irrigation systems, respectively.

The capital and operation costs of drip systems fall generally somewhere between flood and sprinkler irrigation. Drip irrigation saves labor but has the highest installation cost. The successful operation of these systems requires good supervision and maintenance: regular inspection and cleaning of emitters, repair of leaks, flushing of the network (at least twice a year) with necessary acidification (to prevent precipitation of calcium carbonate), and monthly adjustment of the irrigation schedule for permanent plantings, according to seasonal weather and watering requirements.

One of the major constraints of drip irrigation is blockage of the emitters because of the very small orifices (0.1–2 mm). Thus, recycled water should be free of suspended solids. Some dissolved compounds such as Ca_2 and Fe_2 can precipitate.

From the point of view of water quality, drip irrigation systems have the advantage to allow using recycled water with high salinity or high BOD, because the entire root zone is not saturated, thus providing good soil aeration.
Drip irrigation is most suitable for row crops (vegetables, soft fruit) and tree and vine crops where one or more emitters can be provided for each plant. Generally, only high-value crops are considered because of the high capital costs of installing a drip system. Nevertheless, several experiments and real

plot application to extensive crops (wheat and alfalfa) have shown that it is possible to consider drip irrigation for these crops as well. It is important to stress that relocation of subsurface systems can be prohibitively expensive. For irrigation of urban parks and other green areas, some dripper systems are buried underground to reduce the risk of human contact with recycled water. The capital and operating costs of such systems are, however, higher, and a very good filtration of effluent is required.

Bubbler irrigation, a technique developed for localized irrigation of tree crops, avoids the need for small emitter orifices, but requires careful setting for its successful application. In this case, water is allowed to ''bubble out,'' even under a very limited pressure, from open thin-walled vertical tubes (d.1–3 cm) connected to the buried lateral irrigation tubes (d_10 cm). The main advantages of bubbler irrigation are its low cost, ease of installation and operation, as well as lower vulnerability to water quality.

When compared with other systems, the main advantages of drip irrigation are as follows:

• Increased crop growth and yield achieved by optimizing the water, nutrients, and air regimes in the root zone.
• High irrigation efficiency: no canopy interception, wind drift, or conveyance losses and minimal drainage losses.
• Minimal contact between farm workers and effluent.
• Low energy requirements: the trickle system requires a water pressure of only 100–150 kPa (1–1.5 bar).
• Low labor requirements: the trickle system can be easily automated and allows combined irrigation and fertilization.
• Accurate control of leaching and drainage (with adequate design, maintenance, and scheduling of irrigation).
• Easier removal and reinstallation during harvesting periods compared to sprinklers.

In summary, drip irrigation is best suited to areas where water is scarce, land is steeply sloping or undulating, water and/or labor are expensive, recycled water has high salinity, or the production of high-value crops requires frequent water applications.

4.3.5 Subsurface Irrigation

In subsurface irrigation, water is applied directly to the root zone via perforated or porous diffusers, placed 10–50 cm below the soil surface Figure (17). The spreading pattern depends on the soil properties as well as on the distance between adjacent emitters and their discharge rates.

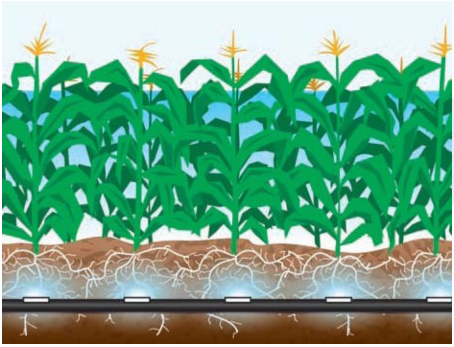

Figure 17: The wetting pattern of subsurface irrigation.

The main advantage of these systems is the health safety due to the absence of direct contact with recycled water. A potential problem here is that the narrow orifices of the emitters may become clogged by roots, particles, algae, or precipitating salts. Such clogging is difficult to detect as readily as when the tubes are placed over the surface in above-ground drip irrigation. Injecting an acidic or herbicidal solution into the tubes may help to clear some types of clogging, though the problem may recur periodically. Special drippers with a specific chemical are available that do not allow roots to enter the dripper.

In underground drip irrigation, the delivery of water via the feeder tubes can be constant or intermittent. For uniformity of application, there should be some means of pressure control. If the lines are long or the land is sloping, there can be considerable differences in the hydraulic pressure and therefore in delivery rate, unless pressure-compensated emitters are used. However, such emitters are expensive and usually of higher variation in flow and as a consequence of lower uniformity in water application.

Existing experience has shown that this method is feasible for fruit trees and other perennial row crops. The major constraint for their implementation is the high capital and operation costs and the high frequency of renewal.

4.4 Final Considerations for the Choice of Irrigation Method

Irrigation methods used depend on site topography, soil type, the species of plants to be grown, cost, effluent quality, labor availability, power requirements and public health and environment considerations.

The most important factor in decision making as to irrigation method appears to be financial, i.e., the irrigation system cost. Nevertheless, the health risks associated with the different methods, as well as water savings, should be also taken into account.

Effluent generally should be applied to the site by trickle, spray or drip irrigation, to avoid over-application and unintended environmental effects that could occur with furrow or flood irrigation systems. Use of the latter may indicate the need for laser levelled sites. Ideally, recycled water should be applied closely to the root zone using micro-sprayers or drip emitters. Among the numerous benefits of these systems is the ability to apply high-frequency irrigation better adjusted to the crop irrigation requirements. In this case, storage capacity and soil capability to retain moisture are no longer decisive. The major constraint is the need for continuous operation, because any short-term interruption can quickly result in plantation damage. In drip or trickle irrigation, pressurized water is discharged through micro-emitters. The water is dripped thereby minimizing the risk of aerosols. In spray irrigation, water is pumped through pipelines and discharged through sprinklers that can vary from high pressure 'big guns' that can generate aerosol drifts of up to 1 km, to small low-pressure micro-sprays that minimize the risk of aerosol drift and reduce the potential for odour. High pressure systems should only be used for effluent which meets the pathogen reduction criteria for use on raw human food crops, with suitable buffer distances. High pressure systems should not be used when weather conditions are such that spray drift will be excessive.

Furrow irrigation is suitable while leaching demand is high. To avoid human contact and allow pressurizing, recycled water should be conveyed in closed conduits and distributed via resistant plastic tubes. Flood irrigation methods include border check, border ditch, basin, contour bank, hillside and furrow irrigation. Flood irrigation generates little or no aerosol activity and gives an even distribution of nutrients in properly designed, laser graded systems. The potentially greater risks to groundwater should be managed.

It is important to emphasize that the irrigation method is one of several possible health control measures, along with crop selection, wastewater treatment, and human exposure control. Each measure interacts with the others, and, thus, any decision as to irrigation system selection has an influence on wastewater treatment requirements, human exposure control, and crop selection (e g., row crops are dictated by trickle irrigation). At the same time, the feasibility of the irrigation technique depends on crop selection. The choice of irrigation system might be limited if wastewater treatment has been already implemented without any possibility for plant upgrading and water quality improvement.

