Use of Treated Wastewater in Irrigated Agriculture

A Design Framework

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CORETECH

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Irrigation and Water Engineering Group
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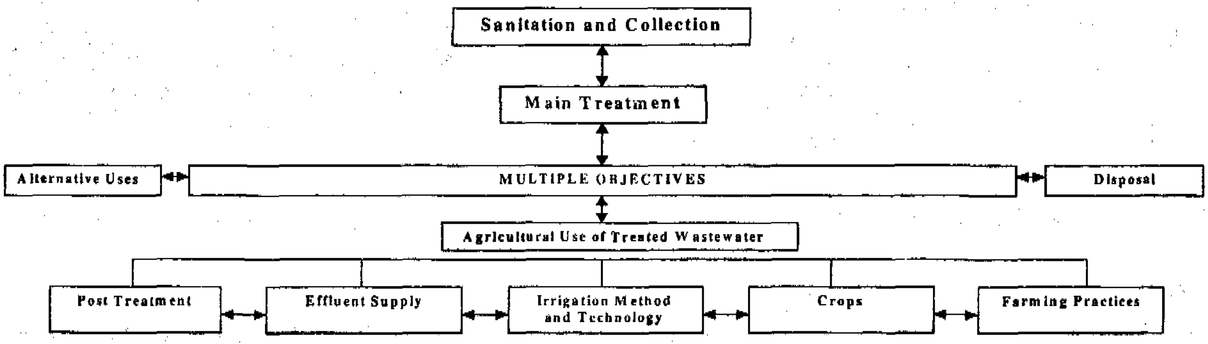
Figure 4 Design Framework for Agricultural Use of Treated Wastewater (Martijn and Huibers 2001)



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foreword

This Working Document is a contribution to the CORETECH project: Development of cost-effective reclamation technologies for domestic wastewater and the appropriate agricultural use of the treated effluent under (semi-)arid climate conditions. It is the result of a desk-study and literature review under the Work Package nr 4: Development of water distribution methods, irrigation techniques in relation to crop choice and water quality.

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The partners in this research project are:

- Wageningen University, the Netherlands (WAU)
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- Irrigation and Water Engineering (IWE)
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- National Research Centre, Egypt (NRC)
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- National Foundation for Agricultural Research, Greece (NFAR)
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1 Introduction

The beneficial use of reclaimed wastewater in irrigated agriculture is a competing alternative to other forms of treatment, reclamation and disposal. Moreover, within an agricultural system itself there are many competing alternatives for managing the use of reclaimed wastewater. Evaluation and comparison of alternatives is typically based on economic analyses but should also include analyses of environmental, human and animal health impacts and other non-economical considerations. There is an abundance of information on the use of treated wastewater in irrigated agriculture, sometimes presented in the form of checklists for planning considerations. However, available information is often too specific, sometimes controversial and altogether does not provide a functional means of dealing with the many issues in relation to each other. These relationships need to be understood well in advance for the sake of efficient integrated planning. A most optimal balanced design will be different for each case and depends on the objectives and capacities of various stakeholders in a decision making process. Chapter 2 presents the need for multiple-objective and multiple-purpose planning within three main planning phases for wastewater reclamation and reuse. Chapter 3 presents an effort to identify and structure main technical issues that are involved in a decision making process specifically for agricultural use of treated wastewater:

- post-treatment
- supply system
- irrigation method and technology
- crops
- farming practices

Up-stream issues may also play an important role, such as type of sanitation system (e.g. black-grey water separation), primary treatment, effluent disposal options and alternative effluent use options. All issues are shown to relate to (treated) wastewater characteristics that most directly or implicitly affect the design and management of agricultural systems using wastewater (Martijn and Huibers 2001): biodegradable organic matter and suspended solids, inorganic soluble salts, plant nutrients, trace elements, pathogens, disinfectant by-products and the effluent flow-rate. A design framework is proposed to provide a workable tool for iterative planning and design. The proposed framework is considered as a *primary decision making tool* because it displays interactions between decision making items and can therefore facilitate interactions between participants in the decision making process. Once these relationships are understood, then *secondary decision making tools* can be employed which actually serve to facilitate decision making on these related items. Such secondary tools may consist of structured background information with options and limitations, or, more sophisticated, computer models that integrate various items. An important function of the proposed framework is to identify current gaps in knowledge and insights and to identify which kind of secondary decision making tools could be employed to facilitate a decision making process. The focus in this document has been on technical issues. However, a structured presentation of the technological possibilities, impossibilities and unknowns, does in itself not intend to provide overall best solutions. Ultimately the design framework and structured background information serve to facilitate an iterative design and planning process. Real case scenarios can then integrate social, political, economical, cultural, gender, and various other issues into the decision making according to their criteria. Secondary decision making tools should therefore also be sought for introducing and facilitating non-technical decision making into the decision making process.

2 Planning of Wastewater Reclamation and Reuse

2.1 Objectives

The basis for effective planning of wastewater reclamation and reuse consists of two critical components: project objectives and project study area (after Asano and Mills 1990, in Metcalf and Eddy 1995). There is a wide range of possible project objectives, the definition of which is related to the perspectives of various actors involved in the planning process. The most prominent objectives can be summarised as to provide (Mills and Asano 1998):

1) An incidental secondary benefit to the disposal of wastewater, primarily crop production by irrigation with effluent
2) A water supply to displace the need for other sources of water
3) A cost-effective means of environmentally sound treatment and disposal of wastewater
4) A water supply to generate regional economic development
5) A water supply for environmental enhancement

Mills and Asano (1998) shortly review these objectives, and, reflecting on the experience and primary motivations in the USA, place an emphasis on the second and third objectives mentioned above. That is, water reuse planned as a water supply to offset alternative water development and as a cost-effective means of municipal wastewater pollution control. Metcalf and Eddy (1995) conclude with a simple two-fold definition, stating that wastewater reclamation and reuse basically serves the objectives of:

1) water pollution control, and,
2) *various* forms of water supply

More specific objectives are sometimes forwarded as seemingly most important yet need consideration on the context in which they are formulated. For example;

- "The goal in designing a wastewater reclamation and reuse system is to develop an integrated cost-effective treatment scheme that is capable of reliably meeting water quality objectives" (Asano and Levine 1998).

- "The goal of each water reuse project is to protect public health without unnecessarily discouraging wastewater reclamation and reuse" (Asano and Levine 1998).

The context of the first example is an overview of wastewater treatment technology, whereas the context of the latter example is a discussion on health and regulatory requirements. The *singular* emphasis of both goals is understandable when reviewed in the comprising context but can lead to conflicting interests in real cases in which a myriad of goals and sub-goals may need to be integrated. This brings forward two issues that will be discussed hereafter:

1) the definition of reuse and objectives
2) the need for multiple objective planning

Definition of reuse and objectives

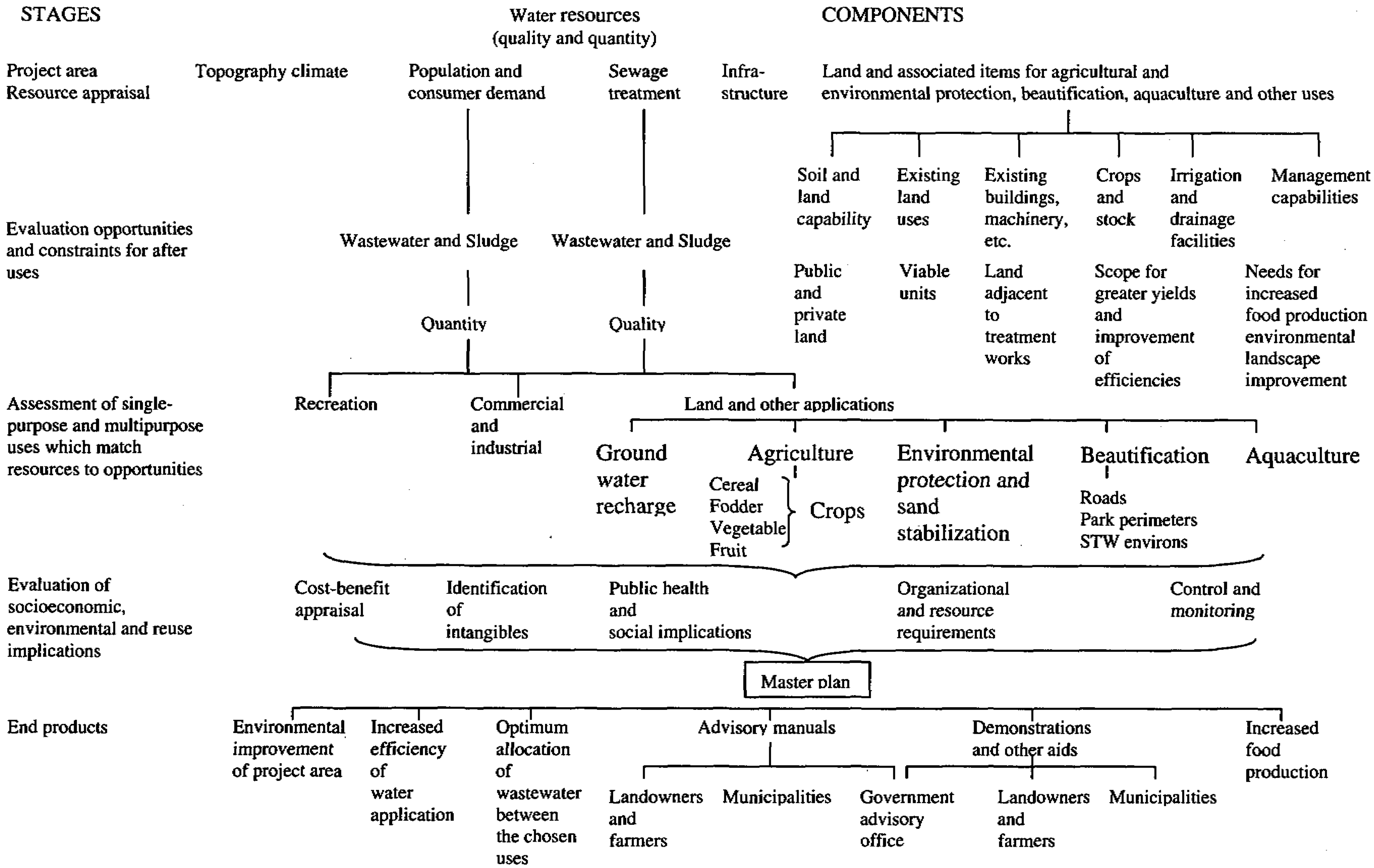
Mills and Asano (1998) state that wastewater reuse is not an objective but it is a means to an objective. In this perspective, wastewater reclamation and reuse is considered as an alternative treatment and disposal system to be judged according to a cost-effectiveness[1] analysis with considerations on both pollution control and water supply benefits. However, it is not clearly specified what are considered the alternative treatment and disposal systems. The definition of wastewater reclamation and reuse is decisive in this matter. *Wastewater reclamation* involves the treatment or processing of wastewater to make it reusable, and *wastewater reuse* or *water reuse* is the beneficial use of the treated water (Asano and Levine 1998). Thus, the question is whether a system leads to the beneficial use of treated wastewater, or, whether the treated wastewater is merely disposed off in a system without beneficial use. In the first case, the term treatment becomes reclamation and the system can be conceived as a reuse system. In the second case, the term treatment remains and the system is merely a disposal system. Here lies a source of complications because there are in fact variable definitions of what is to be considered as 'beneficial' use of treated wastewater. Unless wastewater is discharged into an affluent body of water like the sea, any other form of disposal may potentially lead to direct or indirect, planned or unplanned, use of the discharged effluent. For example, fast-rate land-application of wastewater may serve primarily to dispose off wastewater, with the soil and plants acting as a living bio-filter, with subsequent groundwater or aquifer recharge. A form of pre-treatment is perhaps required to prevent groundwater or aquifer pollution, especially when the considered groundwater or aquifer is used for drinking water or irrigation. Such disposal of effluent in effect leads to an indirect yet beneficial use, and thus "reuse", of (waste)water. Cobham and Johnson (1988) consider land and other applications, including groundwater recharge, in general as part of what on the whole can be considered as a "water reuse system". This is demonstrated in Figure 1. In any case, there can be competing forms of wastewater treatment, reclamation, disposal, and, reuse, none of which are necessarily an objective, but rather can be evaluated most optimally in a multiple-objective approach integrating not only cost-effectiveness, but also social, political, environmental and other non-economical considerations.

