

Socio-Economic and Environmental Effects of Wastewater Irrigation:

State of the Art, Problem Areas and Policy Alternatives

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Socio-Economic and Environmental Effects of Wastewater Irrigation: State of the Art, Problem Areas and Policy Alternatives

Abstract

Wastewater is both a resource and a problem. To the extent the water itself and the nutrient contents of wastewater can be captured and reutilized for agricultural production, wastewater reuse presents a case of resource recycling- a fundamental principle of environmental conservation. However, wastewater reuse and recycling comes at a cost and those cost are externality costs, which are in addition to the normal treatment, maintenance, conveyance and application cost. These additional cost include costs of public health protection, management of wastewater application, addressing public concerns, and mitigating potential eutrophication damages¹.

At present, state of the art technology exists to treat wastewater to any desirable level of treatment and effluent standard, but higher levels of effluent quality come at exceedingly higher marginal cost. Hence, wastewater treatment, and subsequent recycling, will be justified to the point, and in situations, only where marginal reuse benefits exceed or at least equate costs. At the national level, marginal social benefits should exceed marginal social costs, such that all externality costs and benefits are internalized.

Treatment technologies, both mechanical and natural, can supply effluents of consistently higher quality through out the growing period of the crop. Nevertheless, wastewater irrigation requires a carefully selected management strategy to minimize risk to public health and the environment/ecosystem.

Eutrophication may result from excessive loading of plant food nutrients, such as N and P, which are present in wastewater in excess quantity, into the natural environment overtime. Wastewater reuse can help avert such damages by utilizing these plant food nutrients for crop production and other agricultural enterprises such as fish pound aquaculture.

Real risk from adequately treated wastewater irrigation is low but concerns remain. These concerns can be addressed by a communication and education campaign and an early involvement of the community into the project planning and implementation processes. This report reviews state of the art in wastewater

¹ For a methodological framework for analyzing these impacts, see IWMI study: Hanjra, M. A. (2001). *Valuation of Socio-Economic and Environmental Impacts of Wastewater Irrigation in Developing Countries*. Unpublished Report. International Water Management Institute, Colombo, Sri Lanka.

irrigation at global scale in general, and developing countries in particular. , and is intended to generate a wider research interest to help guide policy making in developing countries.

Documented cases of wastewater reuse for agricultural production show considerable success in wastewater reuse over very long periods, without any major health outbreaks, given appropriate health and safety standards and a strong institutional mechanism for implementing these safeguards. In countries, where institutional infrastructure is weak, capacity constraints are binding, and health hygiene and safety standards are poorly understood by the communities, risk in wastewater reuse for agricultural production remains pervasive. It is these like countries and settings, where, on one hand, wastewater use for irrigation production poses significant policy challenges, and on the other hand, offers an unprecedented opportunity for resource recycling and for productivity enhancement for combating poverty faster. Needed are the policy instruments for pro-poor management of wastewater resources in developing country peri-urban and rural settings.

INTRODUCTION

Municipal Wastewater: A Resource

In general, municipal wastewater is generated by the households, industry, and commercial concerns as the result of daily usage, production, and consumption activities. And municipal treatment works are designed to receive raw wastewater and produce a liquid effluent of suitable quality that can be disposed to the natural surface waters with minimum impact to human health or the environment. The treatment process produces 'reclaimed water' and a by-product called sewage sludge. From an agricultural standpoint, though, sewage sludge contains valuable nutrients, sludge is not the focus of this report.

Wastewater treatment and its disposal poses a problem for the municipalities. This is especially true in case of large metropolitan areas and cities with limited space available for land-based treatment and disposal. The scarcity of the land and financial resources presents a problem for proper wastewater disposal. However, wastewater contains materials that have the potential for use in agriculture, aquaculture, and landscape activities. To the extent that these plant food nutrients and water itself can be captured for recycling, it offer the opportunity for resource conservation and mitigation of adverse ecosystem impacts.

Mostly, wastewater is a rich source of plant food nutrients (with the only exception of potassium). Thus, wastewater irrigation may eliminate the need for subsequent fertilizer use thereby delivering input cost savings to farmers.

In areas where water is a scarce resource, the reuse of treated wastewater can help to alleviate stress on freshwater resources, serve as a source for groundwater recharge, and a tool for drought mitigation. A managed and judicious reuse of wastewater resources can also aid in salinity control. Wastewater can be used for ecosystem services such as habitat protection, wetland enhancement, wildlife management, and biodiversity conservation. It can also deliver cost savings on energy usage and thus help to reduce greenhouse gas emissions.

Municipal Wastewater: A Problem

Unfortunately, the use of municipal wastewater comes at a cost which is in addition to the normal treatment, conveyance, and application cost. This cost component is represented by additional management and implementation requirements and safeguards for wastewater reuse in agriculture. More precisely, these are the costs associated with the protection of human health and the environment and any costs incurred to address public concerns regarding the reuse of wastewater.

Another problem is that some nutrients, for example nitrogen and phosphorous,

are present in excess of normal crop nutrient requirements. Hence, wastewater application at agronomic rates can cause nutrient accumulation and possible adverse impacts in the long run. However, these issues can be addressed by proper agronomic management practices. Similarly, nitrogen is present in both organic and inorganic forms. The inorganic component requires mineralization before it can be utilized by the plants. Thus, it has the potential of leaching to groundwater aquifer and freshwater supplies thereby causing nitrate pollution with possible adverse health, environmental, and ecosystem impacts.

The timings of irrigation and plant nutrient requirements need to be reconciled carefully through agronomic and management practices to eliminate any adverse effects on yields and quality of crops.

A relatively high saline and heavy metal content of wastewater poses the risk of salinity and sodicity and contamination of soil and crops especially with prolonged use. The heavy metals accumulated in the soil resources can be loaded to human food chain through various exposure pathways with possible health effects. Nevertheless, a significant amount of health risk comes from the pathogenic organisms, notably helminth eggs and coliforms, present in the wastewater. The potential risk associated with pathogenic infections is the main cause for reluctance for the use of wastewater for crop production. Public health concerns erode community confidence in the safety and reliability of wastewater schemes and may consequently waterdown the demand for wastewater grown products.

Agribusiness concerns regarding potential liability and demand dissipation may pose additional problems for wastewater irrigation.

Social aspects such as lack of public endorsement, concerns about sustainability of wastewater reuse practice, nuisance, poor hygiene, odor, noise, aesthetics, low visibility, and impact on property values and vital groundwater resources are some additional implementation impediments to wastewater irrigation.

1. RETHINKING WASTEWATER IRRIGATION

With the increase in global human population, water scarcity has been increasing. The gap in water supply and water demand has achieved such alarming proportions in some parts of the world that it is posing threat to very human existence. The scientists around the globe are working on new ways of increasing water availability. There was an interesting report on ABC News Radio on 16 December 2000 that researchers in Turkey are trying to use Sahara Desert dust to make snow particles and enhance precipitation rates as dams in the region are running out of water (ABC News Radio, 2000). Where as, in the opinion of Ismail Serageldin, vice president of the World Bank and chairman of Consultative Group on International Agricultural Research, 'water would be one of the major global issues of 21st century' (Seckler, 1996). Rethinking wastewater irrigation is just one way of finding alternative sources of water supply.

Normally, wastewater is composed of 99% water and 1% suspended, colloidal and dissolved solids. This solid component includes organic and inorganic compounds including macronutrients such as nitrogen phosphorous, and potassium as well as essential micronutrients. Nevertheless, industrial wastewater may also contain small concentrations of potentially toxic compounds (WHO, 1989).

Due to the high cost of artificial NPK fertilizers, municipal wastewater is considered as a valuable resource normally rich in all essential plant food nutrients. Often, nitrogen and phosphorous are present in excess of the crop requirements, hence, the application rates of treated wastewater need to be calculated in accordance with the nitrogen and phosphorous requirements of the crop. It is recommended to satisfy the phosphorous requirements first and nitrogen requirement later. While calculating the application rates of wastewater, due allowance need to be made for evapotranspiration losses, leaching and drainage, and soil salinity and sodicity effects. Due to high nutrient content, wastewater can not be applied through out the crop cycle of most plants and careful management is essential to optimize yields. However, some crops such as irrigated pastures or hay crops may be successfully irrigated with wastewater without any adverse nutrient loading impacts.

While concerns remain, treated wastewater can be used for crop irrigation with appropriate management practices.

Wastewater Reuse as a Global Practice

In both developed and developing countries, land application of municipal wastewater is a well established global practice. Much of the treated wastewater is used for irrigation of fodder, fiber, and seed crops and, to a limited extent, for the irrigation of orchards, vineyards, and other crops. Some other important uses

include landscape applications for example, golf courses, freeways, playgrounds, schoolyards, parks etc., groundwater recharge, industrial uses, construction and dust control, wildlife habitat, and aquaculture. In Pakistan, in the vicinity of large cities, including Faisalabad, municipal wastewater, both treated and untreated, is used for vegetable production. An impressive pictogram on IWMI's Home Page (Nov., 2000) depicts the use of wastewater in Haroonabad, Pakistan indicating thereby how popular the practice is among the farmers. But, it is safe? This study attempts to answer this question.

About the Study

IWM's project on improving the potential of wastewater irrigated peri-urban agricultural systems in surrounding areas of Faisalabad Division, Pakistan and Vietnam seeks to analyze socio-economic and environmental aspects of urban wastewater use in agriculture sector. The main purpose of this report is to present a comprehensive review of literature on socio-economic, environmental, and ecological aspects of urban wastewater use for irrigation in both developed and developing countries. For the purpose of this study, urban wastewater includes wastewater from all sources including industrial, commercial and residential; and agricultural effects of wastewater include effects on crop production (yield, input use, cost of production etc.) and economic aspects of other effects including environmental effects, health effects, groundwater effects, social effects (employment, income, poverty etc.) and ecological effects. The overall aim is to provide a holistic picture of costs and benefits of urban wastewater use in agriculture.

While this report presents a review of state of knowledge in wastewater irrigation around the globe, an implicit objective of this review is to identify area of concern in wastewater irrigation so as to guide decision making and assure an appropriate policy response.

Organization of the study

Having presented a brief introduction in this section, next section considers the need for and use of available wastewater treatment technologies with special emphasis on land based and other natural treatment systems. An overview of health related guidelines and controversy surrounding the issues is presented in detail in section 3. In the next section, a brief but useful discussion is presented about the use of wastewater for irrigation and considerations of sustainability.

Public health effects of wastewater irrigation are presented in a schematic manner in section 5. Section 6, the core of this report, is devoted to effects of wastewater irrigation on crops, soils, groundwater, environment, and ecological systems. In view of the fact that economic issues have often been subject to oversight, we

devote a special section of this report to economics of wastewater irrigation. Although a host of economic approaches to wastewater management are available in the literature, in Section 8, we present an innovative approach to wastewater irrigation with special reference to our study area. An overview of global highlights in wastewater reuse is presented in last section of this report though we carefully stay short of arguing that agriculture sector has to ‘compete’ with other non-potable reuse water markets in the long run.

2. WASTEWATER TREATMENT: NATURAL VERSUS TECHNOLOGICAL SYSTEMS

Need for Treatment

Some degree of treatment is generally required before wastewater can be discharged into the environment or used for irrigation. The treatment is necessary in order to:

- ◆ prevent nuisance caused by foul smell, odor, and disamentity effects during storage, transit, and application
- ◆ observe high levels of hygiene and safety standards
- ◆ protect public health
- ◆ prevent damage to crops, groundwater, soil flora and fauna
- ◆ prevent any long term adverse impact(s) on the ecosystem.

In order to understand the need for treatment, it is essential to develop an understanding into the origins, quantities, and composition of wastewater.

Principle Sources of Wastewater

Generally speaking, municipal wastewater is composed of domestic wastewater, industrial wastewater, storm water, and groundwater seepage entering the municipal sewage network. Domestic wastewater consists of effluent discharges from households, institutions, and commercial buildings. Industrial wastewater is the effluent discharged by manufacturing units and food-processing plants. In Faisalabad city, a large proportion of municipal wastewater consists of industrial wastewater discharges. The municipal sewage network also serves as means of disposal of rain, flood, and stromwater. Although, some cities in the world, for example Sydney (Australia), have separate systems for the drainage and disposal of storm water, most cities in Pakistan, nevertheless, have combined sewer system for the collection of both storm water and municipal wastewater. The seepage of groundwater, and irrigation overflow and run off, into the municipal sewer system through defectively sealed or broken joints or cracks is a common phenomenon in Pakistan.

Pattern of Flow

Industrial wastewater flow is likely to follow a similar pattern around the clock because of the process specific water requirements. However, small variations during shift change over times are likely. Moreover, seasonal fluctuations in the industrial wastewater discharges are likely to be significant: more water is likely to be discharged during summer months because of the high water requirements (say for cooling system and other process controls). Another source of industrial

wastewater flow variation may be the agribusiness units processing seasonal products. Where, industrial wastewater constitutes a major component of the total municipal wastewater flow, the fluctuation in the industrial wastewater discharges is likely to be of significant importance for water cycle management.

Per Capita Wastewater Generation

In developed economies, per capita wastewater generation is largely a function of price and reliability of the water supply. However, in a developing country like Pakistan, where water supplies are rationed, availability is uncertain, and water is not priced at its true opportunity cost, per capita wastewater generation may largely be a function of availability and minimum usage requirements.

In general, domestic wastewater reaching municipal wastewater system tends to follow a diurnal pattern (Asano *et. al.* 1985) with flow being low during the early morning hours and first peak generally occurring in the late morning followed by a second peak in the evening- after dinner hour. However, the ratio of peak flow loads to average flow is likely to vary inversely with the size of the community and the length of sewer system..

Some festive occasions, timings of the religious rituals, for example Friday prayer in Pakistan, business hours, tourist season, and presence of large university campuses etc. may also generate peak flows from the domestic sources.