The infiltration rate of soil is an important consideration in the type of irrigation method used and the way it is operated. Effluent should be applied uniformly and at a rate less than the nominal infiltration rate to avoid surface runoff.

Spray and drip/trickle irrigation systems usually involve higher capital and operating costs than flood or furrow systems, but also provide better operational flexibility and may provide greater water use efficiency. Costs of permanent spray systems may be high, however, center pivots, travelling irrigators and semi-permanent spray systems can have a much lower capital cost per hectare than some drip systems.

Attention should be given to treated wastewater constituents which cause clogging of the irrigation systems. Clogging problems with sprinkler, mini-sprinkler and drip irrigation systems might be a serious problem. Growths (slimes, bacteria, etc.) in the sprinkler head, emitter orifice or supply line, cause plugging as do heavy concentrations of algae and suspended solids. The most serious clogging problems occur with drip systems. Filtration may be required just before use. This makes management of drip irrigation system using treated wastewater needing more attendance.

Solutions suggested to the plugging problem are:

- To avoid problems due to suspended algae that are accumulated on the water surface and those problems due to sludge accumulation in the bottom of the reservoir, water should be pumped at a depth of about one meter from the water surface.
- Filtering. Depending on the concentration of suspended solids, algae and other impurities, gravel, sand or other filters are required with micro-irrigation systems.
- Selection of the irrigation method. In case of impurities and in absence of filtering system, micro-irrigation systems should be avoided. Depending on the crop, sprinklers could be a better choice. Even surface irrigation might be the preferred one.

Module 5: Water management strategy to determine the optimal irrigation amount and schedule with different water types (including treated wastewater)

5

5.1 Introduction

Alternative water resources for irrigation include treated municipal wastewater, storm water runoff, and irrigation return flow. The principal concern with regard to irrigation using these waters is related to potential adverse effects on soil and crops as well as the management that may be necessary to control or compensate for water quality related problems.

Success in using treated wastewater for crop production will largely depend on adopting appropriate strategies aimed to optimize crop yield and quality, maintain soil productivity, and safeguard the environment. Several management alternatives are available, and their combination will offer an optimum solution for a given set of conditions. The choice of best management strategies for irrigation with recycled water becomes more limited with increasing salinity, sodicity, or toxic element concentration. For example, under such conditions, leaching and drainage must be increased.

5.2 Choice of Management Strategy of Irrigation with Recycled Water

The user of recycled water should have information about effluent supply and quality Table (13) to ensure the formulation and adoption of an appropriate on-farm management strategy. The required information includes the quantity of available water, means and timing of its supply, as well as the main physical, chemical and microbiological water characteristics.

Table 13: Information on recycled water supply and quality required for the definition of appropriate management strategy

Information on recycled water	Decisions on irrigation management
Effluent supply:	
• **Total amount of effluent that would be made available during the crop-growing season**	• Total area that could be irrigated
• **Effluent available throughout the year**	• Storage facility during non–crop-growing period either at the farm or near wastewater treatment plant
• **Rate of delivery of effluent either as m^3/d or L/s**	• Area that could be irrigated at any given time, layout of fields and facilities, and system of irrigation • Layout of fields and facilities, irrigation system, and irrigation scheduling
• **Type of delivery: continuous or intermittent, or on demand**	• Need to install pumps and pipes to transport effluent and irrigation system

• **Mode of supply: supply at farm gate or effluent available in a storage reservoir to be pumped by the farmer**	
Effluent quality:	
• **Total salt concentration and/or electrical conductivity of the effluent**	• Selection of crops, irrigation method, leaching, and other management practices
• **Concentrations of cations, such as Ca^{2+}, Mg^{2+}, and Na^{+}**	• Assess sodium hazard and undertake appropriate measures
• **Concentration of toxic ions, such as boron and Cl^{-}**	• Assess toxicities likely to be caused by these elements and take appropriate measures
• **Concentration of trace elements, particularly those suspected of being phytotoxic**	• Assess trace toxicities and take appropriate measures
• **Concentration of nutrients, particularly nitrate nitrogen**	• Adjust fertilizer levels, avoid over fertilization, and select crop
• **Level of suspended solids**	• Select appropriate irrigation system and measures to prevent clogging problems
• **Levels of intestinal nematodes and fecal coliforms**	• Select appropriate crops and irrigation system

Basically, an on-farm strategy for using recycled water consists of a combination of the following measures:

- Selection of the appropriate irrigation method (Module Four).
- Proper selection of crops with adequate salt and specific ion tolerance.
- Adoption of appropriate management practices:
  - o Proper soil amendments and soil management.
  - o Leaching and sufficient drainage to dispose of excess water and salts (Module Seven).
  - o Adequate timing for both irrigation and leaching.
  - o Proper use of fertilizers (Module Six).

Special attention should be paid to the selection of irrigation practices when recycled water is characterized by high salinity and sodicity. The most important recommendations are as follows:

- Verify that soil permeability and drainage are adequate.
- Determine initial salinity and sodicity of the soil and reclaim if necessary.

• Determine the chemical composition of irrigation water to assess potential soil and crops hazards.
• Leach to prevent salt accumulation.
• Fertilize and control weeds and insects, because healthy plants withstand salinity better.

Furthermore, in arid and semi-arid areas where there are limited water supplies for irrigation, one option to overcome water scarcity problem could be alternate use of recycled water and the conventional sources of water by:
• Blending conventional water with treated effluent.
• Using the two sources in rotation.

5.2.1 Amount of Water Used for Irrigation

In irrigation, especially with recycled water, it is important to apply an appropriate, well-controlled quantity of water sufficient to meet the crop requirements and to prevent accumulation of salts in the soil. The use of insufficient water leads to decrease in crop production. However, excessive flooding can be more harmful, as it saturates the soil for a long time, inhibiting aeration, leaching nutrients, inducing salinization, and polluting underground water. Poorly managed irrigation has detrimental effects on land productivity, and the cost of land rehabilitation may be prohibitive.

Irrigation requirements depend on the crop, the period of plant growth, and climatic conditions (mainly precipitation and evapotranspiration). In all cases, the water needed for normal plant growth is equal to evapotranspiration (more than 99% of the water absorbed by plants is lost by transpiration and evaporation from the plant surface). Additional amount is required for leaching practices. Water application efficiency must be also considered.

Crop evapotranspiration is mainly determined by climatic factors and hence can be estimated with accuracy using meteorological data. Detailed recommendations for the calculation of crop water use are provided by FAO. A computer program, CROPWAT, can be downloaded from the FAO website to determine the water requirements of various crops from climatic data from almost all continents. Table (14) illustrates the water requirements of some selected crops. Unlike agricultural crops or turfgrass, landscape ornamentals are composed of many species (groundcover, shrubs, trees, etc.) with different water requirements. In addition, the density of landscape planting and microclimate highly influence evapotranspiration and, consequently, water needs.