[1] This is defined as an analysis to determine which alternative system will result in the minimum total resources costs over time to meet project objectives. Non-monetary factors (e.g. social and environmental) are accounted for descriptively in the analysis to determine their significance and impacts (Mills and Asano 1998). At present, monetary factors tend to be the overriding concern in determining whether to implement a wastewater reuse project and how to go about it, even though technical, environmental, and social factors are important in project planning. In the future, however, environmental considerations and public policy issues may be of greater importance than mere cost-effectiveness as a measure of the feasibility of a wastewater reuse project (Metcalf and Eddy 1995).

Multiple Objective Planning

Multiple-objective planning basically means that the objectives of both the wastewater treatment agency and the potential water supply or user agencies are considered in one integrated approach. Only in the last decade has increased attention been given to the water supply benefits. Because most water and wastewater agencies are established for a single-purpose function, planning by these agencies tends to be single-purpose as well. Optimum wastewater reclamation and reuse is however better achieved in a framework of multiple-purpose planning and with co-operative efforts of both wastewater management and water supply or user agencies. Once the multiple benefits and beneficiaries of wastewater reuse are recognised, additional options may be available for sharing project responsibilities and costs among project sponsors (after Asano and Mills 1990, in Metcalf and Eddy 1995). Multiple-objective planning can also involve multiple-use planning. Adopting a mix of effluent use strategies is normally advantageous in respect of allowing greater flexibility, increased financial security and more efficient use of wastewater throughout the year, whereas a single-use strategy will give rise to seasonal surpluses of effluent for unproductive disposal (Cobham and Johnson 1988;in FAO 1992). Figure 1 is presented to illustrate that agricultural use of treated wastewater is a form of land application competing with other forms of land and other applications (e.g. aquaculture), recreational use, and, commercial and industrial use. Besides, agriculture has many use-alternatives considering the different types of crops that can be irrigated with treated wastewater.

Figure 1 Main components of general planning guidelines for wastewater reuse (Cobham and Johnson 1988)



2.2 Project Area

The project area is the second critical component, besides project objectives, that forms the basis of planning (after Metcalf and Eddy 1995). This includes the area from which the wastewater treatment facilities receive their inflow and the area that can potentially be served by reclaimed wastewater. It is however essential to also look beyond the project area and beyond the jurisdictional boundaries of the project sponsor because water movement and water supply are typically dependent on the regional water resources situation. Referring to Asano and Levine (1998) the important project area considerations include:

- the regional water resources situation (both surface and subsurface water)
- the potential reclaimed water applications appropriate for the project area
- the water use patterns per application category
- consultancy from health and water pollution control regulatory authorities
- disposal and storage options to increase project flexibility

A key task in planning a water reclamation project is to find potential users of reclaimed water. A reclaimed water market assessment is thus vital to the success of a reclamation and reuse project (Mills and Asano 1998). This relates in part to the above mentioned project area considerations. It should be noted that potential reusers are not necessarily directly related to land through ownership in a projected reuse area since there can be various forms of land tenancy. For example in the case of Al-Samra, Amman, Jordan, part of the land surrounding the treatment plant is leased to reusers in combination with access rights to treated wastewater to be used for irrigation. The ideal objective in reuse site(s) selection is to find a suitable area where long-term application of treated effluent will be feasible without adverse environmental or public health impacts. Information should be gathered to assess certain issues such as the potential impact on any underlying usable aquifer or groundwater, the cost and location of the land, its present use and availability, soil conditions and many other non-technical issues (after FAO 1992). The design framework, to be presented in Chapter 3, and the reuse facilities plan outline (Table 1 in Chapter 2.3) can both serve as checklists for project area considerations.

2.3 Phases of Planning

Planning for wastewater reuse typically evolves through three phases:

phase 1) conceptual planning
phase 2) feasibility planning
phase 3) facilities planning

Conceptual level planning for wastewater reuse involves definition of the project objectives and project area, cost estimation, and the identification of a reclaimed water market. This preliminary planning provides insight into the viability of wastewater reuse and is a prelude to detailed planning (Asano and Levine 1998). At the feasibility phase of planning, a preliminary market assessment is performed, including direct consultation with potential reclaimed water users (Mills and Asano 1998). Existing water supply and wastewater facilities and long-term needs are assessed. Alternative facilities are screened, considering economics, technical constraints, environmental impacts, and other factors. If water reclamation continues to compare favourably to other alternatives for accomplishing the project objectives, then the most promising water reclamation alternative is refined and investigated further in the facilities planning phase, which represents the final stage of planning. During this phase a thorough cost-effectiveness analysis is conducted for all alternatives and the following seven feasibility criteria are investigated in more detail (after James and Lee 1971, in Mills and Asano 1998):

- Engineering feasibility
- Economic feasibility
- Financial feasibility
- Institutional feasibility
- Environmental impact
- Social impact and public acceptance
- Market feasibility

The results of the completed planning are documented in the so-called facilities planning report on wastewater reclamation and reuse. A detailed outline for a wastewater reclamation and reuse facilities plan is presented in Table 1 (after Asano and Mills; various years). This outline also serves as a checklist for considerations during conceptual and feasibility planning. All of the items listed in Table 1 have been found at one time or another to affect the evaluation of water reclamation and reuse projects. Thus, all of the factors shown do not necessarily need an in-depth analysis but they should at least be considered. Although the emphasis on the wastewater treatment or water supply aspects will vary depending on whether a project is single or multiple purpose, the nature of wastewater reclamation and reuse is such that both aspects must be considered (Metcalf and Eddy 1995). More background information concerning Table 1, such as market analysis, economic and financial analysis, cost and price of water, and, many other planning factors, can be found in Metcalf and Eddy (1995) and in Mills and Asano (1998).

3 A Design Framework

The beneficial use of reclaimed wastewater in irrigated agriculture is a competing alternative to other forms of treatment, reclamation and disposal, as shown in Figure 1 (Cobham and Johnson 1988). Evaluation and comparison of alternatives is based on various analyses performed during the three planning phases (Chapter 2.3), which can be guided by the considerations presented in Table 1 (after Asano and Mills; various years). What is lacking, however, is a framework that recognises the many competing alternatives that may exist within an agricultural system for managing the use of reclaimed wastewater. There is an abundance of information on the use of treated wastewater in irrigated agriculture, sometimes presented in the form of checklists for planning considerations. However, available information is often too specific, sometimes controversial and altogether does not provide a functional means of dealing with the many issues in relation to each other. These relationships need to be understood well in advance for the sake of efficient integrated planning both during conceptual and feasibility planning but moreover during the more detailed facilities planning phase. A most optimal balanced design will be different for each case and depends on the objectives and capacities of various stakeholders in a decision making process. This chapter presents an effort to structure main technical issues in such a way as to provide a workable frame for iterative planning and design of agricultural use of treated wastewater. Main decision making items are identified and discussed based on the effluent characteristics and implications as presented in CORETECH Working Document WP4-1 (Martijn and Huibers 2001) and compiled in Annex 1 of this document. A framework is then proposed for relating these items. The framework in itself can be considered as a *primary decision making tool* because it displays the relations between various decision making items, whereas *secondary decision making tools* may serve to facilitate the actual decision making.

Table 1 Wastewater Reclamation and Reuse Facilities Plan Outline

1. Study area characteristics: Geography, geology, climate, groundwater basins, surface waters, land use, population growth.
2. Water supply characteristics and facilities: Agency jurisdictions, sources and qualities of supply, description of major facilities and existing capacities, water-use trends, future facilities needs, groundwater management and problems, present and future freshwater costs, subsidies, and customer prices.
3. Wastewater characteristics and facilities: Agency jurisdictions, description of major facilities, quantity and quality of treated effluent, seasonal and hourly flow and quality variations, future facilities needs, need for source control of constituents affecting reuse, and description of existing reuse (users, quantities, contractual and pricing agreements).
4. Treatment requirements for discharge and reuse and other restrictions: health and water quality related requirements, user-specific water quality requirements, and use area controls.
5. Reclaimed water market assessment: Description of market analysis procedures, inventory of potential reclaimed water users, and results of user survey.
6. Project alternative analysis: planning and design assumptions; evaluation of the full array of alternatives to achieve the water supply, pollution control, or other project objectives; preliminary screening of alternatives based on feasibility criteria; selection of limited alternatives for more detailed review, including one or more reclamation alternatives and at least one base alternative that does not involve reclamation for comparison; for each alternative, presentation of capital and operation and maintenance costs, engineering feasibility, economic analysis, financial analysis, energy analysis, water quality effects, public and market acceptance, water rights effects, environmental and social effects, and comparison of alternatives and selection, including consideration of the following alternatives:

a. Water reclamation alternatives: levels of treatment, treatment processes, pipeline route alternatives, alternative markets based on different levels of treatment and service areas, storage alternatives
b. Freshwater or other water supply alternatives to reclaimed water
c. Water pollution control alternatives to water reclamation
d. No project alternative

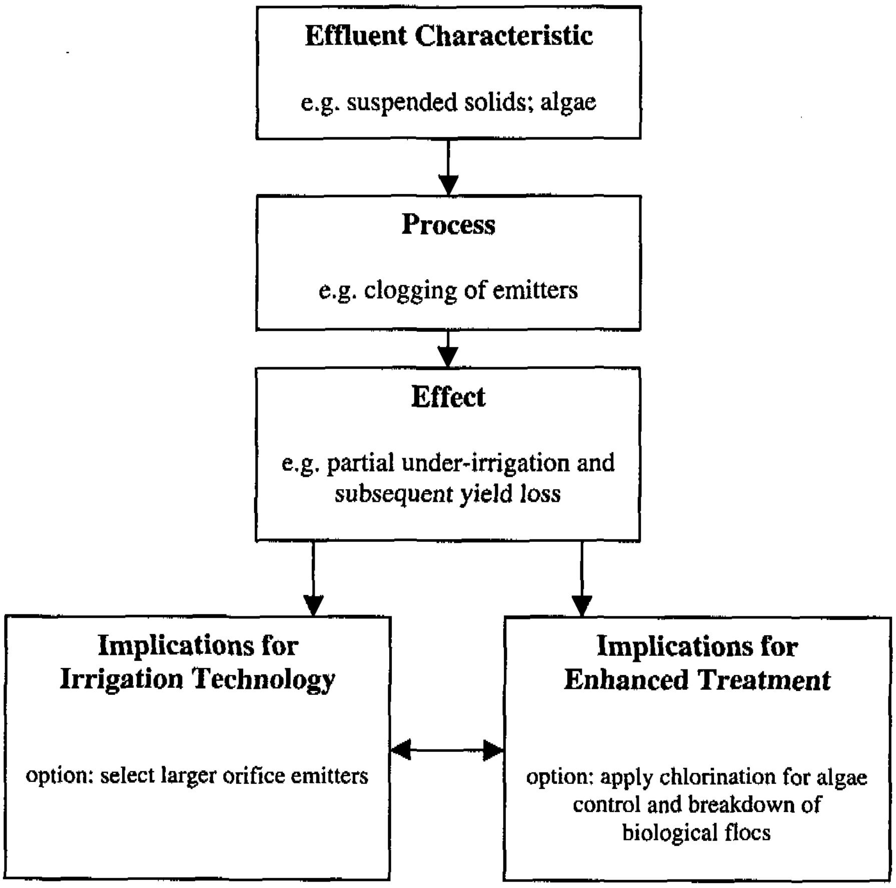
7. Recommended plan: Description of proposed facilities, preliminary design criteria, projected cost, list of potential users and commitments, quantity and variation of reclaimed water demand in relation to supply, reliability of supply and need for supplemental or back-up water supply, implementation plan, and operational plan.
8. Construction financing plan and revenue program: Sources and timing of funds for design and construction; pricing policy of reclaimed water; cost allocation between water supply benefits and pollution control purposes; projection of future reclaimed water use, freshwater prices, reclamation project costs, unit costs, unit prices, total revenue, subsidies; sunk costs and indebtedness; and analysis of sensitivity to changed conditions.