While variations in quantity of wastewater available for treatment are likely, the consequent daily and seasonal variation in flow from the treatment works creates an additional difficulty: it makes impractical to use this wastewater directly for irrigation. Hence, short-term storage of treated wastewater may be necessary to ensure a regular supply for efficient irrigation.

Composition of Wastewater

From a water quality management perspective, the municipal wastewater constituents can be broadly classified into:

- Organic matter
- Pathogens
- Nutrients
- Toxic chemicals, and
- Dissolved minerals.

Though the actual composition of wastewater may differ from community to community, all municipal wastewater contain above constituents. And pollutants belonging to the same category exhibit similar water quality impacts (National Research Council, 1996). A brief overview of the wastewater constituents, parameters, and possible impacts is given in Table 1.

Table 1. Pollutants and Contaminants in Wastewater and their Impacts

Pollutant/ constituent	Parameter	Impacts
Plant food nutrients	N, P, K etc.	<ul style="list-style-type: none"> – excess N: potential to cause nitrogen injury, excessive vegetative growth, delayed growing season and maturity, and potential to cause economic loss to farmer – excessive amounts of N, and P can cause excessive growth of undesirable aquatic spp. – nutrient over loading and eutrophication – nitrogen leaching causing ground water pollution with adverse health and environmental impacts
Suspended solids	Volatile compounds, settleable, suspended and collidal impurities	<ul style="list-style-type: none"> – development of sludge deposits causing anareroxic conditions – plugging of irrigation equipments and systems such as sprinklers
Pathogens	Viruses, bacteria, heliminth eggs, fecal coliforms etc.	<ul style="list-style-type: none"> – can cause communicable diseases (discussed in detail later)
Biodegradable organics	BOD, COD	<ul style="list-style-type: none"> – depletion of dissolved oxygen – development of septic conditions – unsuitable habitat and environment – can inhibit pound breeding amphibians – fish mortality
Stable organics	Phenols, pesticides, chlorinated hydrocarbons	<ul style="list-style-type: none"> – persist in the environment for long periods – toxic to environment – may make wastewater unsuitable for irrigation
Dissolved inorganics	TDS, EC, Na, Ca, Mg, Cl, and B etc.	<ul style="list-style-type: none"> – cause salinity and associated adverse impacts – phototoxicity – affect permeability and soil structure
Heavy metals	Cd, Pb, Ni, Zn, Ar, Hg etc.	<ul style="list-style-type: none"> – bioaccumulate in aquatic organisms (fish and planktons) – accumulate in irrigated soils and the environment – toxic to plants and animals – systemic uptake by plants – subsequent ingestion by humans or animals – possible health impacts – may make wastewater unsuitable for irrigation
Hydrogen ions	pH	<ul style="list-style-type: none"> – especially of concern in industrial wastewater – causes acidity and alkalinity – possible adverse impact on plant growth – impact beneficial soil flora and fauna
Residual chlorine	both free and combined chlorine	<ul style="list-style-type: none"> – leaf-tip burn – groundwater contamination – carcinogenic – greenhouse effect

Source: Partly adapted and updated from Asano et. al. 1985.

The general composition of raw wastewater, and treated effluents, may depend upon:

- ◆ composition of water supply
- ◆ number and types of commercial units
- ◆ number and types of industrial units, and
- ◆ characteristics of the residential community etc.

Table 2: The composition of raw wastewater for selected countries

Parameters	Composition of raw wastewater (mg/l)			
	USA	France	Morocco (Boujaad)	Pakistan (Faisalabad)
BOD	110-400	100-400	45	193-762
COD	250-1000	300-1000	200	83-103
SS	100-350	150-500	160	76-658
TKN	20-85	30-100	29	NA
TP	4-15	1-25	4-5	NA

Source: Partly adapted and updated from Yagoubi *et. al.* (2000). For Pakistan data source IUNC, 1996.

Conventional Wastewater Treatment Techniques

Municipal wastewater comprises of preliminary treatment, primary treatment, secondary treatment, and tertiary (or advanced) treatment. In most countries, like US, Europe, and Japan, secondary treatment is the national standard for wastewater before it can be discharged to surface waters. An overview of these treatment processes as described by National Reassert Council (1996) in the context of wastewater irrigation is summarized below:

Preliminary wastewater treatment includes removal of girt and screening. The screening removes rags, sticks, and coarse solids that may interfere with the mechanical equipment. Girt removal separates heavy, inorganic, sand-like particles that may settle in the channels and thus interfere with the treatment process. Thus, preliminary treatment prepares wastewater for subsequent treatment(s), but it effects little change in wastewater quality. The residues from preliminary treatment is mostly inert matter that is of no use in agriculture.

Primary wastewater treatment: The objective of the primary wastewater treatment is the gravity sedimentation of readily-removable suspended solids and BOD. About half of the suspended solids and one thirds of BOD may be removed. Wastewater constituents that exist in the form of settleable solids or are sorbed to the settleable solids may also be removed. Primary treatment brings some reduction in the effluent concentrations of nutrients, trace elements, potentially toxic organic compounds, and pathogens.

Secondary wastewater treatment: is achieved by using biological treatment processes. Microorganisms in suspension (e.g., activated sludge, trickling filter, rotating biological contractor or one of its variants), in ponds or other processes are used to remove biodegradable organic matter. In this process, the organic matter is oxidized by the microorganism to generate carbon dioxide, other products, and energy for their own survival and support. The microorganisms flocculate to form settleable particles. This excess mass can then be separated in sedimentation tanks. The concentrated suspension so collected is called secondary sludge or biological sludge. During secondary treatment process, wastewater constituents may become associated with secondary sludge. These may include organic compounds, trace elements, and pathogenic organisms.

The biological processes used for secondary treatment of wastewater may be high rate biological processes or low rate biological processes. The high rate biological processes use small basin volumes and high concentrations of microorganisms compared with the low rate biological processes. The high rate biological processes include the activated sludge processes, trickling filters or biofilters, and rotating biological contractors. On the other hand, commonly used low rate biological processes include aerated lagoons and stablization ponds (Asano *et al.* 1985). Of these, the use of stablization ponds is common in arid and semiarid regions such as Middle East and parts of Africa. Hence, the working of waste stablization ponds is in reviewed in later. The details of other systems can be found in appropriate texts.

Tertiary wastewater treatment: The most common form of tertiary treatment is the disinfection for the control of pathogenic organisms and viruses. Filtration through granular media or coagulating chemicals can be used to reduce BOD loads and the concentrations of suspended solids in the treated effluents. Activated carbon adsorption can be used to remove trace elements or persistent organic compounds. Excess Nitrogen is removed by nitrification followed by denitrification. Excess phosphorous is removed by chemical precipitation or microbial uptake.

Usually chlorine is used as a disinfectant for treated wastewater effluent. Chlorine is an economical disinfectant but it reacts with organic compounds to form

chlorinated organo compounds that are a potential source of concern. Alternative disinfectants include ozone and UV light (NRC, 1996).

It is pertinent to note that tertiary treatment is used only if water quality discharge requirements, the quality of the receiving waters, or other end uses of the reclaimed wastewater warrant a higher quality effluent than produced by the secondary wastewater treatment. Also, there are many variations to the treatment in practice. For example, primary treatment is sometimes eliminated and long term retention in lagoons may be a substitute for both primary and secondary wastewater treatment etc.

Natural Systems for Wastewater Treatment for Crop Irrigation

The degree of wastewater treatment required for crop irrigation depends on the nature of crops, local conditions, and regulatory requirements. Wastewater treatment cost studies show that higher levels of treatment come at exceedingly higher marginal costs (Schleich *et. al.*, 1996). However, these higher marginal treatment costs may sometimes be justifiable in view of the value of the crop, degree of water scarcity, and public concerns. The cost minimization should remain an overriding objective of wastewater treatment plant in the absence of any binding constraints, such as environment quality standards, however, studies show that treatment plants prefer water quality enhancement over cost minimization (Schwarz and McConnell, 1993) to comply with the latter.

In what follows, we present an overview of the state of the art techniques that can be used as a cost effective and sustainable alternative or complement to expensive mechanical wastewater treatment systems.

Waste stabilization ponds are a popular form of land based treatment system in Middle East and African region. Shereif *et. al.* (1995) report the findings of a demonstration project for the treatment and reuse of a raw domestic sewage in Suez, Egypt. This conventional wastewater stabilization pond has anaerobic, facultative, and maturation components with total residence time of 21 days and the effluent from this simple, inexpensive, yet effective, treatment system conforms with WHO standards for unrestricted agricultural and aquaculture applications. Treated effluent is useful growth medium for local fish species: talipia and grey mullet. Harvested fish yields, with out supplemental feeding or pond aeration, range between 5-7 metric tons per hectare per year. The fish is free from any pathogens and thus safe for human consumption. The fecal coliform counts represents 99.99% removal efficiency. The nutrient rich effluent from the fish ponds can later be used to grow tree and cultivate crops like barley, maize, beets, and ornamentals. The system is effective in removing excess nitrogen, phosphorous, and boron. However, effluent salinity is higher due to dissolved NaCl in the sewage. The salinity can be reduced by mixing treated effluent with

freshwater before using it for crop cultivation.

This study clearly demonstrates the effectiveness and utility of waste stabilization ponds for low cost treatment of domestic sewage for combined reuse in agriculture and aquaculture. Waste stabilization pond technology is particularly suitable for small scale applications because it is inexpensive, easy to operate, and produces effluent of an acceptable quality. No adverse impacts are noticed as the treatment method is essentially an extension of the natural environment. However, the ponds technology may not be useful land is limiting factor. Moreover, they have a complex biology which needs careful management.

Conventional wastewater treatment using primary sedimentation and secondary biological treatment is very efficient. But, high energy costs, technology requirements, and frequent maintenance problems render it ineffective for use in rural areas and low income urban communities. Many of the conventional treatment processes can be accomplished using oxidation ponds at a substantial lower costs provided that land is available at a reasonable cost. A laboratory scale model used by El-Ghory *et. al.* (1995) to demonstrates the effectiveness of oxidation ponds for primary treated domestic wastewater treatment and to evaluate the reuse of pond effluent in aquaculture. With a 25 days retention period, a remarkable improvement in the water quality and 99.99% fecal coliform reduction are recorded. Tilapia fish feeding on the oxidation pond treated effluent gave very high yields. This study confirms the effectiveness of oxidation ponds as a low cost and most appropriate technology for secondary treatment of wastewater in developing countries.

Another success story of wastewater stabilization ponds comes from Morocco. In order to prevent pollution of water resources and the environment by wastewater discharges, the waste stabilization pond system of Boujaad, Morocco was constructed in 1992. The Boujaad waste stabilization pond system represents the classical pond configuration with anaerobic ponds and facultative ponds followed by final maturation ponds. The system covers an area of 3.6 hectares and has a design capacity of 2500 cubic meter per day. An efficiency and performance analysis of this system shows that treated wastewater quality in terms of physio-chemical parameters, such as BOD₅, COD, SS, TKN, and TP), is, however, relatively poor. The relatively low efficiency may be attributable to highly diluted incoming raw wastewater, which in turn may be attributable to the infiltration of the groundwater into the sewage system. However, from a biological perspective, the system has a significant treatment efficiency both in terms of faecal pollution reduction and helminth eggs control. Infact, the treated effluents don not contain any helminth eggs. Thus, the treated effluents can be used for irrigation purposes as the quality of these effluents meets the WHO Guidelines for wastewater use in agriculture and aquaculture (Yagoubi *et. al.* 2000). The Boujaad case study shows

that: (1) microbiological pollution load at the plant inlet is higher during the summer period, May to September, as compared to winter period, October to November, (2) for anaerobic ponds, the microbiological abatement between cold and hot period do not differ statistically, however, (3) for the facultative and maturation ponds, the microbiological abatement between cold and hot periods differs statistically by a margin of 95 per cent.

The latter would imply that facultative and maturation ponds are much more efficient during the winter period than during the summer period. This finding may have important technological and efficiency implication for the use of waste stabilization ponds in hot and dry regions- a typical attribute of Middle East.

The above studies show that wastewater treatment using waste stabilization ponds is very efficient, low cost, and low maintenance process. However, wastewater treated in waste stabilization ponds needs treatment in anaerobic and facultative ponds for restricted irrigation. Further treatment in maturation ponds (or chlorination) is required for unrestricted irrigation. Mara (2000) show that land requirement for the latter are more than twice than that for the former. It is therefore, recommended that unrestricted irrigation should only be selected if it is financially desirable. More simply, one should choose unrestricted irrigation only if net discounted profit is more than discounted costs of maturation ponds. Where as net discounted profit refers to the *difference* in net present value of unrestricted crops and net present value of restricted crops grown.

Mara notes that under Israeli and Brazilian conditions, a “hybrid” waste stabilization pond-waste treatment and storage reservoir (WSP-WSTR) can be used to overcome the land scarcity and seasonality disadvantages. The proposed hybrid system supplies effluents which are safe for both restricted and unrestricted irrigation. Further combinations and arrangements of waste stabilization ponds are discussed later in this report.

The use of wastewater storage and treatment reservoirs, after pretreatment in anaerobic ponds, is advantageous as it permits the whole years wastewater to be used for irrigation and thus allowing a much larger acreage of crops to be grown and there by mitigating the high land requirement disadvantage.

A comparison of primary and secondary treated wastewater and facultative ponds effluent in terms of their suitability for crop irrigation is given in table 4.