Table 14: Water Requirement of Selected Crops

Type of crop	Amount of irrigation water (mm/growing period)	Sensitivity to water supply
Alfalfa	800-1600	Low to medium high
Banana	1200-2200	High
Bean	300-500	Medium-high
Cabbage	380-500	Medium-low
Citrus	900-1200	Low to medium high
Cotton	700-1300	Medium-low
Groundnut	500-800	Low
Maize	500-800	High
Potato	500-700	Medium-high
Rice	350-700	High
Sunflower	800-1200	Low
Sorghum	450-650	Medium-low
Wheat	450-650	Medium-high

Source: FAO, 2002

Water requirements should be calculated to adjust irrigation rate periodically, at least monthly, to ensure that the correct amount of recycled water is applied at the right time to meet crop requirements, taking into account climate variations. It is recommended to apply recycled water only under dry weather conditions, with regular inspections to avoid ponding of recycled or runoff water.

5.2.2 Irrigation Scheduling

Irrigation scheduling is the application of water to the plant by the amount needed and when it is needed to achieve maximum crop production. Therefore, irrigation scheduling deals with how much water should be applied and when that water is to be applied. In other words, it deals with the amount and frequency of irrigation water.

In the previous section, we discussed the amount of water needed by the crop (crop consumptive use) and the capability of soil to store water in it for plant use. From that discussion, we conclude that the frequency and amount of irrigation water depend on:

• Crop consumptive use or the water needed by the crop.

• The availability of water, if the water available is small then the crop consumptive use decreases. However, this might result in reduction in crop yield and if the available water is too low then the plant will wilt.

• The capacity of the root zone soil to store water. As the soil acts as a reservoir for water storage with a limited capacity, we should limit the amount that we apply each time. This amount should be less than or equal to the space available for it in the root zone. Any extra water might be lost through drainage.

5.2.2.1 When should we irrigate and much to apply?

The above discussion leads us to the important question which is when we should irrigate. This question is usually answered using several methods:

1. By observing the plant: when the plant starts temporary wilting, that means the rate at which water is extracted by the plant is less than plant consumptive use. This occurs when the rate of water extraction is reduced because of the reduction in the available water. Therefore, water should be applied to the plant to provide it with its water requirements. We might exclude the wilting which occurs around noon to some crops. Around noon, the crop consumptive use is maximum because the solar radiation and temperature are maximum. In some crops, we allow that wilting and monitor the wilting of crops at times other than noon time. In general, the appearance of the crop is used by most farmers all over the world to decide when they should irrigate. This requires experience with the crop type and its value. The disadvantage of this method is that it requires experience and the crop will suffer from some water stress before we apply water to it which reduces its yield.

2. By observing soil moisture in the field: As plants extract moisture from the soil, the moisture content decreases with time. If we monitor the moisture content, then when it goes below a certain level, we apply irrigation. The level at which we apply irrigation depends on soil type and crop type. For most vegetables, we allow the available moisture to drop up to 50% of the total available water before we apply irrigation. The depletion level is determined either by measuring the moisture content or by judging the depletion level from the appearance and feeling the soil. Judging using feel and appearance requires some experience. Measuring the moisture content is the most accurate method. This could be done using gravimetrical method. The disadvantage of this method is that it takes 24 hours to oven dry the soil sample which means we might be late in irrigating our crop one day. Using tensiometers or neutron probes could be utilized efficiently in deciding when to irrigate. We should take into account that moisture content changes with soil depth. In irrigation, we are concerned with the moisture content in the root zone. However, plants take most of their water from the top half of the root zone. Therefore, we should monitor moisture content at a depth of 15 to 30 cm for most vegetables. The average extraction of soil moisture by plant roots between irrigations in an arid region is shown in Figure (18):

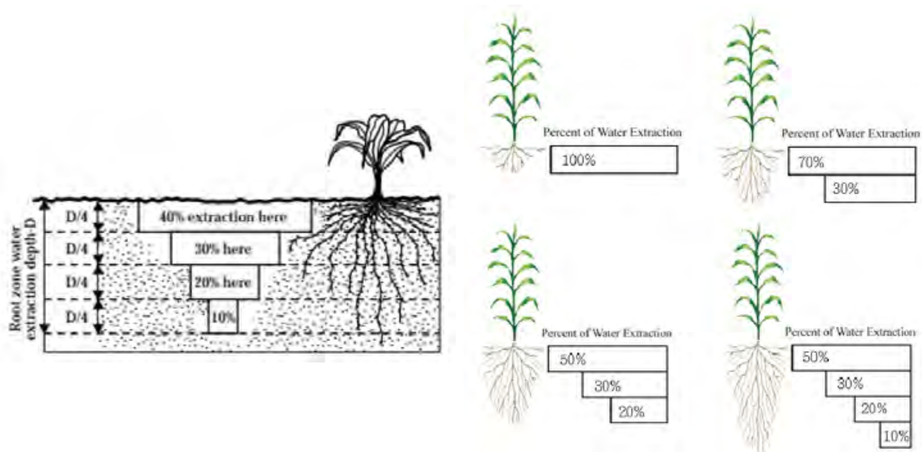

Figure 18: Water extraction from soil profile

In Figure (18), we see that crops in arid regions take 70% of their moisture from the above 50% of the root depth. This requires from us to monitor the moisture in the above 50% of the root depth as it will dry first. In most vegetables, the root depth is less than one meter (50 to 80cm). That is why we recommend monitoring the moisture content at a depth of 15 to 30 cm. One should take into account that the top 5 to 10 cm of soil dry quickly due to direct evaporation. Therefore, we should look at the moisture below that top portion.

3. By maintaining minimum moisture content through estimating crop consumptive use theoretically: The soil acts as the reservoir to store water. The maximum amount that the plant can use is:

$$\textbf{TAW = (FC-PWP) RD}$$

Where
TAW: total available water for plant use
FC: field capacity (volumetric moisture content)
PWP: permanent wilting point (volumetric moisture content)
RD: root zone depth of the plant

The moisture content should not go down to PWP as the crop wilts there. The management allowable deficit (MAD) is the maximum moisture deficit that we allow in the root zone. It is defined as:

$$\textbf{MAD = fTAW}$$

where f is a constant depends on crop type and is taken 50 % for most crops. Thus:

$$MAD = f\ (FC\text{-}PWP)\ RD$$

The actual water deficit is defined as:

$$Deficit = (FC\text{-}\theta)\ RD$$

When the actual deficit is equal to or greater than the MAD, irrigation water should be applied.
The actual deficit is estimated using a budget technique from initial moisture content and actual ET (calculated from CROPWAT). Or:

New Deficit = previous Deficit + ETa - Irrigation - Precipitation

The maximum irrigation interval could be estimated as:

$$\begin{aligned} \text{Maximum interval} &= MAD/ETa \\ &= f\ TAW\ /Eta \end{aligned}$$

5.3 How Important Is Proper Irrigation When Using Reclaimed Water?

Proper irrigation, applying just what is needed and not over-irrigating, is just as important or even more impor¬tant when using reclaimed water.

Over-irrigation results in applying more water than the soil within the plant root zone can hold. This results in leaching of water, and the N and P within it, into deeper soil layers or into groundwater.