Source: after Asano and Mills (1990) in Metcalf and Eddy (1995)

3.1 Effluent Characteristics and Implications

The main effluent characteristics and the implications for use of treated wastewater in irrigated agriculture are presented in CORETECH REPORT WP4-1 (Martijn and Huibers, 2001). In general these effluent characteristics are related to some sort of process (e.g. salinisation or supply of mobile plant macro nutrients in the irrigated field) with an effect that can be enhanced, prevented, or, mitigated by the appropriate selection, design and operation of: post-treatment, effluent supply, irrigation method and technology, crops and farming practices. The 'implications' thus refer to appropriate decision making on items that constitute part of an agricultural reuse system. Annex 1 of this report provides a compact overview of effluent characteristics, related processes, effects and implications. Much like the Wastewater Reclamation and Reuse Facilities Plan Outline (Table 1 in Chapter 2.3), this outline can serve as a checklist for planning considerations at early stages of agricultural reuse planning where most of the issues shown do not deserve an in-depth analysis but at least some consideration. As an example, Figure 2 below shows a simple schematisation of how a single effluent characteristic can lead to implications for irrigation technology on the one hand and enhanced treatment on the other.

Figure 2 Schematised example of effluent characteristics and implications



The example used in Figure 2 immediately brings up three discussion points. First, there is some doubt as to whether some forms of enhanced treatment are to be considered as part of the treatment process, i.e. should be done at the treatment plant, or whether they are to be performed at the farm as part of the farming infrastructure and farming practice. In this sense the often used argument that low-cost secondary treatment suffices for use of effluent in irrigated agriculture does not always hold strong when tertiary treatment (e.g. chlorination) is required at farm level. The same argument may apply to the level of filtration required for removing other suspended solids, which once again can be performed at the treatment plant or in the field as part of the irrigation technology. This also brings forward the second item that there may be several options to deal with a potential effect derived from an effluent characteristic. In the example of emitter clogging, comparison and evaluation is required on the options of filtration, chlorination, and/or, selection of larger orifice emitters; measures which can be used in conjunction or can be considered as competing alternatives. Finally, and this may affect the decision making on earlier mentioned options, each measure will have its own implications for further planning issues. For example, irrigation methods using relatively large orifices are generally less efficient than those using smaller orifices. This affects the size of the irrigable area, possibly one of the first planning considerations, but also affects processes related to irrigation efficiency such as leaching of pollutants to groundwater. On the other hand chlorination, that enables the use of efficient localised irrigation systems, may lead to serious environmental and crop productivity hazards. Key questions that thus need to be resolved are for example: "how serious is the environmental impact from the use of chlorination?" or even better "what are the alternative options to prevent clogging hazards due to algae in localised irrigation systems?" Annex 1 of this document presents a compact overview of treated wastewater characteristics and implications that lead to the formulation of many such questions. An in-depth and integrated analysis, comparison and evaluation of all issues is perhaps not practically achievable or functional in planning. However, the structured information presented in Annex 1 may at least serve as a checklist during iterative planning when decisions are made on main items as discussed in the next chapter.

3.2 Decision Making Items

Decision making "items" is a somewhat arbitrarily chosen term to indicate components that constitute part of an agricultural system using treated wastewater. Implicit to the technical approach taken in this document, in this case items have been selected on the basis of having a clear technical identity. This doesn't mean that selected items are unaffected by non-technical decision making, on the contrary, but it does mean that the decision making process in this case is guided by technical requirements and options. The main decision making items concerning the use of treated wastewater in irrigated agriculture are based on an extensive literature review (Martijn and Huibers 2001) and summarised as follows:

- Post-Treatment
- Effluent Supply
- Irrigation Method and Technology
- Crops
- Farming Practices

The reuse location and the reusers (i.e. people irrigating with treated wastewater) are, in this approach, not considered as decision making issues. Notwithstanding that they deserve adequate attention at early stages of planning, the basic assumption is that the basis of planning has been established and thus a reuse location and reusers have already been identified. This is certainly a valid assumption for the facilities planning phase, when the reusers themselves are in fact, or should be, active participants in the decision making process. It should be noted however that the framework, to be presented in Chapter 3.3, may serve as tool during conceptual and feasibilities planning phases when reuse locations and reusers are still negotiable. The choices made on post-treatment, effluent supply, irrigation method and technology, crops and farming practices, must coincide with the objectives, constraints and capacities of the potential reusers and may be severely limited by inappropriate site selection (e.g. type of soils, or, distance from treatment facilities). Hence why the proposed framework may serve to identify and resolve bottlenecks and optimise at early stages of planning. Finally, it should be noted that up-stream (from the reuse location) issues should also be included as 'items' in the decision making for agricultural use of treated wastewater. For example, a sanitation system that separates black from grey domestic wastewater leaves the bulk of household produced wastewater free from pathogens, thereby eliminating one of the most restricting effluent characteristics. This could be an extremely motivating factor for (peri-)urban-agricultural use of treated wastewater producing fresh products for nearby markets. Decentralised Sanitation and Reuse (DESAR)(Van Lier and Lettinga 1999), the type of primary treatment, effluent disposal options and alternative effluent use options are however issues that deserve more attention than can be provided in this document.

3.2.1 Post-Treatment

Post-treatment is casually used to indicate enhanced treatment of effluent from primary and secondary treatment facilities. In this sense it can be viewed in most cases as secondary, tertiary, or, in some cases, as quaternary treatment. Such treatment can take place at a treatment plant, or, in-site at a specific reuse location (e.g. chlorination in storage ponds or during irrigation). In any case, post-treatment is aimed at attaining user-specific water quality requirements. Multiple-use planning (Chapter 2.1) may require the supply of different water qualities and thus different levels of post-treatment following the main (primary and secondary) treatment may be required. Post-treatment for agricultural use of treated wastewater is primarily concerned with the additional removal of nitrate, total nitrogen, phosphate, suspended solids, potential chemical precipitates (e.g. iron and manganese) and pathogenic micro-organisms, and, with the control of algae growth. Post-treatment methods may consist maturation ponds, constructed wetlands, duckweed ponds, algae ponds, sand filters, biorotors, oxidation ponds, ozonation ponds, and many other treatment methods. A fairly interesting issue is the use of so-called hybrid storage/treatment ponds. The effluent supply system (see Chapter 3.2.2) may require water storage on a seasonal and operational basis, which has the additional advantage that it allows for enhanced treatment of effluent during storage.

3.2.2 Effluent Supply

The supply of effluent, in terms of flow-rates, receives main attention during the reuse facilities planning and more specifically during design of the recommended plan. The recommended plan should include: description of proposed facilities, preliminary design criteria, projected cost, list of potential users and commitments, quantity and variation of reclaimed water demand in relation to supply, reliability of supply and need for supplemental or back-up water supply, implementation plan, and operational plan. The recommended plan follows after comparison and selection of alternatives (Table 1 in Chapter 2) has taken place. Thus, options, amongst others, for treated water storage and freshwater alternatives have already been considered, and, the potential users have been identified. The recommended plan is thus aimed at tailoring facilities with regard to effluent supply and effluent demand. Multiple-use planning may require different user specific water supply facilities. The flow-rate of effluent supply and demand may be variable and incompatible over time, and, this incompatibility may be resolved in various ways. Ideal options may include; seasonal and operational storage facilities on effluent demand basis, totally scheduled irrigation on effluent supply basis, and, alternative safe disposal of un-reusable and un-storable effluent. The supply of effluent from a treatment plant, or, from decentralised treatment facilities, to the various potential users may be a mix of the following options depicted in Figure 3.

Storage

Although not considered a step in the treatment process, a storage facility is, in most cases, a critical link between the wastewater treatment plant and the irrigation system (FAO 1992). To make full use of reclaimed wastewater, there is a need for effluent storage, on both an operational and seasonal basis (Feigin et al. 1991). Storage is needed for the following reasons:

- To equalise daily variations in flow from the treatment plant and to store excess when average wastewater flow exceeds irrigation demands; includes winter storage (FAO 1992) especially if no alternative way of disposal exists (Feigin et al. 1991)
- To meet peak irrigation demands in excess of the average wastewater flow (FAO 1992; Feigin et al. 1991)
- Minimisation of disruptions in irrigation during period when effluent is not delivered from the treatment plant, if no alternative water source is available (Feigin et al. 1991)
- A safeguard against the possibility of unsuitable effluent entering the irrigation system. Storage provides a possibility for additional treatment and dilution (Feigin et al. 1991)

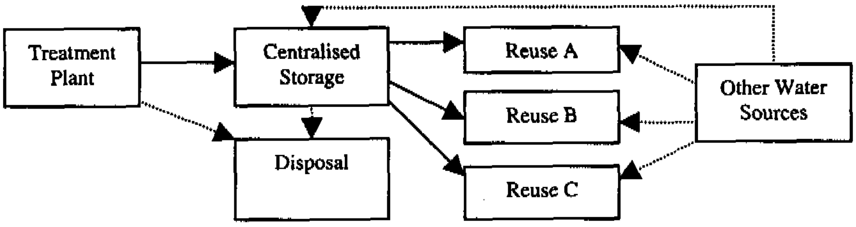
Options for storage of reclaimed water include constructed surface reservoirs or tanks, natural lakes and below ground storage systems. Seasonal impoundment in surface reservoirs is the more common way to store effluent specifically intended for agricultural use, whereas discharge or subsurface storage require careful considerations on subsequent alternative uses of the water sources in which the effluent is mixed. A subsurface storage system may consist of direct groundwater recharge and subsequent pumping, or percolation through the soil and dilution in an aquifer. Groundwater recharge is also achieved incidentally in land treatment and disposal systems where municipal and industrial wastewater is disposed of via percolation and infiltration (Metcalf and Eddy 1995). Artificial groundwater recharge is operated at experimental scale in infiltration-percolation basins and in the river bed in the Cap Bon area (Tunisia, ed.) and used for irrigation. According to the *state of the art* of soil-aquifer treatment (Bouwer 1991; Brissaud and Salgot 1994), improved operation of this facility would lead to a groundwater quality meeting unrestricted irrigation requirement (Rekaya and Brissaud 1991, in Bahri 1998). There are several advantages to storing water underground (Metcalf and Eddy 1995; Asano and Levine 1998):

1) The cost of artificial recharge may be less than the cost of equivalent surface reservoirs
2) The aquifer serves as an eventual distribution system and may eliminate the need for surface pipelines or canals
3) Water stored in surface reservoirs is subject to evaporation, to potential taste and odour problems caused by algae and other aquatic growth, and to pollution
4) Suitable sites for surface reservoirs may not be available or environmentally acceptable
5) The inclusion of groundwater recharge in a wastewater reuse project may also provide psychological and aesthetic secondary benefits as a result of the transition between reclaimed wastewater and groundwater

Figure 3 Effluent supply options with different storage concepts

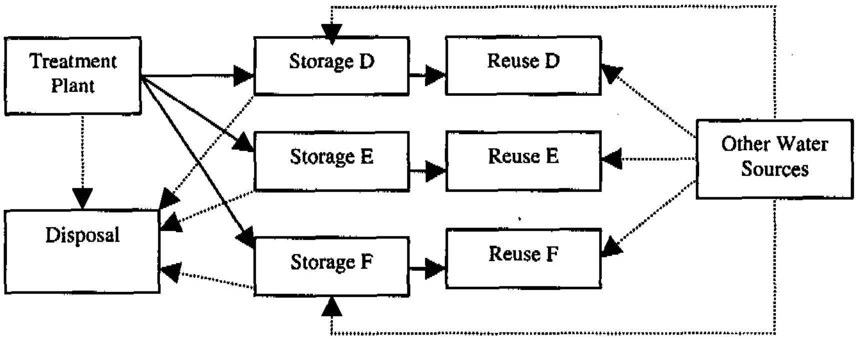
a) Centralised Storage

- Surface storage at the treatment plant or at the irrigation scheme
- Sub-surface storage; groundwater or aquifer recharge and subsequent pumping
- Hybrid storage and treatment
- Effluent supply in combination with alternative water sources
- Full or partial disposal