Table 4: Comparison of Primary and Secondary Treated Wastewater and Facultative Ponds Effluent and its Suitability for Crop Irrigation

Source: Marecos do Monte *et. al.* (1996). WST 33, no. 10-11, p. 312

Batch reactors: Among agricultural enterprises, dairy farms and milk processing units may be significant contributors of industrial wastewater especially in rural communities. The treatment and reuse of dairy farm effluents should be an integral part of wastewater management plan. An empirical demonstration of this premise comes from UAE (Hamoda and Al-Awadi, 1995) where dairy farms and milk processing plants are a major contributors of industrial wastewater. The wastewater load generated at dairy farms in UAE is mainly contributed by: (1) milking parlours, and (2) milk processing plant. The dairy farm effluent contains considerable loads of solids, organics, and nutrient pollutants. Although some facilities are provided for the primary treatment of dairy farm effluents, stringent environmental regulations necessitate further treatment of wastewater. The existing treatment facilities, consisting of batch-operated primary settling tanks, are unable to produce desirable quality effluents. However, a wastewater treatment system involving these primary settling tanks alongwith an aerobic, suspended growth, biological system using sequencing batch reactors can remove about 94% COD and 96% SS from the dairy farm effluent. The new system can be easily integrated with the existing treatment facilities for dairy waste treatment and effluent reuse in crop irrigation.

Downflow reed-bed system: Downflow reed-bed system consist of one or more stages; each stage contains several parallel sub-beds with some operating and the others resting. The downflow beds are unsaturated, air filled, systems which greatly enhance the aerobic decomposition of wastewater constituents (Brix, 1994). In these beds, pollutants are removed by a range of physiochemical and biological processes as the wastewater flows from inlet to outlet.

The University of Birmingham, UK launched a research project to explore the use of reed-bed treatment systems for the reclamation of high strength agricultural wastewater (“dirty waters”). These wastes generally contain less than 3 per cent of dry matter and originate from water contaminated by manures, crop seepage, cleaning materials or milk. Due to a very high BOD loads and ammonia-nitrogen concentrations, this wastewater presents a substantial pollution threat to the water cycle and the environment. Horizontal flow reed-bed with limestone chipping proved ineffective to treat these high strength effluents. However, the downflow reed-bed system proved effective to reduce adequately the BOD₅ of these high strength effluents as reported by Sun *et. al.* 1998. The results show that significant reductions in BOD, COD, SS, and phosphorous can be obtained in downflow reed-bed systems when they are used to treat strong agricultural wastewater with BOD levels as high as 1500 mg/l. The study provides a foundation to investigate the mechanism of the treatment process, identify the influence of operating parameters on treatment results, and develop a design criteria for the optimization of reed-bed system performance.

Land disposal: is considered to be one of the best wastewater treatment process especially for arid and semi-arid regions. Land treatment systems are capable of achieving nutrient removal levels comparable to the best available conventional wastewater treatment technologies. Additional benefits include recovery and reuse of wastewater and plant food nutrients for crop production. In addition, the land based systems are natural, low cost, and energy saving and thus one of the best treatment options for arid and semi-arid regions (Young and Epp, 1980).

Tanik and Comakogul (1996) investigate the removal efficiencies of nutrients, namely N and P, from medium strength domestic wastewater by infiltration through three types of porous media. The porous (crushed stone) media consisted of gravel, sand, and fine particles such as silt and clay with size range of 10mm to 0.55 mm (grain diameter). Nutrient removal was determined on the basis of two parameters, N (as TKN) and P (as orthophosphate). In order to replicate the arid conditions, the study used hot summer months - mid June to end August. The authors conclude that: Though rapid infiltration is the least efficient compared with other land treatment systems (minimum 50% efficiency with crushed stone); the removal efficiency increases with the decreasing size of soil particles implying that clay and loam soils may be more effective for wastewater nutrient recycling where as there may be potential nutrient leaching risk with wastewater irrigation in sandy soils; climatic conditions have a significant effect on the performance of the infiltration system. Arid climate accelerates the nitrification and denitrification processes in N removal and precipitation process in P removal.

Finally, the researchers emphasize that land based treatment system in this model did not require any pretreatment of wastewater before disposal. Not only the investment and operational costs of rapid infiltration system are very low, compared with other treatment facilities, additional benefits accrue in the form of water reuse and nutrient recycling. The study, however, does not provide an assessment of microbiological efficiency of rapid infiltration system.

The reuse of treated wastewater for crop irrigation is becoming more popular in arid and semi arid areas of Middel East and North Africa. Treatment of wastewater prior to agricultural use is essential: firstly, from the point of view of public health protection; and secondly, to respect local social and religious beliefs (Mara, 2000). In view of these requirements, coupled with water scarcity, dry land farming, hot climatic conditions, and high economic value of fresh water resources, a great deal of research and development effort for the reuse of wastewater has been going in the Israel. In the following sections, we report findings of four recent studies evaluating design, performance, and operational efficiency of land based wastewater treatment system in Israel.

Stablization reservoirs in Israel: are used for two baric purposes viz: (1) the

storage of partially treated wastewater for controlled release, and (2) further treatment of partially treated effluents for irrigation. The storage is necessitated by the 'rainy winter- dry summer' climatic conditions. The storage not only enables to meet large irrigation water demands during the dry and hot summer but it also helps to achieve compliance with environmental regulations as winter stored effluents can be released into the dry river system to provide ecosystem services. Further treatment of partially treated effluents is warranted by several factors including complex nature of pollutants, environmental concerns, breakdown of sewage treatment plants and the need for compliance with wastewater irrigation quality standards (Junico, et. al. 1994, and Junico, 1996).

Waste stabilization ponds used in Israel are normally 7-15 meters deep. They may be designed as steady-state flow reactors with constant effluent inflow, outflow and depth (e.g. deep stabilization ponds) or accumulative batch reactors with a relatively abrupt discharge. The later, type under investigation here, follows an annual empty-full-empty cycle. The investigations by Juanico and Shelef (1993) show that COD and BOD removal by stabilization reservoirs is determined by the percentage of fresh effluents within the reservoir and not the mean residence time of the effluent. The seasonal storage of wastewater in stabilization reservoirs reduces COD, BOD, and TSS by 50-80 percent and total coliforms by 90%. Thus, microbiological performance of waste stabilization reservoirs is relatively poor (as effluent can be used for restricted irrigation only). Moreover, stored water quality follows a seasonal pattern: the quality of effluent is optimal at the commencement of the irrigation season (mid May) but it deteriorates quickly as water level falls and fresh water flows. Design alternatives based on a shift from seasonal to multiseasonal and from single to two or more reservoirs are needed for supplying effluent of unrestricted irrigation quality.

As noted above, microbiological performance of waste stabilization reservoirs is relatively poor: the mean coliform removal efficiency during detention period, before the start of the irrigation period, is as high as 99.6 to 99.999% but it drops down to just 91-95% by the end of the irrigation period (as fresh wastewater flows). The main parameters affecting faecal and total coliforms removal efficiency in stabilization reservoirs have been investigated by Liran *et. al.* (1994). Their findings suggest that the microbiological performance of stabilization reservoirs is affected by both operational parameters as well as environmental parameters. During the irrigation period, when the reservoir is operated as flow reactor, coliform removal is determined by the percentage of fresh water within the reservoir: a higher percentage of fresh effluents (inflows) reduces the coliform removal efficiency. On the other hand, during detention periods, non-irrigation periods, when reservoir acts as a batch reactor, the mean residence time is the single operational parameter affecting coliform removal efficiency. This pattern

suggests that a proper combination of non-steady-state flow operation during winter months and batch operation during summer months can help to achieve higher coliform removal during the entire irrigation period.

Thus, coliform removal efficiency in waste stabilization reservoirs is high in both coastal and surface layers while it is low in case of bottom layers. These findings suggest that coliform removal efficiency can be improved by operational and design changes such as vertical mixing of the wastewater column and constructing elongated shape reservoirs. Nevertheless, elongated reservoirs require more land and this may be a limiting factor in land poor communities, as pointed out by Mara (2000).

The basic operational regimes for the stabilization reservoirs are continuous flow, in series, or batch. However, they can be operated in many different combinations such as: single continuous flow, continuous flow in series, sequential batch in series or parallel, quasi-sequential batch or other combinations. A performance analysis of batch reactors as wastewater treatment units based on three real case studies and simulation models is reported by Juanico (1996). The analysis suggests that stabilization reservoirs in batch mode, when properly designed and operated, can remove BOD, COD, TSS etc by 'upto one order of magnitude' and 'faecal coliforms by upto five orders of magnitude'. A significant removal of heavy metals, pathogens and other pollutants is also achieved. The quality of the effluent alongwith control release capability allows a wide crop rotation and easy irrigation management. The performance analysis of various forms of batch reservoirs indicates that sequential batch reservoirs, either in parallel or in series, perform the best. The reservoir inlet can be closed before the outlet is opened to enable supply of good quality effluents during the whole irrigation season. Nevertheless, sequential reservoirs in series are more economical than sequential batch in parallel. However, it can be argued that the operational regime of the reservoir should be selected on the basis of irrigation water demand. For example, glocourse irrigation may have year round water demand while fruit trees and quick growing crops have seasonal irrigation water demand only. Similarly, if the reservoir is meant for controlled release to the environment, in order to comply with the regulations, it has a seasonal demand only (as it has supply restrictions in other periods). Such seasonal water demands may significantly affect effluent discharge curve and hence the selection of the operational regime of the reservoir.

The main synthesis of wastewater reuse experience in Israel is that:

- ◆ waste stabilization ponds can be successfully used for storage, further treatment, and subsequent controlled release of the treated wastewater for crop irrigation or vital ecosystem services.
- ◆ Waste stabilization ponds are a natural, low cost, and microbiologically

and biochemically (and perhaps ecologically) acceptable alternative to expensive conventional wastewater treatment techniques.

Although wastewater irrigation is relied as an environmentally sound wastewater disposal alternative in Israel, there is one serious problem: it has the potential to cause salinity as sewage has a higher concentration of dissolved salts and these salts have negative environmental effects on crops, soils, groundwater and ecosystem. As the removal of sewage salts is very expensive, prevention of sewage salt enrichment may be the best alternative. Baruch *et. al.* (1996) describe a set of new initiatives and technological solutions undertaken by the Israeli government to address the salinity problem caused by salt enrichment of sewage. These initiatives are:

- ⇒ Search for new technologies to reduce salt consumption;
- ⇒ Use of situation specific technology;
- ⇒ Programs for raising awareness of environmental implications of salinity; and
- ⇒ Implementation of state-of-the-art regulations.

This approach illustrates that solutions to common environmental pollution problems, such as soil salinity, require a multi-dimensional approach to address the issues related to technology, its use, public awareness and legal aspects.

Assessment of Land Based Treatment Systems

The studies reviewed above show that wastewater treatment using waste stabilization ponds is very efficient, low cost, and reliable method of wastewater treatment easily adaptable and generally well suited to the environmental conditions in the Middle East and North Africa. Even WHO (1989) noted that waste stabilization ponds are the most appropriate treatment option for meeting the effluent quality requirements in warm climates which are characterized by water scarcity, high temperatures, erratic and low rain fall, and higher than normal water requirements.

Anaerobic and facultative ponds can treat domestic wastewater to meet both EU discharge standards and WHO Guidelines for wastewater reuse for restricted crop irrigation. They remove excreted pathogens to a much higher degree than that achieved by other processes (unless disinfection with chlorination is used). Further treatment in maturation ponds achieves the effluent standard required to comply with WHO's recommendations for unrestricted irrigation. More importantly, waste stabilization ponds have no energy input except the solar energy absorbed by the surface water.

Two disadvantages of waste stabilization ponds often cited in the literature are:

- high land requirements, and
- higher water loss through evaporation.

However, if the land prices are not high, high land requirements is not a disadvantage rather amortized value of the land may prove to be net benefit in the long run. Secondly, appropriately designed waste stabilization reservoirs permit the whole years wastewater to be used and thus more crops to be grown. The high cropping intensity and land use intensity thus achieved may more than compensate for the additional land requirements. High water losses through evaporation can simply be viewed as price for energy savings (Mara, 2000).

It is important to emphasize here that the use of waste stabilization ponds, in the form of anareobic, facultative, and maturation ponds, is a substitute for a full blown tertiary treatment process including chlorination. Chlorination can be achieved by using either chlorine or ozone or UV light. Chlorine is an ozone depleting substance and is believed to have severe negative environmental impacts. Hence, it is possible to exploit this disadvantage of conventional treatment process to motivate environmentally conscious consumers to patronize the products grown with effluents treated by nature based and environment friendly treatment systems such as waste stabilization ponds. However, it will requires a very high degree of treatment integrity and consumer education which unfortunately come at a very high cost in developing countries.

Feasibility of Using Aquatic Plants for Wastewater Treatment

Floating aquatic plants that feed on nutrient rich wastewater and/or reduce the pathogenic bacteria can be used in conjunction with conventional system to improve effluent quality for crop irrigation. They can either be used as single species or multi-species in the form of constructed wetlands. Constructed or artificial wetlands are commonly regarded as a viable tertiary treatment alternative for municipal wastewater. Recently, several major works have been publishes in this area. Two recent studies, one focusing on the nutrient removal efficiency and the other focusing on microbiological efficiency of these aquatic plants are reviewed here.

Single species systems: In an effort to find improved and low cost aquatic treatment systems Bramwell and Parsad (1995) used floating water hyacinth (*Eichhornia crassipes*) to assess its potential for wastewater effluent quality improvements. In order to determine the nutrient removal efficiency of water hyacinth, a series of six tanks, each with dimensions of 3 x 3 x 1 meter containing 5.4×10^3 liters of wastewater and 50 kg of water hyacinth are used in this study. The tanks receive secondary treated wastewater, before chlorination, at a rate of

16200 liters per day for seven days. The results suggest that: the water hyacinth treatment reduces DO significantly; the effluent quality improves in terms of reduction in nitrogen content (by 27.6%); however, there is an increase in total phosphorous (4.48%); and among the micronutrients, potassium shows a reduction (20.2%) while sodium increases slightly (0.88%).

Clearly, P removal efficiency is low as compared to N removal efficiency. It is argued that N and P ratio of both water hyacinth tissues and wastewater effluents can affect their removal efficiency. This also opens up the possibility to use a system of aquatic macrophytes with varying N and P removal capabilities. As the water hyacinth treatment results in lowering of most parameters, the effluent is suitable for irrigation. The researchers suggest the use of young water hyacinth plants for a period of five days for an effective nutrient removal program.