An efficient, properly maintained, and calibrated irrigation system should follow an irrigation schedule based on seasonal water needs for dif¬ferent plant types. However, many users of reclaimed water may over-irrigate more often than those who use potable water for irrigation. A possible reason for this is the typically lower cost of reclaimed water. In addition, many users of reclaimed water are charged only a flat monthly fee, no matter how much they actually use, and may have a greater tendency to "set and forget" their irrigation system.

The nutrient uptake efficiency of a plant is defined simply as the amount of a nutrient taken up by the plant divided by the amount applied. The nutrient uptake efficiency is an effective metric to quantify the added nutrients used by the plant and not lost to leaching or runoff. The factors that influence the nutrient uptake efficiency include the water uptake efficiency and the timing and amount of nutrient applications. The water uptake efficiency of a plant is simply the quantity of water taken up by the plant divided by the quantity of irrigation applied. The higher the water uptake efficiency, the better nutrients are held in the root zone where they can be taken up by plants. So, maximizing water uptake efficiency will also improve nutrient uptake efficiency.

The scheduling of irrigation is one of the most important functions of the irrigation manager. Excessively long intervals without irrigation can lead to water stress and crop loss. Irrigating too often can waterlog the soil and allow excess effluent to runoff or percolate to groundwater, polluting both groundwater and surface water. To ensure that the application site is not overloaded, an irrigation schedule should be based on knowledge of the water content of the soil and the water requirements of the cultivated crop.

There are direct and indirect methods available to estimate the water content of a soil. Direct methods rely on insertion of soil moisture monitors (e.g. neutron probes) at representative sites within the system. Indirect measurements estimate plant evapotranspiration by taking direct measurements of rainfall, temperature and sometimes evaporation and converting these through recognized models into predicted evapotranspiration for the particular crop being grown.

Generally, it is advisable to irrigate the soil to allow a 5 to 10 mm soil water deficit. This allows for a buffer capacity in the soil should rain fall soon after an irrigation event.

The design must allow for adequate resting periods between irrigation to avoid rainfall runoff. For most plant systems a soil moisture deficit of at least 30 mm should be allowed to accrue before further irrigation takes place.

Module Six: Fertigation management to optimize the required fertilizer input considering the nutrient input from irrigation with treated wastewater

6.1 Introduction

The most important nutrients for crops are nitrogen, phosphorus, potassium, zinc, boron, and sulfur. Usually, recycled water contains enough of these elements to supply a large portion of a crop's needs.

The most beneficial nutrient for plants is nitrogen. Both the concentration and forms of nitrogen (nitrate and ammonium) need to be considered in irrigation water. The relative proportion of each form varies with the origin and treatment of the wastewater, but most commonly ammonium is the principal form, usually present in a concentration range of 5 to 40 mg N–NH4/L. The organic fraction, which may be either soluble or fine particulates, consists of a complex mixture including amino acids, amino sugars, and proteins. All of these fractions are readily convertible to ammonium through the action of microorganisms in the wastewater or in soil to which the wastewater is applied. During aerobic wastewater treatment, some ammonium could be oxidized to nitrates through the action of nitrifying bacteria. Common nitrate concentrations in urban wastewater range from 0 to 30 mg $N\text{–}NO_3$/L.

Nitrogen is a macronutrient for plants that is applied on a regular basis. Nevertheless, at very high concentrations (over 30 mg N_{tot}/L) it can overstimulate plant growth, causing problems such as lodging and excessive foliar growth and also delay maturity or result in poor crop quality. Nitrogen sensitivity varies with the development stage of the crops. It may be beneficial during growth stages but causes yield losses during flowering/fruiting stages. The long-term effects of excess nitrogen include weak stalks, stems, and/or branches unable to support the weight of the vegetation under windy or rainy conditions.

Pollution of groundwater from the percolation of nitrogen presents a health concern. This usually results from excessive application of nutrients in areas having permeable soils. When nitrogen is washed from soils and reaches streams, lakes, canals, and drainage ditches, it stimulates algae growth, which can result in plugged filters, valves, pipelines, and sprinklers. In addition, excessive nitrogen application to pastures may be hazardous to livestock that consume the vegetation.

Potassium in recycled water has little effect on crops. The phosphorus content in recycled water is too low to meet a crop's needs. Over time, phosphorus can build up in the soil and reduce the need for supplementation. Although excessive phosphorus does not appear to cause serious immediate problems to crop, it may affect future land use because some plants species are sensitive to high phosphorus concentrations. Phosphorus can also be a problem in surface water runoff as a limiting factor in eutrophication.

6.2 Adjusting fertilizer applications

The fertilizer value of recycled water is of great importance. The typical concentrations of nutrients in treated wastewater effluent from conventional sewage treatment processes are nitrogen 50 (20–85) mg N/L, phosphorus 10 (4–15) mg P/L, and potassium 30 (10–35) mg/L.

In general, irrigation with recycled water (treated urban wastewater) at an application rate of 100 mm/ha would provide the following quantity of fertilizing elements:

- Total nitrogen, N: 16–62 kg (in arid and semi-arid regions up to 90–300 kg)
- Phosphorus, P: 4–24 kg
- Potassium, K: 2–69 kg
- Calcium, Ca: 18–208 kg
- Magnesium, Mg: 9–110 kg
- Sodium, Na: 27–182 kg (in arid and semi-arid regions up to 200–600 kg)

Assuming an application rate of 5000m3/ha year, the fertilizer contribution of the effluent would be:

- N: 250 kg/ha year
- P: 50 kg/ha year
- K: 150 kg/ha year

Thus, all of the nitrogen and much of the phosphorus and potassium normally required for agricultural crop production would be supplied by the effluent. In addition, other valuable micronutrients and the organic matter contained in the effluent will provide complementary fertilizing benefits.
The fertilizing value of wastewater cannot be assessed using only the results of chemical analysis; the analysis should also consider the modifications occurring in the soil among the organic and mineral compounds. These modifications can change the nutrients taken up by the plants and depend on soil characteristics, climate, and type of crops. Additional fertilizers may be supplied during specific crop growth stages.
If the recycled water has high nutrient concentrations, it is desirable to choose plant species with a high demand for these elements to ensure that most of them will be assimilated by the plants. Good assimilation of nutrients by the plants will reduce the possibility of a deep nitrogen percolation and groundwater pollution.
As a rule, the phosphorus content in recycled water is too low during the early growth period to affect crop yield. Soil phosphorus gradually builds up

with time, reducing the need for supplemental phosphorus fertilizers in future years. Excess phosphorus has not been a problem to date in reuse schemes, and no guideline value is given for phosphorus content in wastewater. However, it is recommended to check the phosphorus content in recycled water in conjunction with soil testing for fertilization planning. The use of recycled water for irrigation can only partially meet crop needs.

Farmers should take into account the fertilizer value of recycled water and save money by reducing consumption of fertilizers. They should also keep in mind that an excess of nitrogen can reduce the quality of the crops and that the nitrogen content of recycled water varies throughout the year, as do plant nitrogen requirements, which vary with development stage.

For this reason, nitrogen content of water and soil should be carefully controlled, and measures such as denitrification or crop rotation should be considered when necessary. Algae growth in storage systems induced by excess nitrogen can be minimized by screen filters or chemical control (e.g., copper sulfate).