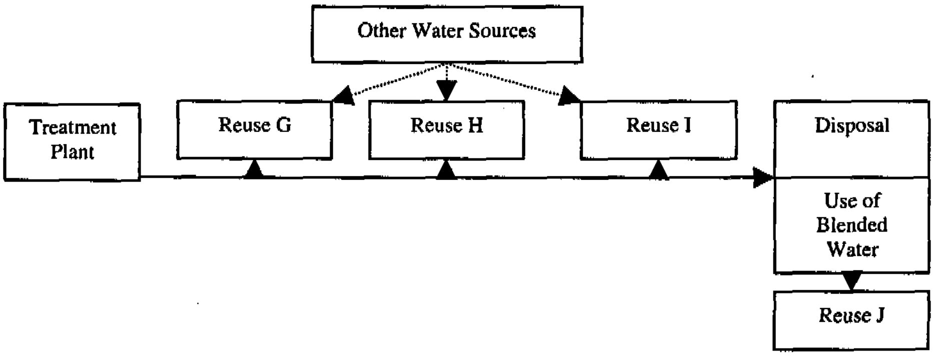
b) Decentralised Storage

- Surface storage at the irrigation scheme
- Hybrid storage and treatment
- Effluent supply in combination with alternative water sources
- Full or partial disposal



c) No Storage

- Direct use at outflow from the treatment plant
- Discharge into dry wadi or canal and subsequent downstream usage
- Discharge into surface streams, reservoirs or lakes and subsequent intended or unintended use of blended water
- Effluent supply in combination with alternative water sources



The topography and hydro-geology of the area between the treatment plant and the reuse area(s) will determine the technical and economical options in choice of method and hardware for effluent storage and conveyance and includes many general, not effluent specific, considerations. Effluent specific considerations may relate to public health safety aspects, potential water quality degeneration during storage and conveyance of the effluent, and, options for hybrid storage and treatment. As shown in Figure 3, options may also be considered for including alternative sources of water into the supply system. Some final notes on monetary versus environmental and social factors in water supply and storage systems are also wanted.

Public Health

Effluent distribution systems can be tagged, e.g. colour coded, to indicate the quality of contained water, and, in many cases it is mandated by authorities that such distribution systems may not cross with distribution systems conveying fresh-water to avoid accidental mixing. It is important to avoid "water theft" and subsequent unguided use, and, to protect the public health by limiting public access to storage reservoirs (e.g. playing children). An important consideration in the design of sewage effluent ponds is prevention of percolation to groundwater, which can be achieved by lining the ponds (Feigin et al. 1991).

Water Quality Degeneration

Since treated wastewater still contains organic material, oxidation processes continue in the storage reservoir and anaerobic conditions may develop, especially in the deeper layers. The upper layer (1-2m) must contain sufficient dissolved oxygen to prevent production of sulfides, which, in addition to having a bad odour, are corrosive. The volatility of sulfides depends on the pH, at pH < 6 all sulfides are volatile (Feigin et al. 1991). Pumping from a depth where the dissolved sulfide concentration is high and the water slightly oxygenated stimulates growth of sulfur bacteria (baggiotoa). As a consequence, a clogging mucous biomass is formed in the irrigation distribution system (after Ravina et al. 1997). The conditions in storage ponds are also ideal for algal bloom. The blooming of photosynthesising green algae in the upper layer (upto about 1 m depth) has certain advantages. The oxygen production, together with the natural mixing of water layers, helps in maintaining aerobic conditions in the pond. The CO_2 consumption increases the pH of the water to >8, which causes further precipitation of heavy metals. Most undesirable are the blue algae, which proliferate in early autumn; they not only consume oxygen, but are slimy and tend to conglomerate, which may cause severe clogging problems in the pumping, filtering and distribution systems (Feigin et al. 1991). Water in reservoirs is also rich in aquatic animals (zooplankton) such as Rotatoria, Copepoda, and Daphnia, which proliferate in the presence of algae. These fauna inhabit the whole reservoir and can reach several millimetres in length (Feigin et al. 1991). The filaments, slimy or otherwise sticky by-products of phytoplankton and zooplankton (e.g. spirulina and oscillatoria) can agglomerate with suspended solids, especially abundant in earthen reservoirs, which may eventually cause clogging problems in irrigation hardware (after Adin 1987; after Ravina et al. 1997). Homogenisation is an important purpose in reservoir retention, ensuring a stable and predictable water source during the irrigation season. The two main types of reservoirs are those with clear layering of the water and those where the water layers are mixed (Yardeni et al. 1994). The first mentioned type of reservoir is preferred for irrigation since water taken from the deeper layer will not hold biological clogging agents whereas this problem does occur in the second type of reservoir mentioned. However, phenomena (e.g. algae bloom) can occur unexpectedly for no apparent reason and control of storage water is therefore not easy (Yardeni et al. 1994).

The parameters characterising an effluent reservoir, which are important for monitoring purposes are (Feigin et al. 1991):

- Concentration of dissolved oxygen
- Temperature
- pH
- Clarity or turbidity
- Biological constituents

Hybrid Storage and Treatment

Effluent stored in reservoirs can be upgraded with several low-cost techniques such as aeration, sedimentation (accompanied by adding flocculents) and biological methods, such as stocking reservoir with fish. Chlorination is a common tertiary treatment applied in storage reservoirs which however deserves serious considerations regarding potential environmental and crop production hazards.

Alternative Water Sources

Storage ponds may be constructed to store runoff water, which is generated during intermittent rainfall events during the wet season. High capital investments are required for the collection, storage and distribution of the water to the consumption sites. The stochastic nature of runoff water supply raises additional reliability difficulties to the efficient use of this water. However, the high quality of the water, and the potential to retain large volumes are advantageous in regions with scarce conventional waters (Oron 1998). There are over 225 combined reservoirs for runoff water and effluent in Israël (Eitan 1994, in Oron 1998) with a total capacity above 85×10^6 m^3.

Environmental Considerations and Public Policy

Surface storage facilities are generally expensive and are thus not always economically feasible or cost-effective. However, multiple-objective planning (Chapter 2.1) would possibly opt for including storage facilities because flexible irrigation management greatly increases the reuse efficiency. Sharing responsibilities and costs might prove to benefit both the producer and the user of treated wastewater. More so in the case where the producer of treated wastewater has limited options for safe disposal of effluent. Although the responsibility for collecting, treating and disposing of urban wastewater will normally lie with a local water or sewerage authority or municipality, farmers wishing to take advantage of the effluent might be willing and able to pay for what they use, as long as they are not asked to pay for general disposal costs. They will base their decision on whether or not they will be better of paying for the effluent rather than doing without it, taking into account the quantity, timing, quality and price of the treated effluent. The local sewerage authority should acknowledge their financial responsibility for the basic system to achieve environmental protection objectives, while the farmers could be charged for any incremental costs associated with additional treatment or distribution required specifically for effluent use in agriculture or aquaculture. In practice, if the effluent use scheme is considered at the time the sewerage project is being planned, treatment costs might well be reduced over those normally required for environmental protection (FAO 1992). At present, monetary factors tend to be the overriding concern in determining whether and how to implement a wastewater reuse project. In the future, however, environmental considerations and public policy issues may be of a greater importance than mere cost-effectiveness as a measure of the feasibility of a wastewater reuse project (Metcalf and Eddy 1995).

3.2.3 Irrigation Method and Technology

Irrigation methods can be classified into two general types, both of which are used for treated wastewater irrigation: (1) surface or gravity irrigation (e.g. furrow and border irrigation) and (2) pressure irrigation. Pressure irrigation can further be classified into localised irrigation (e.g. drip and bubbler) and non-localised irrigation (e.g. gun sprinkler and centre pivot). The ultimate localised irrigation methods consist of low-volume micro-irrigation systems such as drip, micro-drip and micro-sprinklers. The names surface or gravity irrigation and pressure irrigation may seem somewhat misleading and require additional explanation. First of all, some pressurised irrigation methods may actually use gravity (e.g. from water stored in elevated reservoirs) without the need for pumps, which can especially be the case for micro-drip systems that are operational at pressures as low as 1 m water head. Secondly, pressurised irrigation methods may apply water at the soil surface (i.e. surface irrigation) but may also apply water beneath the soil surface, also known as sub-surface irrigation (e.g. sub-surface drip). All sorts of intermediate irrigation methods fulfil the myriad of irrigation methods available, ranging from buried clay-pipes for sub-surface irrigation up to the good old fashioned highly labour intensive watering can. Irrigation technology refers to specific types of hardware used for a given irrigation method; e.g. on-line button and integral drippers for drip irrigation; and may refer to more general irrigation hardware such as filters and chemigation or fertigation facilities and operational storage facilities. Feigin et al. (1991) mention the following general selection criteria: economic considerations, land topography and soil physical characteristics, type of crops, availability of skilled labour, water quality, and, farming traditions. The selection of irrigation method and technology involves considerations on the following topics that deal specifically with implications from treated wastewater characteristics (for more detail; see Annex 1):

- irrigation efficiency[1]
- application frequency
- application flow-rate
- soil wetting profile
- soil salt profile
- foliar/fruit wetting and aerosolisation
- runoff
- clogging hazard: emitters, pipes, filters
- corrosion hazard for hardware
- de-nitrification effect (sprinklers)
- offensive odour production
- automation
- filter facilities
- chemigation and fertigation facilities
- drainage facilities
- flushing facilities for removal of clogging agents
- runoff and flush-water disposal or recovery facilities
- facilities to include alternative sources of water
- operational storage facilities

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[1] Each irrigation method has a characteristic potential to be efficient in the application of irrigation water. The definition of 'irrigation efficiency' can be manifold. The field application efficiency e_a is the relation between the quantity of water furnished at the field inlet and the quantity of water needed, and made available, for evapotranspiration by the crop to avoid undesirable water stress in the plants throughout the growing season (Bos et al. 1974). Problem with this data is that any water used for beneficial purposes, such as leaching of salts, besides meeting crop evapotranspiration, is

considered as in-efficient. Thus, the real efficiency, or, sagacity might be higher. Burt and Styles (1994) mention that the "irrigation sagacity" is a better indicator of wise irrigation water management, because it accounts for the fact that some portion of non-beneficial use is entirely reasonable. Irrigation sagacity is defined as the ratio of the volume of irrigation water reasonably or beneficially used to the volume of irrigation water applied or diverted, expressed as percent. Beneficial uses are defined as: crop evapotransiration, salt removal, climate control, soil preparation, etc., non-beneficial uses are divided into reasonable (water needed for maintaining water quality standards in drains, some deep percolation due to non-uniformity, some deep percolation due to uncertainties in salt management, and, various losses which may be uneconomical to avoid) and non-reasonable uses (excess deep percolation, excess tailwater, etc.).

3.2.4 Crops

Various research cases and practical cases around the world indicate that, depending on the specific circumstances, all sorts of agricultural crops are irrigated successfully with treated wastewater. Examples include crops such as shown in the following Table 2.