The biochemical analysis of plant tissues shows that nitrogen and phosphorous contents are higher in shoots than in the roots, where as sodium and potassium contents are higher in roots than the shoots. This indicates the plant uptake and translocation of N and P to aerial parts and micronutrient accumulation in root tissues. Pending the investigation on the reuse of effluent and plant tissues, the differential uptake and accumulation pattern of macro and micronutrients by the water hyacinth may have policy implications. The study covers only nutrient removal efficiency and not the microbiological efficiency of water hyacinth. However, it is evident that water hyacinth system can be successfully used for polishing secondary treated domestic sewage (under Jamaican or Caribbean conditions). The system is low cost, have low land requirements (0.27 m² per head) and is well suited to the needs of small communities.

Multispecies systems: The use of a system of macrophytic plants, or constructed wetlands, as a viable tertiary treatment alternative for municipal wastewater has been investigated by Karpiscak *et. al.* (1996). The basic objective of this investigation is to determine the improvements in secondary treated water quality, particularly, the removal of: (a) indicator bacteria (coliform), and (b) enteric pathogens (*Giardia*, *Cryptosporidium* and enteric viruses) by using two types of constructed wetlands viz:

1. a multi-species wetlands system planted with cattail (*Typha domingensis*), bulrush (*scirpus onleyi*), giant reed (*Arundo donax*) black willow (*Salix nigra*), and cotton wood (*Populus fremontii*). Also, water hyacinth was used as a floating macrophyte.
2. a single species aquatic system planted with duckweed (*Lemna spp.*) only.

The results indicate that the multi-species wetland system is more efficient in

terms of total nitrogen reductions (by 23.4%) than single- species duckweed system. Though both systems reduce BOD loads to tertiary standards (10 mg/l), the BOD reductions are small in duckweed system. Microbiological efficiency analysis indicates that both the duckweed and multi-species system reduce total coliforms, fecal coliforms, *Giardia*, *Cryptosporidium*, and enteric viruses. While the duckweed system registered a higher rate of removal of parasites, no significant removal of coliophages is noted. The multi-species system, on the other hand, registered a higher rate of removal of indicator bacteria.

On an overall basis, these constructed ecosystems effectively reduce BOD concentrations, nitrogen content, and concentrations of pathogens in secondary treated wastewater. Moreover, many wildlife species were attracted to this wetland site. Thus, this aquatic, multi-species wetland system also has a positive ecosystem impact on habitat quality and wildlife diversity.

3. GUIDELINES FOR WASTEWATER REUSE IN AGRICULTURE AND AQUACULTURE

Need for Guidelines

Wastewater contains a high concentrations of excreted pathogen such as viruses, bacteria, helminths eggs, and fecal coliforms etc. These excreted pathogens have the potential to cause the disease if contracted by a human host in virulent quantities. The World Bank (1986) conducted a comprehensive evaluation of epidemiological evidence on human health effects associated with wastewater use which suggests that:

- *Irrigation with untreated wastewater*: causes a high degree of actual risk from intestinal nematodes and bacterial infections. However, there is little or no risk from viruses. Infectious diseases such as cholera and typhoid fever can be transmitted by irrigation of vegetable crops. Thus, the treatment of wastewater is an effective way of protecting public health; and
- *Irrigation with adequately treated wastewater*: does not cause excess intestinal nematode infection.

The potential risk group includes crop consumers, field workers, especially those working bare foot, cattle, grazing on infested fields or watercourses, and people living near fields irrigated with raw wastewater. Many infectious diseases, for example cholera and typhoid fever, can be transmitted to consumers of vegetables grown on untreated wastewater. Hence, it is essential to protect public health from adverse health effects of wastewater irrigation.

Basis for Guidelines

A meeting of edipemiologists, social scientists and sanitary engineers from around the world was convened by the World Bank, World Health Organization and International Reference Centre for Waste Disposal at Engelberg, Switzerland, in 1985. The meeting reviewed the most recent epidemiological evidence on wastewater use and public health effects and made a set of recommendations called Engelberg Report. The Engelberg Report later became the basis for WHO's Guidelines for the safe use of wastewater (and excreta) in agriculture and aquaculture. A synthesis of WHO guidelines and associated implementation issues is presented below

WHO Health Guidelines

In order to prevent the transmission of communicable diseases while optimizing resource conservation and recycling, the World Health Organization (1989) made the following recommendations for the microbiological quality of treated

wastewater used crop irrigation:

- *Restricted irrigation*: no more than one viable human intestinal nematode egg per liter;
- *Unrestricted irrigation*: above criteria, plus no more than one thousand faecal coliform bacteria per hundred milliliter.

Restricted irrigation refers to the irrigation of crops not intended for direct human consumption, and thus covers the irrigation of industrial crops (e.g. cotton, sisal, and sunflower), crops processed prior to consumption (e.g. wheat, barley, oats), -Category A Crops- and fruit trees, fodder crops and pastures -Category B Crops.

Unrestricted irrigation, on the other hand, refers to all crops grown for direct human consumption, including those eaten raw (e.g. lettuce, salads, cucumber etc.) and irrigation of sports fields and public parks -Category C Crops.

The human intestinal nematodes include: the human roundworm (*Ascaris lumbricoides*); the human hookworm (*Ancliyostoma duodenale* and *Necator americanus*); and the human whipworms (*Trichuris trichiura*)(Mara 2000).

Thus, even if WHO's standard is not met it may still be possible to grow restricted crops without exposing consumers to risk. However, crop restrictions provide protection to consumers only and not to farm workers and their families. Thus, WHO (1989) recommended that crop restrictions need to be complemented with other measures such as human exposure control, appropriate treatment of wastewater and controlled wastewater application.

Human exposure control can be achieved through continuous use of footwear, immunization programmes, and high level of worker hygiene. Simple wastewater treatment technologies such as waste stabilization ponds, discussed above, can be used to produce effluent complying with WHO's Guidelines.

Human exposure control can also be achieved through selection of appropriate irrigation techniques. Among the water application techniques, flooding is the most commonly used irrigation method, especially in Pakistan, as it is low cost. However, wastewater irrigation using flooding poses the greatest health risk to field workers and laborers. Subsurface irrigation, on the other hand, is most efficient in terms of water use efficiency and health protection though it is expensive, clogging of the emitters may create additional difficulties, and requires worker training. Thus, a change in the irrigation method may be an important step towards reducing human health risk in Pakistan where current practice is flooding.

Assessment of WHO Health Guidelines

Microbiological Assessment: In order to assess the validity of WHO guidelines for restricted and unrestricted irrigation, Blumenthal *et. al.* (1996) report findings

of epidemiological studies in Mexico, Brazil, and Leeds. The Mexico case study assesses the effect of restricted irrigation with: (1) raw wastewater; and (2) with semi-treated wastewater of guideline compliance quality on the health of farm workers and their families. Farm workers and their families who engage only in rain-fed agriculture serve as the control group. Consumer risk is assessed from the consumption of wild greens harvested from wastewater irrigated fields and eaten uncooked. Findings of Mexico study show that:

- exposure to raw wastewater is associated with an increased prevalence of human round worm (*Ascaris*) infection in all age groups, particularly in children of farm workers
- exposure to semi-treated wastewater had a low prevalence of human round worm infections in adults but children still have high prevalence of infection.
- There is no excess risk to adults, but there is excess risk in children from the consumption of uncooked wild greens.

Wastewater irrigation poses various forms of excess health risk for kids there by raising equity and human capital formation issues.

Microbiological studies of consumer risks from contamination of vegetables irrigated with wastewater in Brazil (Blumenthal *et. al.* 1996) show that when lettuce is spray irrigated for five weeks with:

- raw sewage (with >100 nematode eggs/l), about 50 eggs/plant are found;
- anaerobic waste stabilization ponds effluents (with >10 eggs/l), about 0.5 egg/plant are found; and
- facultative ponds effluent (with 0.4 eggs/l), zero egg found on the plants.

However, none of the eggs is fully developed to cause infection in the consumers even if lettuce is eaten raw shortly after harvest.

In a glasshouse experiment, microbiological studies of consumer risks from contamination of vegetables irrigated with wastewater in Leeds (Blumenthal *et. al.* 1996) show that when lettuce is spray irrigated for five weeks with contaminated wastewater containing:

- 50 nematode eggs/l, about 1 or 2 eggs/plant is found;
- 10 eggs/l, about 1 less eggs/plant is found;
- ≤ 1 nematode eggs/l, 0.1 to 0.3 eggs/plant is found at harvest.

As none of the eggs isolated from the lettuce is embryonated, no infection is found in immunosuppressed chicks after eating contaminated lettuce. However, the lettuce containing less than three embryonated eggs causes round worm (*Ascaridia*) infection in chickens. This confirms that transmission of nematode infection is possible when eggs are embryonated.

The findings of Mexico, Brazil, and Leeds studies show that WHO's Guidelines of no more than one human intestinal egg per liter protect crop consumers but not necessarily field workers and their families, especially children. The implications of this finding are that farm worker and their families may be exposed to risk if wastewater systems are not reliable, sewage overflow causes recontamination of treated wastewater, and wild vegetables are harvested and consumed raw. This is a typical of the situation of Faisalabad, Pakistan where animal grazing on wastewater irrigated properties and water courses, wildlife hunting and raw crop consumption is common. In these circumstances, promulgation of stricter nematode guidelines may be prudent though it may entail very high, and thus debatable, compliance costs.

Blumental *et. al.* suggest that:

- (1) a monitoring requirement need to be added to WHO (1989) Guidelines;
- (2) guidelines be modified to ≤ 0.5 eggs per liter to prevent nematode infection; and
- (3) $\leq 10^4$ faecal coliform per 100 ml standard for wastewater reuse be considered to prevent bacterial and viral infections.

The epidemiological evidence developed by Blumental *et. al.* makes WHO, 1989 guidelines debatable. Presently, researchers are divided between two schools on the question of appropriate level of nematode and faecal coliform levels in wastewater to be used for irrigation. The two schools of thought are: less stringent epidemiological evidence school lead by WHO, and the "no risk school" lead by the US.

The no risk philosophy can not be adopted by many countries, especially developing countries, who badly require wastewater for irrigation (Marecos do Monte. *et. al.*, 1996) but can not find financial resources for expensive treatment systems. Under the no risk scenario, the only options left for these countries would be either no wastewater reuse or wastewater reuse (illegal) without any regard for the tough (and thus impractical) guidelines.

Financial Assessment:

WHO microbial guidelines for wastewater irrigation of vegetables eaten raw recommend no more than 1000 faecal coliforms per 100 ml and less than one

helminthi eggs per liter of wastewater. USEPA/USAID Guidelines(1992) are more stringent than WHO guidelines. The USEPA Guidelines require no detectable faecal coliform per 100 ml alongwith other regulatory and operational requirements. Thus, the US EPA considers that an annual risk of 10^{-4} is acceptable for microbial contamination of drinking water.

Shuval *et. al* (1997) developed a risk assessment approach to conduct a comparative risk analysis in order to evaluate the financial feasibility of WHO and USEPA microbial health guidelines. Their cost estimate for the two scenarios of wastewater treatment (WHO standards and USEPA standards) show that meeting the USEPA Guidelines would require an extra expenditure of US\$3-30 millions per case of disease prevented. This a major additional cost as the technology required to treat the wastewater to rigorous USEPA standards is very expensive. The authors question if the additional treatment expenditure is justifiable especially when the risk of contacting the disease is already negligible.

On the other hand, WHO guidelines can be achieved using low cost, efficient land based treatment systems such as waste stablization ponds which can achieve consistently reliable and very high microbial standards. Studies conducted in Morocco show that properly designed and operated waste stablization ponds can achieve 99.99 faecal coliform removal, leave no helminth, and no schistosoma. Thus, for the developing countries, WHO guidelines present a more financially feasible and technologically attainable alternative to USEPA guidelines.

European Guidelines for Wastewater Reuse

Most of the Mediterrian European countries, with the only exception of Germany and France, have not established any guidelines for the use of wastewater for irrigation. Researchers argue that any prospective Euro guidelines must include existing guidelines of France and Germany and experience of other countries with similar level of development. The EU guidelines must cover two large areas:

- agronomic aspects: focusing on soil and ground water protection and yield maximization; and
- the sanitary aspects: related to public health protection.

Thus, the inclusion of microbiological criteria is considered very important in the development of European guidelines. Marecos do Monte *et. al.*(1996) lend support to above arguments based on the results of a field study conducted in Portugal. The study calibrated the effects of three type of reclaimed wastewater versus potable water and commercial fertilizers on a group of crops and soil parameters. The three type of wastewater include: primary effluent, secondary effluent, and facultative pond effluent. Thus, three type of wastewater used for irrigation are distinguishable on the basis of chemical and biological parameters.

The findings of this study supports above arguments.

Development of Chemical Guidelines for Wastewater Reuse

The foregoing discussion on WHO guidelines shows that the guidelines focus *only* on microbiological quality of wastewater used for irrigation. Secondly, the main aim of these guidelines is human health protection. They do not make any explicit reference to the chemical quality of wastewater used for irrigation. Perhaps, an implicit assumption is that wastewater treatment processes that can produce effluent of an acceptable microbiological quality automatically reduce the concentrations of toxic chemicals to acceptable levels. However, due to the complex nature of pollutant discharged into the sewage system by modern society, and especially accidental or otherwise release of toxic pollutants into the public sewage net work, this assumption may not necessarily be met.

Chang, *et. al.* 1996 noted that though some countries have developed irrigation water quality criteria based on numerical limits of pollutants, as summarized in Table 5, only few of these criteria were developed specifically for wastewater irrigation. Also, the guidelines and manuals (e.g. Pettygrove and Asano, 1985; US. EPA, 1992 etc.) dealing with reclaimed wastewater reuse for irrigation *do not* adequately address human health and safety issues related to the introduction of toxic pollutants into the ecosystem through wastewater irrigation. Hence, Chang *et. al.* examine a methodology for developing globally applicable human health related chemical guidelines for wastewater irrigation. The two approaches used are:

1. Preventing pollutant accumulation in waste receiving soil, and
2. Maximizing soil's capacity to assimilate, attenuate, and detoxify harmful chemicals.