6.3 Should fertilizer be applied when irrigating with reclaimed water?

Depending on the N and P concentrations in reclaimed water, the quantity of reclaimed water used for irrigation, and the timing of the N and P supplied, it may be possible that little or no additional fertilizer will be needed (if sup¬plied in the right amount at the right time). Supplemental fertilizer applications will depend on the desired crop irrigated.

However, the amount of N and P supplied by reclaimed water is not necessarily the amount that will be used by plants. For example, 1.6 kg of N per 1000 square meter supplied in small amounts over an entire growing season will likely not produce the same results compared to the same 1.6 kg of N per 1000 square meter supplied at times that it can be best utilized by plants. Less than ideal utilization may require application of more than 0.4 kg N per 1000 square meter of supplemental fertilizer to achieve the same results that would be expected from recommended fertilization schedules. Fertilization plans should be adjusted based on the timing of the supply of N and P from reclaimed water.

The nutrient uptake efficiency of a plant is defined simply as the amount of a nutrient taken up by the plant divided by the amount applied. The nutrient uptake efficiency is an effective metric to quantify the added nutrients used by the plant and not lost to leaching or runoff. The factors that influence the nutrient uptake efficiency include the water uptake efficiency and the timing and amount of nutrient applications. The water uptake efficiency of a plant is simply the quantity of water taken up by the plant divided by the quantity of irrigation applied. The higher the water uptake efficiency, the better nutrients are held in the root zone where they can be taken up by plants.

So, maximizing water uptake efficiency will also improve nutrient uptake efficiency. Excessive irrigation will reduce the water use efficiency and, in turn, the nutrient uptake efficiency. The timing of nutrient applications affects the nutrient uptake efficiency, depending on how well it matches plant uptake patterns. The more similar nutrient applications are to the uptake pattern of the plant, the higher the nutrient uptake efficiency will be. In addition, the nutrient uptake efficiency is usually lowest in highly/excessively fertilized plants. To take advantage of the N and P in reclaimed water more fully, it is recommended that high fertilizer rates not be followed. Effective utilization will depend on the timing of the supply and proper irrigation practices.

6.4 What are the concerns when irrigating with reclaimed water?

Several significant issues with using reclaimed water for irrigation include:
• The timing of the supply of nutrients.
• The relative amounts of N to P in the re¬claimed water compared to the relative amounts beneficial to plants.
• The potential to over-apply a nutrient (P in particular) in the process of meeting the irrigation needs of the landscape.

Depending on the timing of the N and P supplied by reclaimed water, the amount of N and P in reclaimed water may not be enough to support optimum growth during the height of the growing season. Hence, supplemental fertilization may be desired.

In addition, the plant may not need or use the N and P supplied toward the end of the growing season or during the winter dormant season. Care must be taken when using reclaimed water to achieve the desired results and to avoid applying excess N and P at certain times of the year.
The relative amounts of N to P of reclaimed water are rarely the same as those needed by plants. For example, if the plant requirement for one nutrient is met, the requirement of the other is likely not met or is exceeded. If the requirement for one nutrient is not yet met, supplemental fertilizer can be applied, if desired. Care should be taken to never exceed the plant requirement of either N or P_2O_5 when irrigating with reclaimed water, since this could result in runoff or leaching of excess N and P.

Finally, care should be taken when irrigating with reclaimed water in locations where the soils contain ample P or where P pollution of surface water or groundwater is a problem.

6.5 Final Remark

While reclaimed water contains N and P that can poten¬tially be used by plants, these nutrients can be effectively utilized only when delivered in the right manner and at the right time.
Effectively utilizing the N and P in reclaimed water and avoiding unintended environmental impacts will depend on the following:

• Knowing the amount and timing of the supply of N and P in reclaimed water.
• Knowing the N and P uptake pattern of the plants irrigated with reclaimed water.
• Practicing proper irrigation to avoid over-irrigation, maximize nutrient uptake efficiency.

Currently, there is not enough information to make specific recommendations on the amount of N and P in reclaimed water that plants will use or the amount that fertilizer applications can be reduced when irrigating with reclaimed water. The amount of N and P in reclaimed water that plants use will vary on a case-by-case basis and will depend on the amount supplied, the timing of supply, and the efficiency of the irrigation system.

In general, for those who wish to maximize the nutrient uptake efficiency, it is best to begin on the low end of fertilizer applications when irrigating with reclaimed water. A topic of current research is to find detailed recommendations on the amount of N and P that plants will use from reclaimed water and the amount that fertilizer applications can be reduced when irrigating with reclaimed water.

Module Seven: Monitoring of electrical conductivity(proportional to salt concentration) in the irrigation water and in irrigated soil

7.1 Introduction

Water quality is the most important issue in water reuse systems that determines the acceptability and safety of the use of recycled water for a given reuse application. For each category of water reuse, the definition of appropriate water quality is driven by a number of health, safety, sociopsychological, and technical-economic criteria.

As a rule, water quality objectives are set by guidelines and regulations, which in turn determine the treatment technology to be used. Thorough knowledge and appropriate monitoring of water quality is needed to protect public health and minimize the negative impact of recycled water on irrigated crops.

For irrigation with recycled water, parameters of agronomic significance, are of concern depending on the characteristics of the systems where the plants grow. When the parameters vary outside a certain range determined by crop nature, soil, and agronomic practices, water may be unsuitable for agricultural use. Agricultural irrigation guidelines, which define this range of variation of irrigation water quality, have been developed to help farmers, operators, and decision makers. If recycled water quality does not match these guideline values, growers can either select more tolerant crops, manage soil characteristics, or change agronomic practices.

Some parameters are chosen and used for regulatory purposes and to monitor the treatment efficiency of a process or before reuse, depending on the type of reuse or regional specificities. For agricultural reuse, water salinity is of great concern.

7.2 Salinity

Compared to many other irrigation waters, recycled water generally has a low to medium salinity with electrical conductivity of 0.6 to 1.7 dS/m. Some dissolved mineral salts are identified as nutrients and are beneficial for plant growth, while others may be phytotoxic or may become so at high concentrations.

The major salinity sources in recycled water are drinking water (especially hardness and naturally occurring salts), salts added by urban or industrial water use, infiltration of brackish water into sewers, and agricultural irrigation (impact on groundwater salinity). As a rule, residential use of water typically adds about 300_100 mg/L of dissolved salts. Consequently, if the drinking water used by a given municipality is of acceptable quality for irrigation, the treated municipal water will also be of acceptable quality. The main exceptions would be the coastal areas, where infiltration of saline water in sewers is a concern, or where industrial wastes with unacceptable contaminants are discharged into urban sewers (e.g., brines).

Salinity in the soil is related to, and often determined by, the salinity of irrigation water. The rate at which salts accumulate to undesirable levels in soils depends on the following factors:
• Their concentration in the irrigation water.
• The amount of water applied annually.
• Annual precipitation.
• Evapotranspiration.
• Soil characteristics, both physical and chemical.