Table 2 Crops Irrigated with Treated Wastewater

Alfalfa	Citrus	Maize	Rice
Apples	Clementines	Melon	Sod
Artichoke	Corn	Oats	Sorghum
Asparagus	Cotton	Olives	Spinach
Aubergine	Date palms	Onions	Squash
Avocados	Egg plant	Oranges	Strawberries
Barley	Eucalyptus trees	Ornamental plants	Sugar beets
Beans	Fibre crops	Pasture grasses	Sugar cane
Beet root	Firewood	Peaches	Sunflower
Broccoli	Flower seeds	Pearl millet	Sweet corn
Cabbage	Garlic	Peas	Tomatoes
Carrots	Grapes	Peppers	Turnip
Cauliflower	Green onions	Potatoes	Vegetable seeds
Celery	Green tomatoes	Pistachios	Water melon
Chili peppers	Hay	Plums	Wheat
Christmas trees	Lettuce	Pumpkin	

Sources: Feigin et al. 1991; FAO 1992; Asano 1998

The purpose and success of cultivating any such crops with treated wastewater depends on the following wastewater related criteria (for more detail; see Annex 1):

- Climate and Soil
- Environmental, Human and Animal Health Protection
- Potential Hazards to Crops
- Crop Water Requirements and Cropping Pattern
- Farmers' Objectives, Capacities and Constraints

Climate and Soil

In hot arid regions the sun exerts a lethal effect on pathogens on crops which may be considered in the selection of food-crops, especially when the crop is left to dry in the field for a lengthy period prior to harvest and use. On the other hand, crops that are irrigated over-head (i.e. with wetting of fruit and foliage) in these regions may also be subject to leafburn damage or unsightly deposits from salts contained in effluent. As far as crop selection is also based on existing soils types (e.g. rootability) in the potential reuse location, soil-upgrading options should be considered as an option in site-selection. In some small-scale cases (e.g. in Palestine) potential agricultural land is upgraded by applying a few feet of good soil from nearby construction sites. This is only meant to indicate that crop selection need not per definition be limited by existing soil situations. The employment of greenhouse technology offers possibilities to adapt both climatic and soil conditions for any desired crop cultivation. Moreover, it has the potential prevent many of the soil-related hazards, such as sodification and salinisation, when crops are cultivated on artificial soils. Greenhouse crop cultivation with the use of treated wastewater is not often mentioned in literature. However, a case study on Lebanon performed by M.R.Darwish et al. (1999) indicates that greenhouse production of certain vegetable and flower crops with treated wastewater could be extremely profitable.

Environmental, Human and Animal Health Protection

Environmental protection by means of appropriate agricultural crop selection is mainly related to the capacity of crops for nitrogen removal. M.R.Darwish et al. (1999) for example, in their case study of Lebanon, have considered the nitrogen uptake capacities of various crops in a linear programming model aimed at optimising, amongst others, nitrogen removal from total applied wastewater in a reuse scheme. Afforestation plants can be selected for more general environmental protection purposes, including sand stabilisation, (after FAO 1992) but is not typically considered as agricultural production, unless the plants have some additional beneficial value such as for fruit, timber, fuel and charcoal production.

Human and animal health protection by means of appropriate crop selection is generally mandated by means of legal and regulatory guidelines with a main concern for microbial standards. There are no crop guidelines concerning the prevention of human and animal health risks associated with chemical characteristics of treated wastewater (after Chang and Page 1998). Chang and Page (1998) however present a research on establishing human health related chemical guidelines. This research examines, for example, the bio-accumulation hazards coupled with human diet and consumption of various types of crops, dairy and animal products, containing pollutants in various levels. Current incorporation of chemical characteristics in mandatory crop guidelines is more often aimed at healthy crop production (e.g. toxicity) rather than human or animal health protection. It is generally assumed that the so-called soil-plant barrier provides adequate protection to humans and animals, although it is known that some elements tend to accumulate within parts of plants, sometimes reaching levels dangerous to animal health. The WHO (1984) has published guidelines on levels of organic and inorganic constituents of health significance for irrigation water in general, that are often however conservative, often derived from drinking water standards or tentative, and, not crop specific. Human and animal health risks associated with bio-accumulation of ingested trace elements absorbed to the surface of root crops, fruit or foliage (e.g. alfalfa fed to cattle) requires considerations on farming practices rather than crop selection.

On the other hand there are several crop related guidelines concerning the microbiological quality of treated wastewater used for agricultural irrigation. The most common case is that regulations combine crop restriction with specifications on the irrigation methods, the quality of water and hygienic recommendations or farming practices. Basically both the so-called "nil-risk school" (Israeli and USA researchers) and the "less stringent evidence school" (WHO) work on these principles, albeit with different priorities of required wastewater quality and hygiene regulations. The WHO (1989) "Recommended Microbiological Quality Guidelines for Wastewater Use in Irrigated Agriculture" are relatively simple in their construction regarding crop classification and required hygiene regulations and are more stringent on helminth rather than bacteria or virus control. The new Israëli 'state of the art' guidelines, introduced in 1999, are comprised of a more sophisticated and hard to administer system of crop classification and required hygiene regulations, known as 'barriers', and are more stringent on virus and bacterial control. The Israëli 'barrier' system illustrates perfectly how crop selection can become less restricted when more 'barriers' are installed. The US-EPA (Environmental Protection Agency) "Suggested Guidelines for Reuse of Municipal Wastewater" basically have an equal system of barrier installation. Various types of reuses are subscribed with requirements for treatment, reclaimed water quality and monitoring, set back distances (e.g. buffer zones for sprinkler) and a vast array of additional recommendations. The problem for most developing countries lies in the installation, operation, maintenance and monitoring of required barriers to ensure human and animal health protection. Additionally, there is an ongoing international discussion about the required level of 'barrier' installation, which is attributable to the lack of firm epidemiological evidence of disease occurrence related specifically to the various forms of treated wastewater reuse in agriculture. It should be noted that the reason for international concern on these issues is much related to the fact that most countries are either importers or exporters of certain agricultural products and are thus concerned for the microbiological quality of products. Shuval et al. (1986) suggest that high levels of immunity against most viruses endemic in the community essentially block environmental transition by wastewater reuse (FAO 1992). This basically defends the WHO (1989) guidelines, but does not consider what happens when cultivated crops are exported outside of the community. Labelling of produce, to identify the quality of water used for its irrigation, is not a common practice. Moreover, intermediary salespersons may actually prefer that produce is not labelled, as labelling adds an additional step in the handling and distribution of the produce (after Sheikh and Cort 1998).

In conclusion it should be mentioned that there exists no simple crop classification system that provides adequate information for human and animal health protection without further considering the quality of treated wastewater, the irrigation method, and, the applied hygienic measures or farming practices. However, from the point of view of human and animal potential health hazards, crops and cultivated plants may be classified in general into the following groups (FAO 1992):

1.	Food crops	-those eaten uncooked -those eaten cooked
2.	Forage and feed crops	-direct access by animals -those fed to animals after harvesting
3.	Landscaping plants	-unprotected areas with public access -semi-protected areas
4.	Afforestation plants	-commercial (fruit, timber, fuel and charcoal) -environmental protection (incl. sand stabilisation)

Additional classification criteria could be:

-	Industrial crops	-non-food (e.g. cotton and sisal) -food processing (e.g. canning, drying, roasting)
-	Food crops eaten raw	-those in contact with the soil (e.g. hanging fruits) -those kept well away from the soil
-	Market destination	-export outside of the community -consumption inside the community

Potential Hazards to Crops

The potential hazards that threaten a healthy crop development of accepted quality are mainly associated with inorganic soluble salts, trace elements and plant macro nutrients contained in treated wastewater. An additional hazard is plant water stress, caused by a mismatch between effluent flow-rate and demand for irrigation water. In summary, the potential hazards are (for more detail; see Annex 1):

- Salinity
- Specific ion or trace element toxicity
- Direct injury to foliage and staining of fruits/foliage
- Nitrogen or phosphorus overdose
- Plant water stress

The degree in which crops are affected by these potential hazards depends on various factors, such as the irrigation method and farming practices, but is also crop specific (e.g. type, variety, cultivar, etc.) and may depend on the crop development stage (e.g. germination, vegetative development, fruit setting, ripening, harvest). For example, some crops are actually more salinity tolerant during germination (e.g. rice, corn, peanuts and lettuce) and some crops even respond with better yields and/or fruit quality at increased salinity levels (e.g. tomato, sugar beet and carrot; Feigin et al. 1991). Research on these issues over many decades has led to a diverse set of guideline information concerning crop specific tolerances. References to some of these guidelines are given in Table 3. A potential problem with such guideline information is that generalisations may not be valid considering the specific boundaries of the cases from which data is gathered. This sometimes translates itself in varying guideline values: e.g. sunflower (helianthus annuus) is mentioned as a boron sensitive crop (Maas 1985; in Feigin et al. 1991) and as a boron semi-tolerant crop (Wilcox 1960; in Bresler et al. 1994), each with different methods to indicate the threshold level. This only serves to illustrate the cliché that guideline information should be considered with caution. Perhaps in situ experimentation with various types of crops is ultimately the best way to examine effects on yield and quality of yield.

For staining of fruits and foliage there are no crop specific guidelines but rather general guidelines for sprinkler irrigation water quality. If the treated wastewater invariably contains levels of constituents likely to form deposits, such as iron and bicarbonate, then, crops that are not allowed to have unsightly deposits should not be cultivated, or, other irrigation methods or farming practices should be employed that avoid bringing water onto the crop foliage or fruits.

Crops negatively affected by nitrogen overdose include; cotton, sugar beet, sugar cane, cereal crops, fibre crops, processing tomatoes, vegetables and oranges (after Feigin et al. 1991). Problems associated with nitrogen overdose are attributable to a number of processes such as: plant physiological disorders, reduced carbohydrate metabolism, enhanced vegetative growth, increased tissue succulence and delays and non-uniformity in ripening of fruits. Excessive levels of available phosphorus are not very common but when they occur, these may result in nutrient imbalances, leading to Cu, Fe and Zn deficiencies (Ryden and Pratt 1980), necessitating soil or foliar application of micro-nutrients (Feigin et al. 1991). Feigin et al. (1991) do not mention any crops that are specifically sensitive towards phosphorus overdose.

Plant water stress occurs when the soil moisture potential is low (i.e. the force of moisture adherence to the soil is high) and plants are having difficulty in water uptake. The soil moisture potential decreases as the soil moisture content decreases according to a soil characteristic pF-curve and crops may subsequently respond with reduced transpiration, assimilation processes resulting in yield reduction. Such processes are crop and stage of crop specific as described in "Yield response to water" FAO (1979). Water stress may occur for a number of reasons, one of them could be due to reuse system design characteristics. As higher amounts of irrigation water are required during the summer than during the winter, this may pose problems when no seasonal storage facilities are included in the system. In such a case it may be required to make a choice for crops that are capable of dealing with a certain degree of water stress. For example, of alfalfa (*medicago sativa*) it is mentioned that where cropping of several crops is involved, the irrigation supply to alfalfa may be reduced in favour of more sensitive crops (FAO 1992). In this sense, alfalfa could be considered as a buffer crop to allow for more flexible irrigation management. In general, some water stress can still be acceptable without declining productivity for most crops, but the exact duration of such water deficiency and the potential to endure even greater levels of water deficiency depend on the type of crop and growth stage. It should also be considered that crops may respond negatively to excessively applied water. This may occur when wastewater is abundant and disposal options are limited and the agricultural reuse (e.g. fodder production) tends more towards a land treatment system rather than strict beneficial use of available water resources.

Crop Water Requirements and Cropping Pattern

Water requirements in irrigated agriculture are based on the actual water requirements of the cultivated crops, on water required for other agricultural uses (e.g. leaching and land preparation), and, on water required to compensate for unavoidable irrigation in-efficiencies. Water requirements differ per crop and can be calculated using models such as CROPWAT (FAO; various years) or can be based on local irrigated farming knowledge. The cropping calendar, with planting dates affecting the growing period, also determines when a field does not require irrigation, specifically in periods of maturation, field drying and harvesting. The cropping pattern for a given field will thus determine the [2]crop water requirements pattern and, in combination with data on soils and irrigation method employed, will determine the field [3]irrigation water requirements. At system level, the total irrigation water requirements are thus affected by the cropping patterns selected for individual fields, the irrigation methods and types of soil and the efficiency of the irrigation water distribution system. Total demand is variable over time and most likely deviates from the flow-rate of the effluent supply. Options to resolve this incompatibility may include the construction of seasonal and operational storage facilities on the basis of effluent demand, totally scheduled irrigation on effluent supply basis or alternative safe disposal of excess effluent. A case study in Lebanon (Darwish et al.1999) mentioned earlier also examines optimisation of cropping patterns for full effluent utilisation year round, considering diversified cropping patterns, with or without supplementary irrigation with fresh-water. This case study is, however, aimed at a regional level and does not consider the needs of individual users within an irrigation scheme. This makes the optimisation model highly simplified and applicable only for totally scheduled irrigation at large scale level. The computer model CROPWAT (FAO; various years) is a relatively easy to use tool for calculations on [1]crop water requirements and [2]irrigation water requirements under diverse cropping patterns and at various scales. This can be used both for determining the optimum scenarios for scheduled irrigation but also for determining required effluent and fresh-water supply to accommodate users' defined cropping patterns.