The first approach generates numerical limits on pollutant loadings in accord with the principle of ecological sustainability though such limits are very stringent and thus difficult to achieve for most communities.

The second approach generates maximum permissible limits on pollutant concentration by taking into account multiple exposure pathways and pollutant transfer rates there of. The researchers use second approach to generate preliminary pollutant limits for inorganic elements and organic compounds for land application of wastewater. The exposure pathway considered is the conventional food chain transfer of pollutants via fruits, vegetables, tuber/root, and grains grown on wastewater affected soils. The authors conclude that:

- In communities with effective industrial wastewater treatment programs, the treated industrial wastewater can be used for crop

production. The only restriction is that amount applied should not exceed crop water requirements;

- In communities with out effective industrial wastewater treatment programs, industrial wastewater use must be restricted because of possible presence of chemical pollutants and their food chain transfers; and
- For all land application of industrial wastewater, best agronomic management practices must be followed.

Table 5. (File to be inserted)

IRRIGATION WATER QUALITY CRITERIA OF SELECTED COUNTRIES

Source: Chang *et. al.* (1996), WST. 33, 10-11, pp.466.

Religious Perspective on Wastewater Irrigation

Islam, the religion of about 96% population of Pakistan and about one fifth of the human race emphasizes cleanliness. Water is the main medium for achieving this cleanliness. According to the teachings of Islam, water becomes unclean as the result of its use by mankind. The pure water (*Tahūr*) may be used for any purpose including religious rituals and ablutions. The water that has been used for ablution or mixes with some impurities becomes inferior in quality (*Tāhir*) although it is still clean, and it, therefore, can be used for any general purposes, such as drinking, cooking, washing etc., except for ablution. However, the water that has changed its natural properties such as color, odor, and taste significantly as the result of mixing of pollutants or human use, say for personal cleanliness etc., becomes unclean (*mutanajjis*), that is wastewater, can not be used for 'any religious mundane purpose' *as such* but may still be used for crop irrigation which involves no washing (Farooq and Ansari, 1983).

The Organization of Eminent Scholars of Saudi Arabia considered the question of treated wastewater reuse and issued a religious ruling (*Fatwa*) in the Daily Newspaper, *Al-Madina*, Jeddah, on 17 April, 1979. According to this religious ruling:

treated wastewater may be used by people even for ritual washings.

The Organization mentioned that wastewater can regain its original characteristics if:

- wastewater itself causes unclean characteristics to disappear (sedimentation)
- wastewater is mixed with large quantity of clean water (dilution)
- impurities disappear with the passage of time, or by the effect of sun or winds etc.

Thus, an esteemed body of Muslim scholars, the Organization of Eminent Scholars of Saudi Arabia has unanimously expressed its approval for the reuse of wastewater effluents for all purposes even for religious washings (Farooq and Ansari, 1983, Ali, 1987, Mara, 2000).

Thus, the use of wastewater for crop irrigation is perfectly legitimate from the Islamic religious perspective. Any wastewater irrigation proposal should, therefore, be evaluated on a case by case basis in regard to health concerns, cost structure, and public acceptance.

The Way Forward

The modern wastewater treatment technology capable of producing high quality 'no risk' effluents is unaffordably expensive for the developing countries. However, land based or aquatic natural treatment systems are capable of producing effluent of an 'acceptable risk' quality and more importantly, they are low cost and well suited to the climatic conditions of most developing countries. Hence, from the perspective of developing countries, a rational middle of the road approach for wastewater reuse standards is more appropriate. Wastewater reuse schemes can be evaluated on a case by case basis with due regard for human health, opportunity cost, and environmental concerns. For example, a permit system could be used with each applicant seeking permission to use the wastewater for a specific use on a specific farm for a certain period of time. If the wastewater use permit is, say, for the production of cereal crops, normally processed before consumption, in a zone of minimum human exposure, water of restricted crop irrigation standards, or even lower quality, may be allowed. On the other hand, in cases where crops grown are eaten raw or there is substantial human exposure, treated wastewater of a more stringent quality, say secondary treated and chlorinated, may be permitted for use only. Such middle of the road is superior over other approaches advocating more stringent effluent quality standards as it will assure optimal wastewater reuse, economic efficiency, and risk minimization.

The general conclusion from this section is that: from microbiological, chemical, and religious perspective, treated wastewater may be used for irrigation in Pakistan although appropriate management practices are necessary to minimize any potential risks.

4. WASTEWATER REUSE IN AGRICULTURE

Crop Irrigation Criteria

According to the text-book definition, irrigation is the application of water to the soil for the purpose of supplying moisture to the crop plants for normal growth. When the source of water used for irrigation is wastewater, it is called wastewater irrigation. Like normal irrigation practices, successful wastewater irrigation should be based on criterion such as:

- crop water requirements; both quantitative and qualitative
- appropriate irrigation schedule and method of irrigation
- leaching requirements and drainage potential of the soil
- optimal supply of plant food nutrients, and
- Health, environmental, and social requirements

A detailed discussion of these criteria can be found in appropriate sources.

Ecologically Sustainable Development Criteria

For the purpose of this study, ecologically sustainable development (ESD) criteria is used for evaluating the impacts of wastewater irrigation. This criteria is preferable to conventional economic analysis criteria, as argued by the World Bank (Pezy, 1992 and Munasinghe, 1993),² as it allows the assessment of holistic impacts against a common yardstick in a dynamic framework. The EDS criteria consist of four sub-criteria viz:

- Improved valuation, resource pricing, and incentive mechanism (\$\$)
- Intergenerational and intragenerational equity (❖❖)
- Conservation of biological diversity and ecological integrity (♣♣)
- Precautionary principle (∅).

A negative sign with one of the four symbols indicates negative effect for the relevant criteria and vice versa. Where as NA means not assessed and represents a situation where a clear opinion can not be established by the authors.

These criteria have been used to evaluate the effects of wastewater irrigation on crops in next section. These criteria are based on indicators of ecologically sustainable development as given below. However, it is important to emphasize

² A similar criteria has recently been used by Sydney Water (Australia) for the development and evaluation of its 'Draft 2000-2005 Environment Plan'.

that the ESD assessment is based solely on the impressions gained by the authors through the review of the study and does not, in any way, imply a value judgment on the quality of the study in questions, its contents or findings. The ESD assessment are strictly the opinion of the authors. Hence, the ESD evaluation should be used with caution.

Ecologically Sustainable Development Indicators

For the purpose of EDS assessment of ‘effects on crops’, following indicators have been used:

Health effects

Coliform and helminth concentrations

Effect on yield

Effect on nutritional value

Water and nutrient recycling

Effect on soil properties

Effect on soil nutrient content

Effect on trace elements and heavy metals content

Effect on soil salinity and sodicity

Effect on soil aeration, structure, permeability and drainage

Effect on groundwater resources (short and long term)

Eutrophication potential

Pathogenic transfer to groundwater

Effect on wildlife

Effect on natural resources

Economic value

Marketability

Economic efficiency

5. PUBLIC HEALTH EFFECTS OF WASTEWATER IRRIGATION

Wastewater contains three kinds of pathogenic microbes which are of concern for their effects on public health. These wastewater pathogens include: bacteria, viruses, and parasites such as protozoa and helminths. A list of pathogens present in raw domestic sewage and diseases caused is given in Table 6. The pathogenic organisms, present in the wastewater, have the *potential* to cause the disease. About 30 wastewater (and excreta) related diseases are of public health importance and many of these are of specific importance in wastewater reuse schemes (WHO, 1989). A review of public health effects of wastewater reuse is presented below.

TABLE 6. Examples of Pathogens Present in Raw Domestic Sewage and Diseases Caused

Pathogen category	Examples	Disease caused
Bacteria	<i>Shigella sp.</i>	–Bacillary dysentery
	<i>Salmonella sp.</i>	–Salmonellosis (gastroenteritis)
	<i>Salmonella typhi</i>	–Typhoid fever
	<i>Vibrio cholerae</i>	–Cholera
(enteropathogenic)	<i>Escherichia coli</i>	–a variety of gastroenteric diseases
	<i>Yersinia sp.</i>	–Yersiniosis (gastroenteritis)
	<i>Campylobacter jejuni</i>	–Campylobacteriosis (gastroenteritis)
Viruses	Hepatitis A virus	–Infectious hepatitis
	Norwalk viruses	–Acute gastroenteritis
	Rotaviruses	–Acute gastroenteritis
	Polioviruses	–Polio
	Coxsackie virus	–‘flue-like’ symptoms
	Echoviruses	–‘flue-like’ symptoms
Protozoa	<i>Antamoeba histolytica</i>	–Amebiasis (amoebic dysentery)
	<i>Giardia lamblia</i>	–Gardiasis (gastroenteritis)
	<i>Cryptosporidium sp.</i>	–Crypodosporidiosis (gastroenteritis)
	<i>Balantidium coli</i>	–Balantidiasis (gastroenteritis)
Helminth	<i>Ascaris sp.</i>	–Roundworm infection
	<i>Taenia sp.</i>	–Tapeworm infection
	<i>Necator americanus</i>	–Hookworm infection
	<i>Trichuris trichuria</i>	–Whipworm infection

Source: NRC, 1996. p. 90.

Review of Public Health Effects

There is an extensive amount of literature available on the public health effects of wastewater reuse. An exhaustive review of this literature is certainly not the subject of this report, however, a selected number of recent studies are reviewed here because public health effects of wastewater reuse have strong socio-economic and environmental dimensions.

A more detailed and comprehensive review of epidemiological studies on disease transmission associated with wastewater reuse can be found in other sources such as Shuval *et. al.* (1986) and Shuval (1990). This review concludes that only untreated wastewater has been implicated in the transmission of infectious diseases. Even in countries advocating zero risk approach, the available epidemiological evidence suggests that: except for the use of raw sewage for crop production, there have not been any documented cases of infectious disease caused by reclaimed wastewater use in the US (USEPA, 1992). However, recent investigations on public health effects of wastewater reuse, especially in Middle East and Mexico, portray a different picture as is evident from our review below.

Table: Empirical Evidence Of Public Health Effects Of Wastewater Reuse

<i>Year and Author(S)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Implications</i>
Shuval <i>et. al.</i> 1986	A comprehensive review of credible epidemiological studies on wastewater irrigation.	Health risk assessment model and Empirical evidence	<ul style="list-style-type: none"> •Pathogenic microbes in high to low disease risk order are: helminths, bacteria, and virus •epidemiological evidence suggests that very stringent wastewater irrigation standards are overly restrictive 	<ul style="list-style-type: none"> •proposed guidelines for unrestricted wastewater irrigation viz: 1 nematode egg/l and 1000 coliform per 100 ml. •basis for WHO health guidelines
Borsnan and O'Shea 1996	Impact of cumulative abatement of untreated wastewater discharges on coliform concentrations (concs.) in lower Hudson-Raritan Estuary	Water sampling and analysis to monitor concentrations of total coliforms and fecal coliforms	<ul style="list-style-type: none"> •Decline in coliform concs. as the result of abatement in wastewater discharges •Major stimulus: Clean Water Act •Affected through: infrastructure provision and improvements such as: construction, upgrading, increased surveillance, and maintenance of wastewater distribution system •abatement of illegal connections, wet weather overflows, and reduced discharge 	<ul style="list-style-type: none"> • Water quality improvements to swim-able levels •Enhanced recreational resource value •Cost savings on bathing advisories
Olivieri <i>et. al.</i> 1996	Assessment of potential health risk associated with potable use of advanced treated wastewater	Indicator organisms, and chemical risk assessment of raw water supply vs. reclaimed water Baseline epidemiological data on reproductive health and neural tube defects	<ul style="list-style-type: none"> •Secondary treatment using water hyacinths plus advanced treatment generates reclaimed water of acceptable potable quality •Health risk associated with the •Potable use of reclaimed water is < existing water supply in San Diego. 	<ul style="list-style-type: none"> •Water Hyacinths systems as treatment alternative •Community attitude to potable reuse? •Financial and economic feasibility

<i>Year and Author(S)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Implications</i>
Downs <i>et. al.</i> 1999	Risk screening from exposure to contaminated surface water and ground water due to untreated wastewater irrigation in Mexico	Risk assessment based on detection of pathogens, ingestion, and morbidity patterns.	<ul style="list-style-type: none"> •high total coliforms in surface water and lower levels in ground water •faecal contamination of water resources as a potential risk of gastrointestinal disease •frequent diarrhoea and skin irritation reported •infants and children at risk from nitrate pollution •risk exists outside and inside irrigation district 	<ul style="list-style-type: none"> •Pathogenic risk intervention should be a priority •Nitrate pollution risk determination and possible treatment
Cifuentes <i>et al.</i> 2000	Risk factor affecting giardia infections in agri. population in Mexico	Households exposed to untreated wastewater vs. rain fed agri. villages	<ul style="list-style-type: none"> •Children have highest prevalence of infection •Risk of infection correlated to unprotected drinking water and lack of faeces disposal facilities •Untreated wastewater exposure has no excess risk •No risk from agri. activities 	<ul style="list-style-type: none"> •Provision of Primary health care and <ul style="list-style-type: none"> • w/water treatment facilities •Equity and human capital formation issues
Habbari <i>et.al.</i> 2000	Transmission of geohelminthic infections among (primary school) children due to raw wastewater irrigation in Morocco	Disease prevalence rate in kids in communities with raw wastewater irrigation vs. no raw wastewater irrigation Role of defensive behaviours and demographic factors	<ul style="list-style-type: none"> •Ascariasis prevalence five times higher in wastewater-impacted regions •Contact with wastewater and wastewater irrigated land and public water supply associated with higher infection rates •Trichuris infection rate did not vary •Raw wastewater use in Beni-Mallal can lead to a high risk of geohelminthic infections 	<ul style="list-style-type: none"> • Adequate treatment of wastewater for irrigation •Water supply and sanitation program •Exposure control •Public health education program

Assessment of Public Health Effects

Above synthesis shows that untreated wastewater is not safe for crop irrigation while adequately treated wastewater can be safely used for crop irrigation, that is, without any major public health concerns. However, a strategic management approach is inevitable for the success of any wastewater irrigation program and risk minimization.