Dissolved salts increase the osmotic pressure of soil water and consequently lead to an increase in the energy plants must expend to take up water from the soil. As a result, respiration is increased, and the growth and yield of most plants decline progressively as osmotic pressure increases.

Water salinity can be reported either as total dissolved solids (TDS, mg/L) or as electrical conductivity (ECw), measured in mmhos/cm or most correctly in dS/m. The relationship between ECw and TDS is approximately:

$$\boxed{\textbf{ECw (dS/m) = 640 X TDS (mg/L)}}$$

The symbol ECe is used to designate the electrical conductivity of the soil saturation extract.

Recently, the classification of saline water has been reconsidered Table (15) on the basis of research and practical observations.

This classification must be used only as a guideline to determine the level of salinity of irrigation waters. It is important to stress that Table (15) cannot be used to assess the suitability of saline water for irrigation, because a number of other conditions must be taken into account, including crop, climate, soil, irrigation method, and management practices.

Generally, non-saline water is characterized by TDS < 500 mg/L and ECw < 0.7 dS/m, maximum salt content in slightly saline waters is TDS < 2000 mg/L and ECw < 3dS/m, and water is considered as brine when TDS > 30,000 mg/L and ECw > 42 dS/m.

As a rule, recycled urban water salinity is below 2 dS/m, with some exceptions in dry countries and coastal areas.

Table 15: Classification of Irrigation Water According to Salinity

Salinity class	Range of variation	
	Electrical conductivity, EC_W (dS/m)	Total dissolved solids, TDS (mg/L)
Non-saline water	<0.7	<500
Saline water	0.7-42	500-30000
Slightly saline water	0.7-3.0	500-2000
Medium saline water	3-6	2000-4000
Highly saline water	6-14	4000-9000
Very highly saline water	14-42	9000-30000
Brine	>42	>30000

Source: FAO, The use of saline waters for crop production, Irrigation and Drainage Paper no.48, 1992

7.2.1 Code of practices to overcome salinity hazards

The most important factor for crop selection is the salinity of the irrigation water. In general, TDS of > 4000 mg/L or conductivity of > 6 dS/m represent a significant quality problem for irrigation. In some cases, high chloride concentrations are the controlling parameter affecting reuse potential for irrigation. Good salinity management practices can allow irrigation with total dissolved solids up to 7000 mg/L. In some cases, application of saline water for irrigation of agricultural crops (conductivity range 2–7 dS/m) leads to improvement of fruit quality due to higher sugar content. The rate of salt accumulation in the soil depends upon the quantity of salt applied with the irrigation water and will increase as water is removed from the soil by evaporation and transpiration. The adverse effects of salinity are usually associated with an increase in soil salinity and the osmotic pressure in the soil solutions, and thereby with adverse effects on both crop and soil. Plants will use more and more energy to extract water from a saline soil solution and therefore put less into their growth. It is, therefore, important to prevent harmful concentrations of salts in the root zone of irrigated crops or at least to maintain a portion of the root below salinity levels that a given crop can tolerate.

The main management practices for the safe use of saline recycled water for irrigation are as follows:

• Source control.
• Selection of crops or crop varieties that will produce satisfactory yields under the existing or predicted conditions of salinity or sodicity.
• Special planting procedures that minimize or compensate for salt accumulation in the vicinity of the seeds.
• Irrigation to maintain a relatively high level of soil moisture and to achieve periodic soil leaching.
• Land preparation to increase the uniformity of water distribution and infiltration, leaching, drainage, and removal of salinity.

• Special treatments such as tillage and addition of chemical amendments, organic matter, and growing green manure crops to maintain soil permeability and tilth.

The crop grown, quality of irrigation water, rainfall pattern, climate, and soil properties determine to a large degree the kind and extent of management practices needed.

7.2.1.1 Source Control

Source control is the first and the most affordable measure for water reuse managers to address salinity issues. It is important to protect urban wastewater for beneficial reuse by treating or diverting poorer quality industrial and commercial brine waste streams in separate sewers or ocean outfalls (brine-disposal measures). It is important to underline that, as a rule, no limits on TDS concentrations exist for discharge of industrial wastewater in urban sewers. Other measures for source control include the rehabilitation and repair of leaky sewers infiltrated by brackish water. Some restrictions can be made on the use of certain types of residential softeners and other products for domestic use that are major sources of salts in wastewater. Such salinity control measures offer significant economic and public benefits not only for crop production and increased life of plumbing and irrigation systems, but also for all urban and industrial users.

7.2.1.2 Crop Selection

Not all plants respond to salinity in a similar manner; some crops can produce acceptable yields at much higher soil salinity than others. This is because some crops are better able to make the needed osmotic adjustments, enabling them to extract more water from a saline soil. Plants capable of good growth in saline environments and of extracting salts from the natural environment should also be considered in these cases. The ability of a crop to adjust to salinity is extremely useful. In areas where a build-up of soil salinity cannot be controlled at an acceptable concentration for the crop being grown, an alternative crop can be selected that is both more tolerant to the expected soil salinity and able to produce economic yields. The relative salt tolerance of most agricultural crops is known well enough to provide general salt tolerance guidelines. For specific crops, local tests can also be carried out to study their salt tolerance.

Crops can be divided into four groups depending on their salt tolerance at the root zone:

1. Sensitive crops can be used when the water is suitable for irrigation of most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices, except in soils of extremely low permeability.
2. Moderately sensitive crops can be used if a moderate amount of leaching

occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

3. Moderately tolerant crops should be selected when the water cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required.

4. Tolerant crops should be selected when the water is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. In this case, the soil must be permeable, drained adequately, and irrigation water applied in excess to provide considerable leaching.

Guidelines for the use of recycled water with varying salinity for irrigation of these four groups of crops are provided in Table (16) Table (17) summarizes the most relevant management practices for crop selection to avoid salinity hazards.

Table 16: Guidelines for the Classification and Use of Brackish Water for Irrigation

Class		Non saline	Slightly saline	Medium saline	Highly saline	Very highly saline
crop	TDS (mg/l)	<500	500-2000	2000-4000	4000-5000	>9000-30000
	ECw (dS/m)	<0.7	07-3.0	3.0-6.0	6.0-14.0	>14.0-42
I	Sensitive crops	No limitation on use No yield reduction	Slight to medium restriction on use Up to 50% yield reduction possible	For restricted use only More than 50% yield reduction possible	Not recommended for use with this class of crops	Not recommended for use
II	Moderately sensitive crops	No limitation on use No yield reduction	Slight restriction on use Up to 20% yield reduction possible	Medium restriction on use Up to 50% yield reduction	For restricted use only More than 50% yield reduction possible	Not recommended for use
III	Moderately Tolerant	No limitation on use No yield reduction	No limitation on use No yield reduction	Slight to medium restriction on use Up to 20–40% yield reduction possible	Medium restriction on use 40–50% yield reduction possible	For restricted use only More than 50% yield reduction possible
IV	Tolerant Crops	No limitation on use No yield reduction	No limitation on use No yield reduction	No serious limitation on use Practically no yield	Slight to medium restriction on use 20–40% yield reduction possible	For restricted use only More than 50% yield reduction possible; suitable for halophytes