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[1] Crop Water Requirements: water needed for meeting evapotranspiration by the crop to avoid undesirable water stress in the plants throughout the growing season.

[2] Irrigation Water Requirements: crop water requirements + irrigation water required for other agricultural uses (e.g. leaching, land preparation, etc.) + water required to compensate for unavoidable irrigation in-efficiencies.

Table 3 References to Crop Guideline Information

Salinity

- Relative salt tolerance of agricultural crops; FAO (1985); in FAO (1992)
- Salt tolerance of ornamental shrubs, trees and ground cover; after Maas (1986); in Feigin et al. (1991)
- Salt tolerance of trees; Maas (1986); in Feigin et al. (1991)
- Salt tolerance of vegetables; Maas (1986); in Feigin et al. (1991)
- Salt tolerance of forage crops; Maas (1986); in Feigin et al. (1991)
- Salt tolerance of field crops; Maas (1986); in Feigin et al. (1991)
- Plant tolerance (shrub, tree, palm, ground cover and vine plants) to irrigation by reclaimed water including salt (in spray and in soil); Johnson and Parnell (1998)

Specific ion or trace element toxicity; (in soil water)

- Recommended limits for trace elements in reclaimed water used for irrigation; adapted from National Academy of Sciences-National Academy of Engineering; Lund et al. (1976), Fuller (1977); in FAO (1985)
- Guidelines for interpretation of water quality for irrigation; Ayers (1975); in Pescod (1988)
- Guidelines for interpretation of water quality for irrigation; FAO (1985); in FAO (1992)
- Relative Boron Tolerance of Agricultural Crops; Maas (1984); in FAO (1992)
- Relative Tolerance of Selected Crops to Exchangeable Sodium (adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982); in FAO (1992)
- Chloride Tolerance of some Fruit Crop Cultivars and Rootstocks; adapted from Maas (1984); in FAO (1992)
- Relative sensitivity of crops to sludge applied heavy metals; Logan and Chaney (1983); in Feigin et al. (1991)
- Boron tolerance of agricultural crops; after Maas (1986); in Feigin et al. (1991)
- Tolerance of various crops to exchangeable sodium percentage (ESP) under non-saline conditions; after Pearson (1960); in Feigin et al.(1991)
- Chloride tolerance limits for fruit crop cultivars and rootstocks; after Maas (1986); in Feigin et al. (1991)

Direct injury to foliage

- Relative susceptibility of crops to foliar injury from saline sprinkling water; based on direct accumulation of salts through the leaves; after Maas (1986); in Feigin et al. (1991)
- Chloride Tolerance of some Fruit Crop Cultivars and Rootstocks; adapted from Maas (1984); in FAO (1992)
- Plant tolerance (shrub, tree, palm, ground cover and vine plants) to irrigation by reclaimed water including salt (in spray and in soil); Johnson and Parnell (1998)

Staining of fruits/foliage

- Guidelines for interpretation of water quality for irrigation; Ayers (1975); in Pescod (1988)
- Guidelines for interpretation of water quality for irrigation; FAO (1985); in FAO (1992)

Nitrogen or phosphorus overdose

- Guidelines for interpretation of water quality for irrigation; Ayers (1975); in Pescod (1988)
- Guidelines for interpretation of water quality for irrigation; FAO (1985); in FAO (1992)
- Effect of overdose of N on crop production and quality; Feigin et al. (1991)
- Effect of overdose of P on crop production and quality; Ryden and Pratt (1980); in Feigin et al. (1991)

Plant water stress

- Yield response to water; FAO (1979)

Farmer's Objectives and Capacities

The objectives of the potential agricultural reusers can be manifold and may involve anything between high input intensive agriculture to low external input agriculture (LEIA). Extreme examples are high yielding cash-crop cultivation such as roses versus animal feed production such as alfalfa. Considerations for choice of crops include:

- the revenue to be gained through the cultivation of specific crops; which may affect the reusers' willingness to invest in facilities such as storage and post-treatment
- the marketability of specific crops, including public willingness to buy certain types of effluent irrigated crops
- a diversified cropping pattern; to decrease risks

The users' capacity in meeting crop related management requirements, e.g. preventing pathogen contamination, should be well considered. Farmers' agricultural tradition and skills with irrigated agriculture can be important considerations in the choice of crops. The use of indigenous crops, for example, can be preferred by farmers over newly to be introduced crops, at least during the first few years of effluent irrigation (Ismail Daiq from the Palestinian Agricultural Relief Committee, perscom.1999). Potential reusers are however not necessarily farmers of origin (e.g. settled Bedoein in Palestina) or at least may have no previous experience in irrigated agriculture.

3.2.5 Farming Practices

Farming practices in general refer to a course of action in the application of resources (e.g. money, labour, equipment, land, water, nutrients, etc.) in such a way as to attain specified objectives within boundaries of a farmer's capacities and constraints. Farming skills (e.g. experience with irrigated agriculture) can be defined as a human capacity and thus the total package of access to resources and farming skills can be defined as a farmer's capacity. Lack of access to resources and farming skills may form constraints, together with other issues such as legislative guidelines towards the reuse of treated wastewater in irrigated agriculture (e.g. constraining the choice of crops). Objectives to be achieved through farming practices are in the ideal case aimed at a sustainable and beneficial use of available resources to the users' satisfaction with respect for environmental, human and animal health impacts. As such, objectives may derive not only from treated wastewater users themselves, but form an integral part of a wastewater reclamation and reuse system with potential multiple objectives as discussed in Chapter 2.2. Fine tuning of potential reusers' specific objectives with overall objectives is typically performed during the reuse facilities planning phase (Table 1; Chapter 2). Decision making on post-treatment, effluent supply, irrigation methods and technology and crops can be perceived partially as a farming practice in itself. Hence why the potential reuser should be an active participant throughout the various planning stages. However, farming practices as intended in this chapter refer more to technical efforts such as the application of a source of calcium to the soil to prevent sodification hazards. All previously mentioned decision items (and site selection; see Chapter 3.2) have an effect on the required and optional farming practices, therefore, the reusers' objectives, capacity and constraints to perform and finance these farming practices should be considered well in advance. The design framework, to be presented in Chapter 3.3, may serve as a tool for considerations during early phases of planning. An idea of the required farming practices and available options at an early stage of planning could, for example, opt for the inclusion of a fresh-water resource into the irrigation water supply system. At first such an inclusion might seem too expensive or otherwise undesirable, but when considering the many benefits it might even prove to become economically most effective. Another example is the inclusion of storage facilities, which are generally costly but allow the reuser to perform many potentially required practices such as frequent efficient irrigation applications and irrigation at night. The required farming practices may relate to the following issues that deal specifically with implications from treated wastewater (for more detail; see Annex 1):

- Soil management
- Crop management
- Irrigation hardware management
- Human, animal and environmental health management

Soil Management

control of salinisation:
- leaching of salts from the cultivated soil layer by means of natural rainfall infiltration, which requires pre-winter rainfall soil ploughing, or, by means of intended over-irrigation
- mixing water of different sources to attain a lower irrigation water salinity level
- maintenance of high soil-moisture potential in the rooting profile; frequency and rate of irrigation applications

control of sodification:
- applications of sources of Ca (e.g. $CaSO_4$) to the soil
- mixing water of different sources to attain a better SAR value
- maintenance of relatively high soil salinity levels which reduces the physical effects of sodification in case of high ESP levels

retaining plant macro nutrients:
- control of the CEC (Cation Exchange Capacity) and pH with $CaCO_3$ applications, soil mulching, adding composts, etc.
- prevention of top-soil erosion
- efficient irrigation to avoid leaching
- frequent irrigation applications for regular supply of mobile nutrients ready for direct crop-uptake

control of the plant macro nutrient balance:
- phosphate applications to counter nitrogen overdose
- stimulation of denitrification and volatilisation processes
- mixing water of different sources to attain a lower irrigation water nitrogen level

control of trace element/toxic ion accumulation:
- efficient irrigation to reduce the loading rate of trace elements onto the soil
- organic matter and pH control in cultivated soil layer; stimulating solubility of trace elements for movement away from the cultivated soil layer
- efficient chemigation applications; measuring residual chlorine with field kits

Crop Management

control of direct foliar injury or salt deposits:
- sprinkler irrigation at night when evaporation rates are lower
- low-frequency or continuous sprinkler irrigation
- washing off salts with applications of fresh-water after effluent irrigation

Irrigation Hardware Management

control of clogging:

- flushing of pipelines
- emitter cleaning or replacement
- filter cleaning
- chemigation to break down clogging agents and limit proliferation of algae

control of corrosion:
- rinsing with freshwater

Human, Animal and Environmental Health Management

control of odour nuisance:
- scheduling of time barrier between field work and irrigation applications
- maintenance of a well aerated soil; mulching, tillage, efficient irrigation, etc.
- irrigation at night when average wind velocity and public activity is lowest

control of pathogen exposure:
- field worker protective clothing
- scheduling of time barrier between irrigation applications and cattle grazing or field work
- harvesting and drying of fodder or other crops prior to use
- plastic covering of soil to prevent contact between crop and contaminated top-soil
- preventing public access to fields, storage ponds and effluent distribution system
- maintenance of wind-breakers to limit sprinkler aerosolisation drift
- irrigation at night, when wind velocity is lowest, to limit sprinkler aerosolisation drift and when public activity is lowest
- application of desinfectants to kill pathogens
- efficient irrigation; to prevent leaching of pathogens to groundwater or aquifers in case of karstic sub-soils
- prevention of (uncontrolled) runoff water and top-soil erosion

control of nitrate and trace element leaching to ground- or surface waters:
- see soil management

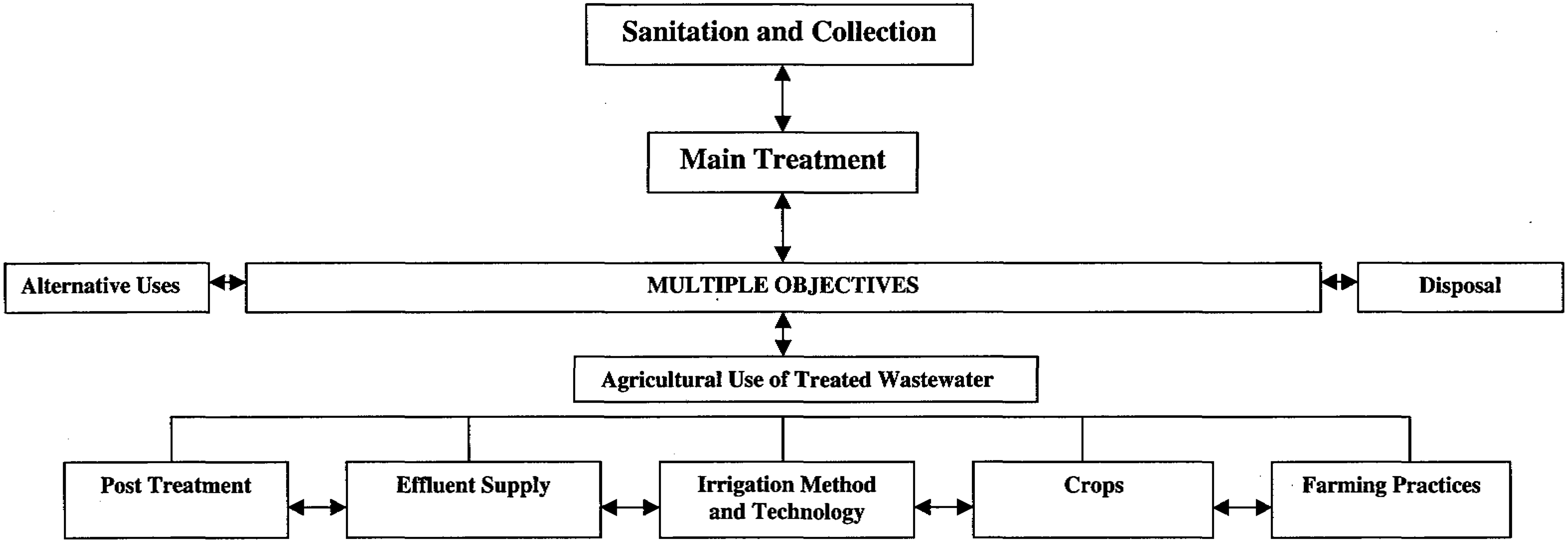
control of trace element bio-accumulation:
- see soil management
- harvesting of fodder; avoiding direct ingestion of contaminated top-soil by grazing cattle