Is potable reuse an option? Among alternate uses, the extreme possible candidate for treated wastewater may be the potable use to mitigate drinking water shortages. A tremendous research effort involving experts across the disciplines indicated that not only systems exist to treat wastewater to an equal or even better quality than existing potable water supply but health risk from any future potable use is not different than existing health risk (Olivieri *et. al.*, 1996). However, any future potable reuse will depend upon the attitude of (San Diego) community which in turn may be influenced by degree scarcity.

Simpson (1999) reports that strong water scarcity driven community based initiatives exist for potable reuse of wastewater in south east Queensland, Australia. Indeed, the potable reuse in Queensland is largely a community driven process, with ever increasing support, which has prompted the local government to devise a potable reuse policy. Infact, community is willing to consider potable reuse if treatment system reliability can be demonstrated (State government can benefit from San Diego health effects study for this purpose). The state government is considering a strategic approach for possible implementation of 'potable reuse' in near future. To this end, a community awareness and education program is already underway.

In the context of public health effects of wastewater reuse, it is pertinent to note that arguments have appeared in the literature about the *actual* virulence of coliform bacteria. Studies on determinants of diarrhoeal disease in infantile (VanDerslice and Briscoe, 1993) show that for an equivalent increase in fecal coliforms, contamination of water sources, not in-house potable water, poses the greatest risk of diarrhoea because family members are likely to develop immunity to pathogens commonly found in the household. Investigations on determinants of diarrheal disease in Jakarta by Alberini *et. al.* (1996) also lend support to the findings of Vanderslice and Briscoe that: pathogens are less virulent if they originate from within the household (though defensive behaviour may be an important determinant of disease). This implies that adequate protection of natural water resources from wastewater contamination is vital than affecting subsequent potable water storage improvements.

Conclusions

Based on the above discussion, we can conclude that:

- Pathogenic organisms are inherent to domestic sewage;
- the pathogens have the potential to cause the diseases in human beings and animals;
- The use of wastewater effluent must accompany management strategies to protect public health; and
- The main focus of the management strategy, discussed later, should be to reduce the concentrations of pathogens to acceptable levels through adequate treatment, crop restrictions, and grazing restrictions, and human exposure control etc.

6. EFFECTS OF WASTEWATER IRRIGATION ON CROPS, SOIL, GROUNDWATER, AND ENVIRONMENTAL RESOURCES

Wastewater usually contains undesirable constituents such as salts, trace elements and heavy metals, organic compounds, and pathogens. Such constituents *may* have deleterious effects on public health, crops, soils, groundwater, property values, and the environment. The effects of wastewater irrigation for each of these categories, except health effects, already described in detail, are discussed below.

It is pertinent to note that the effects of wastewater irrigation on health, crops, soil, water resources, environment and ecosystem can translate into socio-economic impacts as they ultimately affect human life support systems. Again, often the fine line between these impacts as being classified into social, economic, or environmental impacts does not exist as they are mutually inclusive. Hence, the so called socio-economic and environmental classification is only for convenience purposes as the life support systems tend to be holistic and not discrete.

Effects on Crops

The use of treated municipal wastewater provides an alternative to land based disposal of municipal wastewater. It also enables the recycling of nutrients for biomass production. Treated wastewater can provide (1) plant food nutrients, and (2) and all water needed for crop requirements. Normally, wastewater is a rich source of nutrients. Nevertheless, plant food nutrients in wastewater are available in proportions that may not be suitable for *direct* crop production and these proportions can not be manipulated, like chemical fertilizers, to suit crop nutrient requirements. Often, satisfying one nutrient requirement may imbalance the other nutrient level, either below or above the desirable level, there by necessitating careful agronomic management of wastewater as a resource. The nutrient deficiency or oversupply may cause toxicity and adverse effects on crop yield. Also, some trace elements and organo compounds, present in wastewater, are phototoxic to plants if applied above the maximum permissible limits, e.g. Boron, used in detergents, is highly toxic to some plants.

The effects of wastewater irrigation may differ widely for different crops. Crop scientists have attempted to identify and quantify the effects of wastewater irrigation on crop yield and quality parameters. Some of recent studies focusing on the effects of wastewater irrigation on crop production are reviewed below (some back date studies have also been included because of their empirical content).

Table: Empirical Evidence Of Effects Of Wastewater Irrigation On Crops

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Day <i>et. al.</i> 1975	Effect of treated municipal wastewater irrigation on wheat growth, yield and quality parameters	Well water+ normal NPK dose vs. well water+ simulated NPK dose vs. treated wastewater , no fertilizer	Wastewater irrigation leads to: °Higher wheat grain yields °Higher protein content in grains ° No change in total fibre content and thus feed quality °Wastewater supplied more PFN than control thus giving more tillers and higher yield and protein content.	Treated w/w: a potential source of irrigation water plus a rich source of fertilizer •Fertilizer cost savings Higher potential yields	+ve\$\$\$ +ve❖❖ NA♣♣ +ve∅
Mortvedt and Giordano 1975	Effect of Zn and Cr contamination (high in tannery wastewater) on maize crop	Soil application of high Zn and Cr municipal wastes Successive maize crop vs. control	°Higher corn forage yields (in general) °Zn available to maize °Lower Zn concentrations and no change in Cr conc. in maize tops °Cr uptake but no effect on crop growth	•Irrigation with tannery wastewater under careful management may be possible	+ve\$\$\$ -ve❖❖ +ve♣♣ +ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Sidle <i>et. al</i> 1976	Uptake of heavy metals by reed canarygrass and maize over time	Wastewater irrigation for 11 years Base year as control	<ul style="list-style-type: none"> °Higher Cu and Zn conc. and total uptake in reed canarygrass °Lower Cu and Zn conc. and total uptake in Maize than reed canarygrass °Highest heavy metal accumulation in soil sown r-grass (low removal rate) °Plant conc. of Cu and Zn do not pose hazard to food chain °Heavy metal removal through crop plant uptake 	<ul style="list-style-type: none"> •Animal feed program (Cu level in w/w irrigated r-grass may be a problem for sheep feed) •Loadings+ removal @ modelling to evaluate life of a land disposal sys. 	<ul style="list-style-type: none"> +ve\$\$\$ -ve❖❖ -ve♣♣ -ve∅
Day and Tucker 1976	Effect of treated municipal wastewater irrigation on sorghum growth, yield and quality parameters	Well water+ normal NPK dose vs. well water+ simulated NPK dose vs. treated wastewater , no fertilizer	<p>Wastewater irrigation lead to:</p> <ul style="list-style-type: none"> °Higher leaf length (more forage) and maturity period (low cropping intensity) °Higher sorghum grain yields °Similar protein content, but ° Less amino acid content in grains °Wastewater ‘has something in addition to fertilizer elements’ that simulated grain production thus more giving higher yield than control(s) 	<ul style="list-style-type: none"> •Treated w/w: a potential source of irrigation water plus a rich source of fertilizer •Fertilizer cost savings •Higher potential yields 	<ul style="list-style-type: none"> +ve\$\$\$ +ve❖❖ NA♣♣ +ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Bole and Bell 1978	Suitability of five forage species for optimal utilization of municipal wastewater irrigation system for forage production	Lagoon treated municipal wastewater Relative growth and nutrient utilization Efficiency of: alfalfa, reed canarygrass, bromegrass, wildrye, and tall wheatgrass	<ul style="list-style-type: none"> °Higher alfalfa yields than other grass sp. °Double N-yield of alfalfa °N uptake by all grass, except wheatgrass, exceeds w/w N supply °P supply in w/w exceeds plant uptake ° For optimal utilization of wastewater, alfalfa is most suitable forage crop (max. N and water uptake). Alfalfa can optimise w/w utilization as it has its own N supply system (nodules) °For optimal wastewater disposal, reed canarygrass is more suitable as it can remove most nutrients and withstand flooding 	<ul style="list-style-type: none"> •w/w supplied enough P but not N for forage production • A system of forage sp. such as alfalfa and reed canary-grass may be designed for optimal utilization and disposal of w/water 	<ul style="list-style-type: none"> +ve\$\$ +ve❖❖ -ve♣♣ +ve∅

Year and Author(s)	Main Objective	Methodology	Major Findings	Conclusions/Implications	ESD Assessment
Marten <i>et al.</i> 1980	Effect of municipal wastewater irrigation on feed quality and yields of maize vs. reed canarygrass	Parameters: feed quality, dry matter, digestible Drymatter of maize vs. r-grass Two rates (levels) of treated municipal wastewater irrigation	°Maize more digestible than r-grass °Higher dry matter and digestible dry matter yields for maize °Differences <i>decline</i> progressively with higher amounts of w/w applications in maize °Higher crude protein in r-grass, and °Higher crude protein yield per hectare °differences <i>increase</i> progressively with higher amounts of w/w applications in r-grass °In effluent irrigated systems, r-grass can yield more protein per hectare, but least digestible dry matter (desirable).	•Perennial grasses have superior quality than maize to remove w/w nitrogen • A managed r-grass and maize sys. can be used for efficient renovation of w/w effluent	+ve\$\$\$ +ve♦♦♦ -ve♣♣ +ve∅
Ajmal and Khan 1985	Effect of textile factory effluents on soil chemistry, and germination and growth of two vegetables viz kidney beans and lady's finger	– Untreated textile effluent in dilutions of v/v 25, 50, 75, and 100% vs. –Normal irrigation water as control –Effect on kidney beans and lady's finger	°Textile effluent rich in BOD, COD, Cl, SO ₄ , and trace metals such as Ns, K, Ca, Mg and highly alkaline °Higher dilution applications led to higher conc. of these elements in soil with top-soil conc. higher than subsoil °Plant Na increased correspondingly (absorption and translocation) ° Irrigation with 100 and 75% textile effluents inhibited germination, and retarded growth °Irrigation with 50% effluent enhanced growth	•Diluted textile effluent may be used for crops with-out affecting soil quality •Textile effluent as a source of water and nutrients •Industrial policy design	+ve\$\$\$ +ve♦♦♦ NA♣♣ +ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Ali 1987	Risk assessment of reclaimed municipal wastewater for irrigation of food crops such as alfalfa, onions, summer squash	–Sprinkler application of secondary treated + chlorinated w/w –with and without fertilizer treatments –fecal coliform counts on vegs.	°Non detectable fecal coliforms on summer squash after 24 hours of sprinkler irrigation °Nondetectable fecal coliforms on onions after 15 days of irrigation °Secondary treated wastewater + chlorination may be used for vegetable production, normally cooked before consumption °Lower levels of treatment may be enough for crops undergoing processing before consumption	•Scientific evidence for wastewater reuse guidelines for KSA • Middle of the road approach with flexible permit sy. for w/w irrigation	+ve\$\$ +ve❖❖ NA♣♣ +ve∅
Singh and Mishra 1987	Effect of urea plant effluent on soil and germination, growth, dry matter, and pigment contents of corn and rice	– Untreated urea plant effluent in dilutions of v/v 2.5, 5, 10, and 50% vs. Tap water irrigation as control	°Highly alkaline urea plant effluents °Chemical properties of soil adversely affected by effluent conc. of $\geq 10\%$ °Higher growth and protein content of corn and rice with 2.5 and 5% effluent conc. (N absorption and utilization) °Adverse effect on seed germination, dry matter and pigment contents, and yield of both rice and corn for effluent applications with conc. $\geq 10\%$	•Urea factory effluent as a source of liquid fertilizer •Diluted fertilizer industry effluent may be used for crop irrigation •Point source pollution control •Eutrophication control	+ve\$\$ -ve❖❖ -ve♣♣ +ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Misra and Behera 1991	Effect of paper industry effluent on growth, carbohydrates, and protein content of rice	Untreated paper industry effluent Various dilutions vs. distilled water Effect on rice seedlings as a function of effluent con. and exposure time	°Germination %, growth, and pigment, carbohydrate, and protein contents decline with increase in effluent conc. and exposure time °Protein content most sensitive to effluent conc. °Protein and protein enzymes as bioindicators of effluent phytotoxicity °Pulp and paper industry effluent not suitable for irrigation	•Pollution regulation for pulp and paper industry •Evaluation of phytotoxicity and pollution risk •Point source pollution control •Eutrophication control	-ve\$\$\$ -ve❖❖ NA♣♣ -veØ