Table 17: Recommendations for Crop Selection to Overcome Salinity Hazards

Salinity ECW (TDS)	Recommendations
<0.7 dS/m (TDS < 450 mg/L)	Full yield potential should be achievable with nearly all crops.
0.7–3.0 dS/m (TDS 450–2000 mg/L)	With good management, most fruits and vegetables can be produced. Full yield potential is still possible, but care must be taken to **achieve the required leaching fraction** in order to maintain soil salinity within the tolerance of the crops.
3.0 dS/m (TDS > 2000mg/L)	The water might still be usable, but its use may **need to be restricted to more permeable soils** and **more salt-tolerant crops**, where high leaching fractions are more easily achieved. This is being practiced on a large scale in the Arabian Gulf states, where drip irrigation systems are widely used. 1. If crops are salt-sensitive, solutions are: ***Increase leaching*** to satisfy a leaching requirement greater than 0.25–0.30 (negative points: excessive amount of water is required). ***Select irrigation system*** with uniform application, high efficiency, and frequency of irrigation (drip irrigation and mini sprinklers). ***Scheduling of irrigation*** more frequent irrigation with micro irrigation systems enable to maintain lower levels of salinity in the plant vicinity. ***Drainage*** allows for the leaching of excess salts (in combination with irrigation scheduling). ***Soil conditioners*** are not recommended because the high price and low efficiency in certain periods and conditions. In such a case, consider changing to a more tolerant crop that will require less leaching to control salts within crop tolerance levels. 2. Selection of salt tolerant crops with the ability to absorb high amounts of salts

Source: FAO, User's Manual for Irrigation with Treated Wastewater, 2003

The yield potential of some crops depending on water and soil salinity. Table will be distributed to the participants during the lecture which summarize the yield potential reduction of crops. The salt tolerance data in this table are used for conventionally irrigated crops. However, drip irrigation can maintain a high level of humidity in the root zone and a salinity level almost similar to that of the irrigation water.

Salt tolerance also depends on the type, method, and frequency of irrigation. The prevalent salt tolerance data apply most directly to crops irrigated by surface methods and conventional irrigation management. Salt concentrations may differ several fold within irrigated soil profiles, and they change constantly. At the same time, the plant is most responsive to salinity in the root zone, where water uptake occurs. For this reason, salt concentration should be measured in the root zone. The best performance of irrigation with

highly saline water has been reported for drip irrigation.
Sprinkler-irrigated crops are potentially subject to additional damage caused by foliar salt uptake and desiccation (burn) from spray contact with the foliage. Susceptibility of plants to foliar salt injury depends on leaf characteristics affecting the rate of absorption and is not generally correlated with tolerance to soil salinity. The degree of spray injury varies with weather conditions, being especially high when the weather is hot and dry. Night sprinkling has been proved to be advantageous in a number of cases. The information concerning the susceptibility of crops to foliar injury from saline sprinkling water is limited and indicates the most sensitive crops to be fruits and nuts, such as almond, apricot, citrus, and plum.

7.2.2 Code of management practices of water application

Water and soil management play an important role in the successful use of recycled water for irrigation.

7.2.2.1 Leaching and Drainage

Appropriate water-management practices must be followed to prevent salinization. If accumulated salts are not flushed out of the root zone by leaching and removed from the soil by effective drainage, salinity problems can build up rapidly. Consequently, leaching and drainage are two important water-management practices to avoid salinization of soils.

7.2.2.1.1 Leaching

Under irrigated agriculture, a certain amount of excess irrigation water is required to percolate through the root zone to remove the salts that have accumulated as a result of irrigation and evapotranspiration. This process of displacing the salts from the root zone is called leaching, and that portion of the irrigation water that mobilizes the excess of salts is called the leaching fraction. Salinity control by effective leaching of the root zone becomes more important as irrigation water becomes more saline.
The leaching fraction (LF) is equal to the depth of water that passes down below the root zone divided by the depth of water applied at the surface of the soil. To estimate the leaching requirement (LR), both the irrigation water salinity (ECw) and the crop tolerance to soil salinity (ECe) must be known and used in the following equation:

$$LR = \frac{ECw}{5(ECe) - ECw}$$

Where:
LR = the minimum leaching requirement needed to control salts within the tolerance ECe of the crop with ordinary surface methods of irrigation
ECw = the salinity of the applied irrigation water, dS/m

ECe = the average soil salinity tolerated by the crop as measured in a soil saturation extract (it is recommended to use in this calculation an ECe value that can be expected to result in at least 90% or greater crop yield).

The total annual depth of water that needs to be applied to meet both the crop demand and leaching requirement can be estimated from Equation:

$$AW = \frac{ET}{1 - LR}$$

Where:
AW = the depth of applied water, mm/year
ET = the total annual crop water demand, mm/year
LR = the leaching requirement expressed as a fraction (LF mentioned above).

Depending on the salinity status, leaching can be carried out at each irrigation, every other irrigation, or less frequently. With good-quality recycled water the irrigation application level will almost always apply sufficient extra water to accomplish leaching. With high-salinity irrigation water, meeting the leaching requirement is difficult and requires large amounts of water.

Soil leaching is needed for almost all crops when electrical conductivities of saturation extracts exceed 10 dS/m and for moderately tolerant crops for values over 3 dS/m. The salinity of the upper 0.6m of soil is of greatest concern. In general, application of 10–20 cm of water before planting coupled with a similar irrigation immediately following planting is often sufficient. Leaching by such pre-irrigation can be achieved by flood, sprinkler, or trickle irrigation. Salinity level higher than 10 dS/m may require more leaching.

Rainfall must be considered in estimating the leaching requirement and in choosing the leaching method. In years with average or high rainfall, sufficient leaching may take place as a result of rainfall events. However, this is unlikely to happen in years with less than average rainfall. Rainfall seasonal distribution is also to be considered.

Furthermore, in dry years, the effluent may become more saline as a result of changed water use habits by contributors to the waste stream, greater concentration in storage ponds due to less dilution by rainfall, and greater water loss by evaporation. In order to ensure sufficient leaching, the soil must be sufficiently permeable. This is an essential selection criterion for a successful irrigation with most types of recycled water.

If irrigation with recycled water is managed in such a way that salt does not accumulate in the root zone, then a question needs to be asked: What is the ultimate fate of the added salt? This will depend largely on the underlying stratigraphy and groundwater conditions. If the underlying material is sufficiently porous, more salt could be stored between the root zone and the water table. Nevertheless, this storage directly below the irrigation site is limited and not a long-term solution. Once it is filled, salt will reach the water table, lateral movement is probable, and the salt will move off-site.

7.2.2.1.2 Drainage

Drainage is defined as the removal of excess water from the soil surface (surface drainage) and below the surface (subsurface drainage) so as to permit optimum growth of plants. The importance of drainage for successful irrigated agriculture has been well demonstrated. It is particularly important in semiarid and arid areas to prevent secondary salinization. In these areas, the water table will rise with irrigation when the natural internal drainage of the soil is not adequate. When the water table is within a few meters of the soil surface, capillary rise of saline groundwater will transport salts to the soil surface. At the surface, water evaporates, leaving the salts behind. If this process is not under control, salt accumulation will continue, resulting in salinization of the soil. In such cases, subsurface drainage can control the rise of the water table and, hence, prevent salinization.