Other:
- awareness of the by-product formation from use of chemical desinfectants; e.g. carcinogenic chlorinated hydro-carbons; use of efficient chemigation applications or alternatives to chemical desinfection

3.3 A Design Framework

The planning of wastewater collection, treatment, reclamation, reuse and disposal in general requires a multiple-objective approach in purposes and uses in order to evaluate different alternatives and to reach a most optimal design. Within the more specific case of the use of treated wastewater in irrigated agriculture there are also many different options that require comparison and evaluation. Specific effluent characteristics may lead to effects that can be enhanced, mitigated or prevented by means of appropriate decision making on items as described in the previous chapters. In Figure 4 we present a design framework that displays the relationships between the earlier discussed decision making items and with additional

Figure 4 **Design Framework for Agricultural Use of Treated Wastewater** (Martijn and Huibers 2001)



considerations for up-stream issues. An important function of this framework is to identify gaps in knowledge and insights and to identify which kind of secondary decision making tools could be employed to facilitate a decision making process. Such secondary tools should be directed also at integrating social, political, economical, cultural, gender, and various other issues into the decision making process according to their own criteria. The basic assumptions underlying this design framework are as follows:

Scale of operation

The framework is applicable to any scale of operation, ranging from decentralised treatment and reuse at household level, various levels of urban agriculture, to centralised treatment and effluent-use at regional level.

Origin of wastewater

The framework is developed with a view on wastewater from household origin, although some industrial origin is acceptable since trace elements have been taken into consideration. However, wastewater of pure industrial origin may contain such high amounts of specific elements or may have other characteristics (e.g. temperature) that more detailed attention towards other issues is required.

Sanitation and Collection System

Considerable scope for project optimisation lies at early phases of planning and starts ideally at the source of wastewater. Separation of black and grey domestic wastewater, dry-sanitation, small-bore sewer systems and decentralised approaches are some of the unconventional approaches that offer a better control over the quantity and quality of wastewater and therefore are highly suitable for integrated approaches considering reuse options. Decentralised Sanitation and Reuse (DESAR) is receiving increasing attention within developed countries with the realisation that centralised sewerage systems are not always the best option for geographic and economic reasons (Tchobanoglous et al. 1998). Listing the potential problems for agricultural reuse, separation of the potential problematic compounds at the source seems to be logical (Zeeman and Lettinga, 1999; Zeeman et al., 2000). Separation of the concentrated black water from the bulk of the used household water results in a very small, hazardous and infectious quantity of waste that is relatively easy to treat. The black water consists of toilet water and possibly kitchen waste(water). After adequate treatment it can be dosed in a controlled manner to agricultural production systems. The bulk of the household water can be reclaimed by easy means (e.g. filtration) for reuse in agriculture. Development of innovative systems requires a multidisciplinary approach, in which the value of water (and its constituents) is recognised by all involved stakeholders. Integrating the reuse demands upstream will lead to a novel approach in which water is not merely abused as transport medium for wastes from residential areas to disposal sites.

Main treatment

The main treated wastewater may serve or be subject to multiple objectives. But if none of the chosen alternatives are deemed suitable according evaluation processes, then issues in the main treatment (e.g. the location, scale, level and type of main treatment) may need to be re-considered. Therefore, a two-way relationship is indicated.

Alternative uses and disposal

Alternative use and disposal options are indicated as competing alternatives to the use of main treated wastewater in irrigated agriculture. These issues have been indicated but are not discussed in the previous chapters since they deserve adequate attention but are not in the scope of this document.

Multiple objectives within the agricultural system

The framework is based on the assumption that potential reusers and reuse locations have been identified; i.e. the basis for planning (Chapter 2) has been achieved and potential users themselves are considered active participants in the decision making process. What on the whole is considered to be "agricultural use of treated wastewater" can thus be sub-divided into specific sets of reuse locations and associated reusers. Such sub-division will mainly relate to choices made on post-treatment and effluent supply systems, thus, in initial phases of planning, the framework is applicable to all potential users of effluent from the same main treatment facility. It should be noted, however, that the goal of planning does not have to entail selection of one optimal post-treatment and supply-system. Multiple-objective planning *within* the agricultural system may require the integration of several post-treatment and supply systems using the same source of effluent.

The five main decision items

Post-treatment (Chapter 3.2.1), effluent supply (Chapter 3.2.2), irrigation method and technology (Chapter 3.2.3), crops (Chapter 3.2.4) and farming practices (Chapter 3.2.5) have been selected as the main items that constitute an agricultural reuse system in technical terms. This selection is based on a technical approach and serves to facilitate a simplified yet all-inclusive overview of related technical issues. The framework is constructed in such a flexible manner that it is of no importance which item is decided upon first. This is important since no particular sequence in dealing with these items is warranted in practice. In effect, a sequence is not advised considering the relationships that exist between the items. Decisions made on one item will effect choice flexibility within other items, and, these effects need to be understood well in advance. Table 4 illustrates an example of how single-purpose planning leads to sub-optimal solutions.

Decision making sub-items

The structuring of agricultural wastewater use into five main decision items is a highly simplified presentation of the reality, as each main decision item consists of various sub-items. For example, the decision item "irrigation method and technology" consists of sub-items such as efficiency, degree of automation and wetting profile, to mention but a few. Efforts have been taken to identify and discuss most of the sub-items in Chapters 3.2.1 to 3.2.5, but it is recognised that further literature and practical research may come up with even more and perhaps more relevant sub-issues. In this sense, the proposed framework also serves to facilitate the identification of gaps in past and current research on agricultural wastewater use.

Decision making options

Decision making options constitute the technical possibilities that could theoretically be employed. For example, for post-treatment this would mean a complete listing of all known post-treatment methods and attention for additional options such as centralised versus decentralised systems. Each technical option is evaluated primarily for its purpose in the category that it belongs to but it should be stressed once again that all the main and sub-items are related (see example below). This could lead to the situation where optimisation within a certain decision item may in fact not favour optimisation of the agricultural reuse system at large. Hence why an integrated approach for all main decision items is wanted, and, once again, why a fixed sequence in dealing with these items is not beneficial for overall project optimisation. The technical options discussed in Chapters 3.2.1 to 3.2.5 are based on existing technologies that have been employed or are currently still under development. As mentioned for the sub-items, it is recognised that further literature and practical research may come up with even more and perhaps more relevant technical options.

Table 4 Example of how single-purpose planning leads to sub-optimal solutions

In the selection of the system for supply of effluent to the reuse area, it was not considered that a source of relatively better quality water could have been included with the supply of effluent in order to obtain a better SAR value of the irrigation water. This source of relatively better quality water could have been included but would have required a large and specially designed storage capacity. The reuse area contains soils that are susceptible to sodification hazards for which now expensive and elaborate measures to regulate the soil ESP are required (e.g. application of $CaCO_3$ *powder). A cost-effectiveness analysis shows that the additional costs of having included a storage capacity for fresh-water would have been more economical than the option the reusers are currently facing. Besides this benefit, if that would not have been cost-effectively convincing enough, an increase in the overall irrigation water storage capacity would have allowed for more flexible irrigation management (affecting choice of crops, irrigation method, irrigation efficiencies, etc. etc.). Moreover, the source of fresh-water could have been used to flush the pipelines of pressurised irrigation systems without causing, often unforeseen, problems associated with the disposal of flushing water. Also, this fresh-water could have been used to rinse of salts from spray-irrigated crops thus preventing foliar and fruit damage, and, preventing unsightly deposits of minerals. Earlier identification of the related issues and benefits could have promoted the addition of fresh-water in the supply system. However, a single-objective approach was more aimed at wastewater disposal rather than beneficial use in irrigated agriculture.*

Technical approach

The extent to which 'state of the art' literature separates technical issues from other issues is not always clearly defined. This is most apparent when it comes to health related hazards and dealing with wastewater contained pathogens. However, a structured presentation of the technological possibilities, impossibilities and unknowns does in itself not intend to provide overall best solutions. Ultimately the technical framework serves to facilitate an iterative design and planning process within technically achievable boundaries. Real case scenarios can then integrate social, political, economical, cultural, gender, and various other issues into the decision making process according to their own set of possibilities, impossibilities and unknowns.

Decision making tools

Decision making tools can display interactions between decision making items and can facilitate interactions between participants in the decision making process. The framework in Figure 4 can be considered as a *primary decision making tool* because it displays the relations between various decision making items. Once these relations are understood then *secondary decision making tools* can be employed which actually serve to make decisions on these related items. Such secondary tools may consist of structured background information as presented in the Chapters 3.2.1 to 3.2.5 with technical possibilities, impossibilities and unknowns. Tables with guideline values on various crop salinity tolerances are excellent examples of such secondary decision making tools. More sophisticated secondary tools may consist of computer models that integrate various items such as crop salinity response, water stress response and nitrogen uptake in relation to various irrigation strategies. An important function of the presented framework is to identify the need for and to stimulate the further development of such secondary decision making tools. Finally, it should be noted that secondary tools can also be excellent vehicles for introducing and facilitating non-technical decision making into the decision making process. A good example would be tables showing the estimated net revenue to be gained from the cultivation of various types of crops, which could be used to facilitate a cost-effectiveness analysis.

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ANNEX 1

Treated Wastewater Characteristics and Implications

for

Agricultural Use of Treated Wastewater

Biodegradable Organic Matter and Suspended Solids

Effluent Characteristic	Potential Process	Potential Effect
Biodegradable Organic Matter Mucous biomass Etc.	Decomposition in or near the irrigated field under anaerobic conditions (e.g. in extreme wet soils)	Offensive odors
	Other	See: Suspended Solids

Effluent Characteristic	Potential Process	Potential Effect
Suspended Solids Organic matter Micro aquatic animals Soil particles Etc.	Clogging of irrigation emitters and hence a decrease in field application uniformity	Yield reduction due to partial under-irrigation Note: scale effect depends on the area, or, amount of crops, serviced per emitter
	Clogging of pressurized irrigation water delivery system and hence a decrease in water delivery performance	Yield reduction due to under-irrigation
	Clogging of filters and hence a decrease in water delivery performance	Yield reduction due to under-irrigation
	Clogging of pores in the upper soil surface layer and hence a reduced water infiltration capacity and reduced aeration	Yield reduction due to poor soil conditions Runoff losses; causing inefficient use of water (irrigation and rainfall) and health hazards related to pathogen contaminated runoff water Offensive odors: in case of anaerobic decomposition of biodegradable organic matter in the soil
	Container of: - Plant macronutrients - *Pathogenic microorganisms* - Trace elements	See: - plant macronutrients - *pathogenic microorganisms* - trace elements

Biodegradable Organic Matter and Suspended Solids:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- enhanced suspended solids removal, BOD/COD reduction and algae control through various methods; e.g. filters, chlorination and sedimentation
- hybrid treatment and storage

Effluent Supply

- filters
- positioning of intake; e.g. depth and prevalent wind-direction in ponds
- hybrid storage and treatment

Irrigation Method and Technology

- efficiency, application rate and frequency
- emitter design; size of orifices, location of emitter inlet, type of flow, in-built filter, pressure compensation, self-cleaning mechanism, manual cleaning options, service area per emitter, potential for clogging, detection before yield reduction takes place
- pipe system design; length and diameter to maintain turbulent flow, pressure for flushing, pressure gauges for detection of clogging
- pipe material; smoothness, light transparency
- pipe flushing facilities
- flush-water disposal or recovery facilities
- filters; design; density and size of particles to be removed, flow-rate capacity, pressure requirements, debris-storage capacity, back-flushing efficiency, manual back-flushing, automatic back-flushing
- runoff disposal or recovery facilities
- chemigation facilities
- drainage facilities