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Aziz <i>et.al.</i> 1995	Effect of crude oil refinery wastewater irrigation on growth and yield parameters of four varieties of wheat	Treated oil refinery wastewater vs. groundwater as control Same dose of fertilizer Growth p-meters: shoot length, leaf#, fresh and dry weight/plant Yield p-meters: grain yield, protein, and carbohydrate contents	°Treated oil refinery w/w met irrigation standards, hence suitable for crop irrigation °Wastewater irrigated soil show no change in soil properties °Higher growth, protein, carbohydrate, and grain yield with wastewater irrigation °Better crop performance due to availability of additional nutrients in treated w/w °Varied response of wheat cultivars	•Treated wastewater has no adverse effect on soil quality and can be used for crop irrigation •Need for <i>long term impact evaluation</i> •Industrial pollution abatement policy •National food security policy	+ve\$\$ -ve❖❖ -ve♣♣ -ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Howe and Wagner 1996	Effect of papermill wastewater irrigation and gypsum application on growth rates and sodium uptake by Freser cottonwood and soil	Untreated paper industry wastewater with Four gypsum application rates ww 100, 175, 325, 625 mg Cl/l w/w on ww basis Ind. variable: wastewater pH and gypsum application rate Dep. variables for cottonwood: biomass, stem Na, and Ca, K, and Na in leaves	°Biomass production of c-wood affected by gypsum application not pH °Stem biomass dependent on pH °Higher growth of c-wood with gypsum application at lower w/w pH levels °Stem and leave Na conc. affected by gypsum application rate, not w/w pH °Infiltration rate affected by both gypsum application and w/w pH	•Problem: Na accumulation in paper mill effluent irrigated soils; Management action: gypsum application •Role of Ca amendment in sodic w/w irrigation management •Potential long term effects need attention	+ve\$\$ -ve❖❖ -ve♣♣ -ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
El Hamouri 1996	Effect of wastewater irrigation on micro-biological quality of soil and yield and hygienic quality of salt sensitive (cucumber, turnips) and salt tolerant (alfalfa, corn, zukini, beans, tomato) crops	Domestic origin wastewater with: Raw wastewater vs. waste stablization pond treated w/w vs. groundwater 4 irrigation methods (surface, 2 sy. drip, sprinkler) Faecal coliform and helminth eggs on crop and in soil	<p>°WSP treatment produces effluent of WHO's Guidelines quality for unrestricted irrigation</p> <p>°For salt sensitive crops: cucumber yield is worst affected by high salinity; negative yield effect is more for raw w/w and less for treated w/w, thus</p> <p>°High salinity of w/w affects yield negatively</p> <p>°For salt tolerant crops: small differences in yield among w/w types and groundwater, thus</p> <p>°Much lower salinity effect</p> <p>°No helminthi eggs found on treated w/w irrigated crops and soils</p> <p>°Helminthi egg found on raw w/w irrigated crops and soils</p> <p>°Raw wastewater not suitable for irrigation</p> <p>°Drip irrigation gives highest performance and crop yield</p>	<p>•Treated w/w irrigation instead of groundwater for growing salt sensitive crops in arid and saline areas has advantages viz: low salinity effect on growth and yield, low soil and aquifer salinization, fertilizer cost savings</p> <p>•Arid and saline zone development policy</p> <p>•Wastewater treatment technology</p>	<p>+ve\$\$</p> <p>+ve❖❖</p> <p>-ve♣♣</p> <p>+ve∅</p>

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Shahalam <i>et.al.</i> 1998	The suitability of wastewater irrigation for alfalfa, tomato, and radish crops and its effect on soil, and health and groundwater pollution risk	Below WHO standard treated wastewater vs. freshwater With and without fertilizer sub-trt. Effect on crop growth and yields Soil porosity, pH, sodicity and alkalinity, and drainage Faecal coliform conc. on vegs. and environment	°Yield trends: °Alfalfa: freshwater with fert. > w/w with fert. °Radish: w/w use insignificant effect °Tomato: w/w only > w/w with fert °Wastewater irrigation with fertilizer gives yield at least comparable to freshwater with fertilizer °Higher porosity, lower pH with wastewater irrigation °Higher salinity with w/w irrigation though EC value < limit, inconclusive effect in short run °Subsurface drainage analysis: no contaminants °Tomatoes free of FC after 24 hours °Hygienic quality: no odor or aesthetic effects °	•No risk to crops, soil, humans or environment from below Guidelines wastewater irrigation, however chlorination recommended •Wastewater irrigation: a way forward to solve Jordan's water scarcity problem •National water security policy	+ve\$\$\$ +ve❖❖ NA♣♣ +ve∅

<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
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Parameswaran 1999	The agro-economic feasibility of wastewater irrigation for growing Jerusalem artichoke (<i>helianthus tuberosus</i>) in Australia	Furrow irrigation using raw urban wastewater Various cultivars of artichoke Plant biomass-tops and tuber-	54 °Atrichoke needs high levels of fertilizer, available in wastewater °No signs of nutrient deficiency °No visible damage or growth toxicity due to high nutrient content in w/w °Needs 6 ML/h for crop cycle	<ul style="list-style-type: none"> •wastewater as a resource •Artichoke production, an alternative for land disposal of municipal w/w •Artichoke biomass may be used for many products including ethanol 	+ve\$\$\$ +ve❖❖ -ve♣♣ +ve∅
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<i>Year and Author(s)</i>	<i>Main Objective</i>	<i>Methodology</i>	<i>Major Findings</i>	<i>Conclusions/Implications</i>	<i>ESD Assessment</i>
Reboll <i>et. al.</i> 2000	<p>Effect of wastewater irrigation on citrus growth, leaf minerals and yield</p> <p>Note: citrus plants are considered highly sensitive to salinity (Na, and Cl), a characteristic of wastewater and B-toxicity is a risk for vegetative development: thus wastewater irrigation may have determinantal effects on citrus trees</p>	<p>Flood irrigation with w/w from sewage plant (treated) vs. groundwater</p> <p><i>Growth:</i> height, trunk and canopy diameter</p> <p><i>Yield:</i> fruits/ tree</p> <p><i>Fruit quality:</i> fruit weight, diameter, colour, acidity, ripeness index, TSS, and juice, peel, and flesh %</p> <p>Soil N, and Na, Cl, and B</p>	<p>°Plant height and diameter not affected by w/w irrigation</p> <p>°higher canopy dia. with w/w irrigation</p> <p>°higher nutrient content in w/w may cause excessive veg. growth and late ripening</p> <p>°Fruit yield not affected by w/w irrigation</p> <p>°No effect on fruit quality due to higher B content in w/w irrigation</p> <p>°Overall fruit quality not affected by w/w irrigation</p> <p>°No determinantal effects on citrus plants after three years of w/w irrigation</p> <p>°High B content in w/w but no effect on soil B and no B-toxicity in plants</p> <p>°Soil N and Cl content not affected by w/w irrigation</p> <p>°Higher soil Na content due to w/w irrigation (low permeability)</p>	<p>•Reclaimed wastewater a suitable alternative source of water supply for citrus production</p> <p>•Wastewater irrigation for citrus can reduce fertilizer costs</p> <p>•Citrus is an economically important crop in Spain, therefore w/w irrigation has economy wide implications</p>	<p>+ve\$\$\$</p> <p>-ve❖❖</p> <p>-ve♣♣</p> <p>+veØ</p>

Effects on Aquaculture

Like crop production, public health concerns are an impediment for the use of wastewater in aquaculture because fish is normally consumed directly after harvest and any pathogens or heavy metals that may have accumulated in the fish tissues are likely to be ingested by the human beings. Nevertheless, scientific evidence suggests that potential health effects can be avoided if wastewater is adequately treated before use for aquaculture. To the extent wastewater can be substituted for limited freshwater resources for irrigation of fish ponds, it represents a net saving to the farmers.

Another important aspect of wastewater use for aquaculture is the relatively high nutrient content of wastewater. The fish feeding on nutrient rich wastewater will recycle these nutrients and convert them into protein rich food for human consumption. Apart from these economic benefits, the wastewater reuse for aquaculture will reduce the need for other costly disposal systems and thus deliver disposal cost savings to the community. In fact, systems exist, or could be cheaply designed, where by farm, farmhouse, and domestic effluents can be used for aquaculture and crop production in an integrated manner to achieve water use efficiency, optimal resource utilization, cost minimization, and promoting an environment friendly and ecologically sustainable farming system.

Studies conducted in Suez, Egypt (Esa, 1995 and Shereif *et. el.* 1995), show that waste stabilization pond system treated wastewater can be used for growing fish with average yield as high as 5-7 metric tons/ha/yr. This fish is pathogen free, reared without any supplemental feeding, fit for human consumption, marketable, and of equal or better quality than fresh water fish in Egypt. Moreover, the nutrient rich effluent from the fish ponds can in turn be used to grow tree and cultivate crops like barley, maize, beets, and ornamentals etc.

However, farmers need to be very cautious about the sources of wastewater and level of treatment received before using effluent for aquaculture. There is documented evidence (Johnsen, 1998) that substances present in the industrial effluents, such as news print mill effluent, may induce undesirable effects in fish species causing growth inhibition and possible liver damages.

Laposata and Dunson (2000) investigated the effects of secondary treated, chlorinated, and spray-irrigated effluents on temporary pond breeding amphibians, such as wood frogs, Jefferson salamanders, and spotted salamanders. They found that egg hatching and larval survival of all amphibians is lower in waste irrigated ponds than in natural water ponds. Thus, wastewater irrigation may have determinantal impact on temporary pond breeding amphibians by reducing their egg and larvae survival, and hence recruitment, in irrigated ponds. However, another study on Jefferson salamanders, under terrestrial irrigated conditions,

show that spray irrigation of games land with treated wastewater effluent is not toxic to salamanders (Laposata and Dunson, 2000b). Actually, salamanders do not differentiate between wastewater irrigated or non-irrigated soil. While long term adverse impacts can not be ruled out, a holistic impact assessment of wastewater spray irrigation on salamanders is warranted. Effects of wastewater irrigation on birds and mammals have also been documented in the literature but they are not the subject of this report.

Effects on Soils

The potential limitation to wastewater irrigation is the high nutrient content (N and P) and high total dissolved salts content though other constituents, such as trace elements or heavy metals, may also be a limiting factor in some situations. The key limitations to the sustainable wastewater irrigation, therefore, are: effects of soil salinity and sodicity on current and future land use and excessive nitrate leaching to groundwater (Bond, 1998).

As domestic wastewater is a rich source of total dissolved salts, effluent irrigation may add large amounts of salts to the soil over time. With the evapotranspiration loss of water, salts may accumulate in the root zone with potential harmful effects on the crop plants. Excessive concentrations of salts, naturally found in wastewater, may, therefore, alter water balance in the soil and thus cause soil salinity. The leaching of these salts from the root zone is essential to solve salt accumulation problem, but leaching brings another problem: groundwater pollution (discussed later).

Wastewater also contains high concentrations of Na ions which interact with saline salts to increase exchangeable sodium percentage in the soil which in turn breaks down soil structure. The breakdown of soil structure implies blocking of pores, low soil aeration, low soil permeability, low leaching, and poor drainage. A prolonged use of saline and sodium rich wastewater has the potential to erode the soil structure, and hence productivity, permanently thereby making the land use unsustainable in the long run.

The problem of soil sodicity can be solved by the application of natural (green manure) or artificial soil amendments (gypsum application) but these soil reclamation measures have a cost. Moreover, gypsum application may not be able to solve subsoil impermeability problems. Hence, wastewater irrigation warrants careful agronomic management.

The existing literature identifies three types of impacts of wastewater induced salinity on crops viz: general growth suppression (pre-early seedling), growth suppression due to nutritional imbalance, and growth suppression due to toxic ions (Kijne *et. al.*, 1998). Some of these effects have already been reviewed under

‘effects on crops’.

It is evident that wastewater irrigation may bring twin problems of soil salinity and sodicity. The saline content of the wastewater is of special concern in hot arid and dry climates such as Middle East. As the removal of sewage salts is very expensive, governments in this region are considering new initiatives (described earlier) and technological solutions to address the salinity problem caused by salt enrichment of sewage (Baruch et. al. 1996)

Wastewater irrigation may lead to transport of heavy metal to the fertile soils and cause crop contamination and effect soil flora and fauna. However, certain soil fauna such as earthworms can ameliorate heavy metal content of the soil by bioaccumulation and redistribution. Earthworms are known for their role in improving the soil structure, improving soil aeration, and enhancing water permeability and providing food for many organisms. More importantly, earthworms function as ‘environmental sinks’ since they can bioaccumulate certain heavy metals, such as cadmium, that may be added to the soil through wastewater irrigation. For example, cadmium concentrations in earthworms tissues from wastewater and sludge applied soil are found to be nine times greater than in those from normal fertilizer applied fields. Copper concentrations are slightly higher but zinc concentrations varied insignificantly (Kruse and Barrett, 1985). This study highlights that earthworms can be used as bioindicators of the effect of wastewater and sludge use on the dynamics of natural ecological systems.

Arguments have appeared in the literature about the toxic metal accumulation from the long term agricultural use of sewage and wastewater. McBride (1995), in a critical evaluation of the USEPA heavy metal guidelines, argues that field observations over several decades show that sludge (and possibly wastewater) applied heavy metals can be available in sufficient concentrations so as to harm sensitive plants and soil microorganisms with possible loss of soil productivity in the long run.

Studies conducted in Mexico (Assadin *et. al.*, 1998), where wastewater mixed with river water has been used for crop irrigation for decades, indicate that polluted water irrigation may account for upto 31% of soil surface metal accumulation. Nevertheless, heavy metals (Cd, Pb, Ni, Zn, Cr, and Co) concentration in alfalfa grown on these contaminated soils were about five times less than the soil concentrations (thus soil bioaccumulation is obvious). However, heavy metal concentrations in alfalfa posed no risk to animals or public health. Their key finding is that: the blending of wastewater with river water have diluted heavy metals to low concentrations for crop irrigation but not to more stringent levels acceptable for fish and wildlife use.

In a related study, Assadian *et. al.* (1999) found that pecan orchard tissues show

no signs of heavy metal accumulation though suboptimal growth is noted. Authors argue that stunted growth and tree mortality in pecan orchard may be due to (Na) salt accumulation (causing low permeability) in the soil rather than heavy metal accumulation. Thus, it is suggested that salts, such as sodium salts, rather than heavy metals may be an important contaminant of effluent irrigation in Mexico region. It implies that wastewater mixed with river water may be used for crop irrigation under a careful water and soil management plan.

Soil properties may be a strong determinant of the impact of wastewater on the soil itself and its ability to support crop production. For example, soils with limitations, such as shallow depth and restrictive layers, are very efficient in the renovation domestic wastewater. Monnett *et. al* (1996) found that spray irrigation of secondary treated domestic effluent on such marginal soils poses no risk of nitrogen leaching to surface and subsurface water quality and plant nitrogen uptake is optimal during the entire growth period. Moreover, effluent irrigation has minimal effect on soil nitrogen and phosphorous content.