Salinity problems in many irrigation projects in arid and semi-arid areas are associated with the presence of a shallow water table. In this context, the role of drainage is to lower the water table to a desirable level, at which it does not contribute to the transport of salts to the root zone and the soil surface by capillarity phenomena.

The important elements of the total drainage system are as follows:
- Ability to maintain a downward movement of water and salt through soils.
- Capacity to transport the desired amount of drained water out of the irrigation scheme.
- Facility to dispose of drained water safely.

Such disposal can pose a serious problem, particularly when the source of irrigation water is treated wastewater, depending on the composition of the drainage effluent.

References

• Adaptation to climate change project in Northern Jordan Valley: Component C3, Introduction of reclaimed wastewater to farms in Northern Jordan Valley. Reports submitted to KfW 2016-2019.

• Ali, A., Khan, S., Khan, K.A. (2012). Performance evaluation of a UASB using dairy wastes. ASEAN Journal on Sciences and Technology for Development, 29 (1): 1

• Ardakanian, R., Sewilam H., Liebe J. (2012). Mid-Term-Proceedings on Capacity development for the safe use of wastewater in agriculture. A Collaboration of UN-Water Members & Partners FAO, WHO, UNEP, UNU-INWEH, UNW-DPC, ICID and IWMI. Editors: Proceedings Series No. 8 Published by UNW DPC, Bonn, Germany.

• Asano, T., F.L. Burton, and G. Tchobanoglous (2006) Water reuse: Issues, technologies and applications, Metcalf & Eddy, Inc., McGraw-Hill Book Co., New York, NY.

• Crites, R., and Tchobanoglous, G. (1998). Small and decentralized wastewater management systems. Boston: WCB/McGraw-Hill.

• Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A (eds.) (2010) Wastewater irrigation and health: assessing and mitigation risks in low-income countries. Earthscan-IDRC-IWMI, UK.

• Food and Agriculture Organization (FAO) (1992) The use of saline waters for crop production (FAO Irrigation and Drainage Papers No. 48,).

• Food and Agriculture Organization (FAO) (2002) Crop Evapotranspiration Guidelines for Computing Crop Water Requirements: Guidelines for Computing Crop Water Requirements (FAO Irrigation and Drainage Paper No.56,).

• Fracz, P. (2016). Nonlinear modeling of activated sludge process using the Hammerstein-Wiener structure. E3S Web of conferences 10, 00119. DOI: 10.1051/e3sconf/20161000119

• Guidelines on sanitation and health. ISBN 978-92-4-151470-5. World Health Organization, 2018.

• Halalsheh, M., Sawajneh, Z., Zu'bi, M., Zeeman, G., Lier, J., Fayyad, M. (2005). Treatment of strong domestic sewage in 96 m3 UASB reactor operated at ambient temperatures: a two-stage versus single-stage reactor. Bioresource Technology, 96, 577-585

• Krishna, G.V.T.G., Kumar, P., Kumar, P. (2009). Treatment of low-strength soluble wastewater using an anaerobic baffled reactor (ABR). Journal of Environmental Management, 90, 166-176.

• Lazarova V., and Bahri A. (2004). Water reuse for irrigation: agriculture, landscapes, and turf grass. CRC Press, ISBN 1-56670-649-1.

• Maas, E. V. (1986). "Salt tolerance of plants." Appl. Agric. Res., 1, 12–36.
• Mara, D. (2003). Domestic wastewater treatment in developing countries. Earthscan, London, UK

• Martin, C.A. (2013). Effect of design and operational factors on the removal efficiency of emerging organic contaminants in constructed wetlands for wastewater treatment. PhD thesis, Department of hydraulics, Maritime and Environmental Engineering (DEHMA), UPC. https://www.researchgate.net/publication/270758256_Effect_of_design_and_operational_factors_on_the_removal_efficiency_of_emerging_organic_contaminants_in_constructed_wetlands_for_wastewater_treatment/figures?lo=1

• Metcalf and Eddy (2003). Wastewater engineering: treatment and reuse, Fourth Edition. Revised by George Tchobanoglous, Franklin L. Burton and H. David Stensel. McGraw-Hill Higher Education.

• Metcalf and Eddy (2014). Wastewater engineering: Treatment and Resource Recovery. 5th Edition, McGraw-Hill, New York

• Satalin, M. (2014). Performance of rotating biological contactors in wastewater treatment- A review.https://www.semanticscholar.org/paper/Performance-of-Rotating-Biological-Contactor-in---A-Stalin/3efba61cd7c82459dbc0458c1a1092c60f9a7f3b

• Seder N., and Abdel-Jabbar S. (2011). Safe use of treated wastewater in agriculture: Jordan case study prepared by ACWUA.

• Seghezzo, L. (2004). Anaerobic treatment of domestic wastewater in subtropical regions. PhD thesis, Wageningen University and Research Center. ISBN: 90-8504-029-9

• Stuckey D.C. (2010). Anaerobic baffled reactor (ABR) for wastewater treatment. In: Environmental Anaerobic Technology: Applications and new developments. Ed. H. Fang

• Tchobanoglous, G., Burton, F., Stensel, H.D. (2002). Wastewater engineering: treatment and reuse/ Edition 4. By Metcalf and Eddy, Inc.

• Tilley, E., Ulrich, L., Luethi, C., Reymond, P., Zubruegg, C. (2014). Compendium of sanitation systems and technologies. 2nd revised edition. Duebendorf, Switzerland: Eawag

• United Nations Educational, Scientific and Cultural Organization (UNESCO) (2000), Water Use in the World: Present Situation / Future Needs [online] Available from http://www.unesco.org

• User's manual for irrigation with treated wastewater (2003). FAO Regional Office for the Near East, Cairo.

• World Health Organization (WHO) (2001) Water quality: Guidelines, standards and health assessment of risk and risk management for water-related infectious diseases [online]

• World Health Organization (WHO) (2006), Guidelines for the safe use of wastewater, excreta and grey water, volume 2: Wastewater use in agriculture, Geneva, Switzerland.

• Zacharia, A., Ahmada, W., Outwater, A.H., Ngasala, B., Van Deun, R. (2019). Evaluation of occurrence, concentration, and removal of pathogenic parasites and Fecal Coliforms in three waste stabilization pond systems in Tanzania. The Scientific world Journal. https://doi.org/10.1155/2019/3415617

ReWater MENA

ReWater MENA

MORE AND SAFER WATER REUSE IN THE MIDDLE EAST AND NORTH AFRICA

REWATER MENA

PLATFORM

WWW.ELEARNING-REWATERMENA.ORG

DEVELOPED BY

IWMI International Water Management Institute | CGIAR | Research Program on Water, Land and Ecosystems

الجمعيــة العربيــة لمرافــق الميــاه
Arab Countries Water Utilities Association ACWUA

Sweden Sverige