Crops

- no implications

Farming Practice

- maintenance of a well aerated soil; tillage, mulching, sodicity control
- scheduling of field work
- efficient irrigation applications
- chemigation to break down clogging agents and limit proliferation of algae
- checking uniformity of water distribution in the field and checking for clogging
- cleaning or replacing clogged emitters
- flushing of pipes and disposal or recovery of flush-water
- manual cleaning, or, back-flushing of filters and checking performance
- adjusting irrigation application rate or frequency to allow for infiltration
- selection of irrigation method and hardware, post-treatment and effluent supply

Inorganic Soluble Salts

Effluent Characteristic	Potential Process	Potential Effect
Inorganic Soluble Salts Calcium (Ca) Magnesium (Mg) Natrium (Na) Kalium (K) Borium (B) Chloride (Cl) Carbonates Sulphides Etc. Total: EC (dS/m) TDS (mg/l)	Sodification; an exchange of Ca for Na in certain clay-minerals and hence an impoverishment of the soil structure: - sealing of top-soil - reduced water infiltration capacity and aeration - reduced Readily Available Moisture (RAM) content of the soil; i.e. storage capacity of water available for crop uptake	Yield reduction due to poor soil conditions Runoff losses; causing inefficient use of water (irrigation and rainfall) and health hazards related to pathogen contaminated runoff water More frequent irrigation required due to lower RAM Land workability problems due to absence of soil aggregates Offensive odors: in case of anaerobic decomposition of biodegradable organic matter in the soil
	Salinisation; an increase of the total salt content of the soil and hence the soil-moisture	Yield reduction due to increased water-stress
	Long term accumulation of specific toxic ions in the soil	Yield reduction due to toxicity
	Deposition of salts on crop foliage and fruits	Yield reduction due to foliar injury or leaf-burn Yield quality reduction due to foliar or fruit unsightly staining with precipitated salts
	Precipitation of salts in irrigation system components causing clogging hazards	Poor performance
	Corrosion of irrigation system components Note: calcareous scale deposits from use of hard-water are beneficial in this case as they act as protective coating	Poor performance

Inorganic Soluble Salts:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- measures to reduce evaporation losses
- precipitation of salts
- hybrid treatment and storage

Effluent Supply

- measures to reduce evaporation losses
- facilities to include better quality water in the supply system
- hybrid storage and treatment

Irrigation Method and Technology

- foliar and fruit wetting
- characteristic wetting and salt profile in relation to irrigation application frequency, rate, and timing options, for given type of soil and climate
- efficiency, application rate and frequency
- drainage facilities; in case of secondary salinisation
- chemigation facilities; to dissolve salt deposits
- irrigation hardware; materials that reduce build-up of mineral deposits, material resistance to corrosive elements, special care for contact points of dissimilar metals
- runoff disposal or recovery facilities

Crops

- salt tolerance
- specific toxic ion tolerance
- foliar injury tolerance
- problems yes/no with unsightly staining from salt deposits

Farming Practice

- leaching salts from the soil; using irrigation and/or rainfall
- mixing water of different sources to attain a better SAR value and/or lower salinity level
- managing irrigation application frequencies, rates, and, timing, to maintain a most desired wetting and salt profile
- application of a source of Ca and regulation of soil pH with to prevent precipitation of Ca in case of a high alkalinity level; e.g. with $CaSO_4$ or $CaCO_3$
- adjusting irrigation application rate or frequency to allow for infiltration and suited to the lower RAM (Readily Available Moisture)
- maintenance of an optimal balance between sodicity and salinity in the soil year round
- applying fresh water in the last period of an irrigation application to wash off salts from the foliage or fruits, and, from the irrigation equipment
- irrigation at night with lower evaporation losses
- managing lowest sprinkler irrigation application frequencies as possible
- selection of crops, irrigation method and hardware, post-treatment and effluent supply

Plant Macro Nutrients

Effluent Characteristic	Potential Process	Potential Effect
Plant Macro Nutrients Nitrogen (N) Phosphorus (P) Potassium (K)	Supply of mobile plant macro nutrients Available for direct plant uptake	Yield increase due to direct availability of plant nutrients in the soil-moisture Lower quality of yield due to nutrient imbalance; mainly from N overdose, in some cases P overdose
	Supply of mobile and immobile plant macro nutrients, immobilization and accumulation in the soil, and, future availability for plant uptake after exchange, diffusion and dissolution processes	Yield increase due to release of accumulated plant nutrients in the soil Lower quality of yield due to nutrient imbalance; mainly from N overdose, in some cases P overdose
	Leaching of plant macro nutrients to groundwater, and/or, runoff transport of macro nutrients to surface waters Note: largest concern is for N, especially highly soluble nitrate (NO_3), followed by lesser mobile P	Health hazards due to nitrate pollution of water sources used for drinking water Environmental hazards due to eutrofication of surface waters

Plant Macro Nutrients:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- enhanced nitrogen and phosphorus removal
- hybrid treatment and storage

Effluent Supply

- facilities to include better quality water in the supply system; to dilute excessive high N levels
- hybrid storage and treatment

Irrigation Method and Technology

- efficiency, application rate and frequency
- de-nitrification and volatilisation effect
- fertigation facilities
- drainage facilities
- runoff disposal or recovery facilities

Crops

- nitrogen uptake capacity
- nitrogen overdose tolerance; crop quality effects

Farming Practice

- maintenance of irrigation applications as frequently as possible
- maintenance of an appropriate nutrient balance by means of additional fertilisation / fertigation, suited to selected crops
- application of better quality water to dilute excessive high N levels
- maintenance of a high CEC in the soil to retain macro nutrients
- prevention of soil erosion
- efficient irrigation applications
- adjusting irrigation application rate to maximise infiltration

selection of crops, irrigation method and hardware, post-treatment and effluent supply

Trace Elements

Effluent Characteristic	Potential Process	Potential Effect
Trace Elements Heavy metals Inorganic elements Trace organics Other	Long term accumulation of various trace elements in the soil and subsequent crop uptake or adsorption onto the surface of root crops	Yield reduction due to trace element specific plant toxicity hazards Health risk to consumers of crops, meat and milk products, due to food-chain bio-accumulation; limited by the "soil-plant barrier"; except in case of direct ingestion through consumption of root crops Note: cattle is also liable to direct ingestion of trace elements through uptake of top-soil when grazing Micro-nutrient supply to plants and animals
	Transportation of trace elements through runoff water, erosion of top-soil, and/or leaching from soils, to ground or surface water	Health and environmental hazards due to ground or surface water pollution
	Other e.g. human estrogen induced production of plant-estrogen in alfalfa	Fertility hazards for cattle fed with effluent irrigated alfalfa Note: more research still required

Trace Elements:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- enhanced removal of trace elements through various methods; e.g. use of duckweed in ponds
- hybrid treatment and storage

Effluent Supply

- hybrid storage and treatment

Irrigation Method and Technology

- efficiency; loading rate of trace elements
- drainage facilities
- top-soil wetting; trace element accumulation in top soil
- runoff disposal or recovery facilities

Crops

- specific toxic ion tolerance
- crop water requirement; loading rate of trace elements
- root crops; trace element adsorption
- accumulation of trace elements in food crops

Farming Practice

- efficient irrigation applications; reducing loading rate of trace elements
- adjusting irrigation application rate; maximise infiltration, runoff minimization
- soil pH and organic matter regulation; effect on the solubility of trace elements in the soil
- selection of crops, irrigation method and hardware, post-treatment and effluent supply

Pathogenic Micro Organisms

Effluent Characteristic	Potential Process	Potential Effect
Pathogenic Microorganisms Bacteria Viruses Protozoa Helminths	Transmission of disease to humans and animals through various exposure routes: - incidental physical contact with effluent - inhalation or ingestion of aerosols from spray irrigation - incidental contact with contaminants spread by top-soil erosion, runoff water, or, carried by insects, rodents or birds - consumption or handling of crops irrigated with effluent - consumption of meat or milk from cattle fed with effluent irrigated grasses - accidental drinking of effluent - drinking of groundwater polluted with percolated contaminants Note: only under conditions of irrigation with raw and extremely contaminated wastewater has there been evidence of internal crop uptake of pathogens	Health risks for: - farm workers - residents nearby effluent irrigated fields - crop handlers - human consumers of crops, meat and milk - animal consumers of crops

Pathogenic Microorganisms:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- enhanced removal of pathogenic microorganisms through various methods
- hybrid treatment and storage

Effluent Supply

- facilities to include better quality water in the supply system
- hybrid storage and treatment
- colour coding of effluent supply pipes
- preventing public access to storage reservoirs and distribution systems

Irrigation Method and Technology

- automation
- filters
- chemigation facilities
- foliar and fruit wetting
- top-soil wetting
- aerosolisation
- efficiency
- drainage facilities

Crops

- relative susceptibility for pathogen contamination at the moment the crop is used
- intended use of the crop and related hygienic practices

Farming Practice

- application of desinfectants to kill pathogens on the crop and in the top-soil
- application of fresh water to wash off pathogens from crops
- prevention of edible parts of crops coming in contact with contaminated top-soil
- irrigation at night; when public activity and wind-drift is lowest
- installation and maintenance of wind-breakers; to limit aerosol drift
- installation of buffer-zones; to prevent aerosol drift into public areas
- scheduling of field work or cattle grazing; to avoid access in recently irrigated areas
- protective clothing
- preventing public access to irrigated fields, storage reservoirs and distribution systems
- selection of crops, irrigation method and hardware, post-treatment and effluent supply

Flow-Rate

Effluent Characteristic	Potential Process	Potential Effect
Flow-Rate Volume/unit of time	Seasonal variations in effluent supply flow-rate and mis-match with seasonal variations in effluent demand flow-rate Diurnal variations in effluent supply flow-rate and mis-match with diurnal variations in effluent demand flow-rate	Unproductive disposal of wastewater Yield loss due to excessive irrigation Yield loss due to water shortage

Effluent Flow Rate:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- hybrid treatment and storage

Effluent Supply

- storage facilities; seasonal and operational
- hybrid storage and treatment
- facilities for use of additional water sources

Irrigation Method and Technology

- *efficiency, frequency and application rate*

Crops

- crop water requirements
- drought resistance
- excess water resistance

Farming Practice

- irrigation scheduling; crop water requirements, irrigation water requirements, electricity prices, night-time irrigation to limit aerosol drift and evaporation losses
- cropping pattern and calendar; planting dates, harvest dates, fallow periods
- irrigation scheduling, cropping pattern and calendar; on effluent supply basis or on effluent demand basis
- use of additional water sources
- selection of crops, irrigation method and hardware, post-treatment and effluent supply

Other

Effluent Characteristic	Potential Process	Potential Effect
Other Disinfectant or other chemical by-products	Long term accumulation of specific toxic ions or trace elements in the soil Deposition of salts on crop foliage and fruits Transportation of trace elements through runoff water, erosion of top-soil, and/or leaching from soils, to ground or surface water	Yield reduction; see inorganic salts and trace elements Health risk to consumers of crops, meat and milk products, due to food-chain bio-accumulation; limited by the "soil-plant barrier"; except in case of direct ingestion through consumption of root crops Health and environment hazards due to ground or surface water pollution

Other:

Implications for use of effluent in irrigated agriculture

Post-Treatment

- chemical use efficiency
- alternative methods; e.g. non-chemical desinfection
- hybrid treatment storage

Effluent Supply

- hybrid storage treatment

Irrigation Method and Technology

- chemigation efficiency
- alternative methods; e.g. irrigation technology with low clogging potential towards algae

Crops

- specific toxic ion tolerance
- foliar injury tolerance

Farming Practice

- efficient chemical applications; e.g. use of field kits to measure residual chlorine
- selection of crops, irrigation method and hardware, post-treatment and effluent supply