Similarly, plant characteristics may be important in determining the impact of wastewater irrigation. For example, spray irrigation of a mature Appalachian hardwood forest, at highest irrigation rate, proved to be an effective mean of bioremediation and nitrogen removal that would otherwise have leached to subsoil (Kim and Burger, 1997). Wastewater irrigation also lead to a decrease in forest litter nitrogen due to enhanced decomposition activity.

The source of wastewater used for irrigation may be another determinant of impacts. For example, the impacts on soil flora and fauna from the use of domestic, industrial, commercial, and dairy farm effluent are likely to differ widely. Studies conducted in New Zealand suggest that use of dairy factory effluent for irrigation, for 22 years, influences storage and distribution of soil carbon, nitrogen and phosphorous. The high carbon contents of the irrigation effluent affect redistribution of soil carbon, diverted activities of soil microorganisms and earthworm fauna which in turn affect the decomposition and decay of soil organic matter. Nearly all applied P is stored in the soil while nitrogen storage is minimal there by implying nitrogen leaching and consequent nitrate pollution of the groundwater (Degens, 2000).

Though technical difficulties exit in the isolation and quantification of wastewater induced salinity and its impacts, it is desirable to focus on the regional management of saline effluents and provide farmers with necessary information on hazards of (wastewater) irrigation induced salinity and sodicity. The actions of individual farmer, though important, are unlikely to avert the problem. A range of management interventions may be necessary to break the web of techno-economic, social, and political factors affecting soil salinity (Kijne *et. al*, 1998).

Effects on Groundwater

As noted earlier, the presence of salt and nitrate rich water in the plant root zone is a natural consequence of wastewater irrigation and these salts and nitrates have the potential to affect groundwater quality through leaching. Nevertheless, the actual impact is contingent upon a host of factors including depth of water table, quality of groundwater, soil permeability, size of effluent irrigated area etc....

The depth of water table may, in conjunction with other factors, determine the time duration required for the wastewater salts, nitrates and other contaminants to reach the water table. In areas with shallow water table, such as Faisalabad, Pakistan, the effects of wastewater irrigation on groundwater quality are likely to be higher, but not necessarily determinantal, than areas with deep water tables.

The quality of groundwater, before the effluent irrigation, will determine whether or not the leaching of salts and nitrates may have any harmful impacts. For example, if the salt content of the ground water is already high, which is unfortunately the case in some areas of Faisalabad, the leaching of these contaminants may be of concern. Similarly, if the ground water constitutes a major source of potable water uses, the nitrate contamination of groundwater must be viewed as a source of concern.

The proximity of wastewater irrigation sites to sources of potable water supplies, such as wells or tubewells, may impact the severity of groundwater related effects. Though wells rarely exist in Faisalabad now a days, as their role has been taken over by hand pumps over time, groundwater still constitutes a major source of potable water supplies for most communities (due to rationing or non-availability of municipal drinking water). Hence, the potential of groundwater contamination need to be evaluated carefully before embarking upon a major wastewater irrigation programme in Faisalabad region. The cautious approach is particularly important in view of the fact that groundwater pollution problem take very long time to express itself and more importantly a high degree of potable water pollution already exists in most areas of Faisalbad ([Hanjra and Hanjra, 1994](#)).

In addition to the accretion of salts and nitrates to groundwater, wastewater irrigation, under certain conditions, has the potential to translocate pathogenic bacteria and viruses to ground water (NRC, 1996) with possible health effects as discussed earlier.

From the above discussion, it is clear that as the wastewater contains nitrogen in excess of the plant nutrient requirements, wastewater irrigation may result in nitrogen loadings to the soil. The excess nitrogen may leach to the groundwater in the form of nitrates thereby causing nitrate pollution. The leaching of saline salts, as discussed above, and nitrate may affect the quality of groundwater resources.

The nitrate pollution of groundwater, and freshwater resources, has serious public health, environmental, and economic implications. The nitrate pollution and its control is an independent area of research and certainly not the main focus of this study.

Now, a question arises that are the myths on groundwater pollution due to wastewater irrigation supported by empirical evidence? This question is answered below:

Hussain and Hanjra (1996) report the results of groundwater survey assessing the impact of industrial wastewater discharges on water quality in the vicinity of Faisalabad city. A survey of water quality of wells located within one kilometre radius of Satiana Road Drain in Faisalabad, carrying industrial wastewater to the river system for drainage, shows that out of the 10 wells sampled, nine contained soluble salts level higher than the maximum permissible limit for drinking water or irrigation water quality criteria. The groundwater samples, collected from hand pumps in this zone, show very high concentrations of total dissolved salts, trace elements and heavy metals thus rendering it unfit for any potable use or crop irrigation. Moreover, the salt and heavy metal concentrations in groundwater varied inversely with the distance from the wastewater drain suggesting that proximity to water pollution sources is a problem.

Although the study focused on the evaluation of impact of raw industrial wastewater on groundwater quality, it has important implications for water pollution abatement policy, in general, and wastewater irrigation induced pollution, in particular, as industrial effluents constitute a substantial proportion of municipal wastewater load in Faisalabad.

Farid *et. al.* (1991) report the impact of wastewater irrigation on groundwater quality on Gabal el Asfar farm area in Greater Cairo region. As a large part of this area has been irrigated with untreated or primary treated wastewater since 1915, it is a manifestation of the long term impacts of wastewater irrigation on groundwater quality. The main conclusion is that sewage irrigation has a 'decreasing impact on salinity of groundwater', nevertheless, reclamation of new areas, adjacent to the existing effluent irrigated area, will affect groundwater flow systems and subsequently regional groundwater quality. They also find evidence of coliform contamination of groundwater and, therefore, recommend that handpump water should not be used for potable purposes in this area. In a companion study, Rashed *et. al.* (1995) report that in wastewater irrigated Gabal el Asfar region, concentrations of chloride, sulphate, TDS, and dissolved oxygen in groundwater is much higher than average concentrations in sewage effluent. They document evidence of doubling of chloride concentration in groundwater between 1991 to 1994 and thus changing of groundwater quality from fresh to

brackish-fresh. As 50-70% of irrigation water percolates to groundwater aquifer, it indicates an increased influence of percolated wastewater on groundwater quality in the region. Thus, as salinization and pollution of groundwater, due to effluent irrigation, may impose limitations on future use of water resources in the region, a detailed impact assessment is highly desirable.

Jordan's wastewater reuse system occupy an area of 200 hectares and is considered to be one of the largest in the developing countries. Shatanawi and Fayyad (1996) evaluate the effects of this treatment system on the water quality used for irrigation in Jordan Valley. They find that mixing of treated wastewater adversely affects chemical and microbiological quality of river water there by rendering the river water supplies unfit for unrestricted crop irrigation in the area. Although concentrations of trace elements are below irrigation water guidelines, long term use may lead to trace metal accumulation and thus it requires monitoring on a regular basis.

However, municipal wastewater has been used for the recharge of groundwater in Dan Region, Israel with positive environmental and economic impacts. This system employs soil aquifer treatment for the purification and seasonal storage of wastewater. The groundwater recharge operation is accomplished by a system of spreading basins and recovery wells. The soil aquifer treatment system produced an effluent of very high quality which is suitable for a variety of non potable uses including unrestricted irrigation, industrial use, municipal use, and recreational use. Moreover, soil aquifer treatment system is a low cost, efficient and reliable. As soil aquifer treatment system reduces suspended solids, nitrogen, phosphorous, trace elements, toxic substances, and coliforms to below desirable levels, using treated effluent for groundwater recharge has no adverse impacts (Kanarek and Michail, 1996).

Thus current state of knowledge in effluent reuse for artificial recharge has failed to reveal that water extracted from the aquifer poses greater health risk than currently acceptable potable water supplies. Nevertheless, as conditions vary from site to site, the appropriateness of effluent reuse for artificial recharge is site specific (Bouwer, 1996) . Hence, the findings of Dan region study should be interpreted with caution for applied policy making for other regions.

Downs *et. al* (1999) assess the impact of untreated wastewater recharges on groundwater quality in Mezquital Valley, Mexico. The groundwater serves as the source of potable water supply. Their risk screening for exposure to groundwater pollution indicates that high coliforms levels and nitrate pollution of groundwater aquifer poses a risk to human health in the region. Higher coliforms concentrations are also found in Leon Valley groundwater indicating that coliforms have been transported through the subsurface (Gallegos *et. al.*, 1999).

Clearly, wastewater irrigation in Mexico appears to have a negative impact on groundwater quality.

Vidal *et. al.* (2000) used multivariate principal component analysis to characterize changes in groundwater quality in Lugo, Spain under the contaminating effects of fertilizers and wastewater. The principle sources of rural well water pollution and urban spring water pollution are livestock farm waste and municipal water supply network respectively. The results indicate that saline contamination exists in rural wells where as both organic and saline contamination exist in urban springs. These findings indicate that use of livestock waste and municipal water supply infrastructure has affected potable water resources in Lugo.

The above studies indicate that wastewater irrigation have the potential to adversely effect groundwater resources, however, careful agronomic management practices are likely to mitigate any adverse effects on groundwater quality.

Wastewater irrigation, especially for vegetable production, in the vicinity of Faisalabad city has been practiced for a very long time possibly with out any regard for public health or the environment. This practice may have already affected the regional groundwater and environmental resources severely. Hence, a more scientifically based and agronomically managed wastewater irrigation programme for Faisalabad may indeed help to alleviate some of this stress on the ecosystem. Nevertheless, due to complex web of factors affecting groundwater quality, it is important to emphasize that any major wastewater irrigation programme should be assessed on ecologically sustainable development (ESD) criteria.

Effects on Property Values

Hedonic price models have been used to delineate the effect of environmental attributes on property values. Proximity to a pollution source such as hazardous waste site (popularly known as US Super Fund sites) or wastewater treatment, storage or disposal works may negatively affect local property values because of the *potential* risk to human health, dis-amenity associated with odor, nuisance, noise, aesthetics, and reduced hygienic conditions

Experts agree that groundwater contamination with toxic chemicals can negatively affect property values. Even the perception of risk of groundwater contamination can affect property values. This is because groundwater contamination and other forms of environmental pollution impose many costs on the society. Apart from health risk and high clean up costs of groundwater pollution, loss of tax base and the legal liability issues create serious moral and financial problems for the municipal authorities (Page and Rabinowitz, 1993)

A study in Pennsylvania, US, compared residential property values along polluted

and clean streams and found that the presence of pollution significantly reduces the property values (Epp and Al-Ani, 1979). Pollution related beach closings in New Jersey reduce property values by margin of about 23 percent (Polhemus *et. al.*, 1985). Page and Rabinowitz (1993) estimate the impact of groundwater contamination with toxic chemicals on properties with contamination and adjacent properties with no contamination. The case studies indicate that groundwater pollution negatively affects the value of industrial and commercial properties but not residential properties. Kiel and McClain (1995) report the impact of *rumor* of sitting of an obnoxious facility, such as an incinerator, on house prices in North Andover, USA. A distance premium exists even seven years after the incinerator began operation.

A more precise and scientifically based evidence of effects of water quality on property values is reported by Leggett and Bockstael (2000). They use faecal coliform bacteria as a measure of water quality because coliforms has serious human health implications and residents of waterfront properties, in Chesapeake Bay, Maryland, USA, are provided with detailed information about coliforms variations in waterfront. The study documents evidence of price effect of a change in ambient water quality in terms of coliforms concentrations, that is: water quality matters to the waterfront homeowners and they are willing to pay higher home prices for it. This study demonstrates a 'significant and defensible' effect of fecal coliform levels on residential property values.

The willingness to pay studies for water quality improvements from less desirable to more desirable uses such as from boatable to swimmable (Smith *et. al.* 1983), nonboatable, nonswimmable, and nonfishable to boatable, swimmable, and fishable (Mitchell and Carson, 1984) and improvement in national water quality to swimmable levels (Carson and Mitchell, 1993) indicate price premium for higher water quality and there by show that people discount the risk of water pollution.

However, there is empirical evidence to suggest that water quality improvement premium may be very low in developing countries. For example, the residents of Faisalabad, Pakistan have a positive but low willingness to pay for improvements in potable water quality (Hanjra and Hanjra, 1994). The same is true for Davos, Philippine (Choe *et. al.* 1996). This is because of very low income levels and hence low willingness to pay for environmental quality improvements in poor communities. The Davos study also show that people are willing to pay for water quality improvements but not for air quality improvements.

Willingness to pay estimates for the supply of safe drinking water in Faisalabad though command a positive premium, but it is very low to cover the marginal cost of water pollution abatement (Hanjra and Hanjra, 1993). Nevertheless, the willingness to pay for water quality improvements suggests that people are aware

of environmental problems but water pollution control is not a very high priority for the residents of Faisalabad.

The above studies suggest that water quality deterioration though groundwater contamination or otherwise is viewed as a negative externality by the communities, however, their valuations may differ in a relative sense.

Environmental Impacts

As noted earlier, wastewater is rich in plant food nutrients such as nitrogen and phosphorous. A proportion of the nitrogen applied to the land via wastewater irrigation is in excess of the plant nutrient requirements and this surplus nitrogen may:

- accumulate in soils
- translocate to surface water
- enter the atmosphere via volatilization, or
- leach to groundwater.

Similarly excess phosphorous may be translocated to various parts of the ecosystem.

Water having relatively high amounts of dissolved nutrients is termed as eutrophic (meaning well nourished) in literature. The continued use of nutrient rich wastewater can lead to eutrophication. By definition, eutrophication is the process by which water bodies are made more eutrophic or nutrient rich through an increase in their nutrient supply over time (Smith et. al. 1999). The external supplies of nutrient can be added to water bodies through:

- Point sources (sources which are localized and more easy to monitor and control), and
- Nonpoint sources (sources which are much more diverse, diffuse, and hence difficult to monitor and control).

Wastewater effluent irrigation constitute a point source of eutrophication while pollution caused by agricultural runoff and nitrogen leaching represents a nonpoint source of pollution.

The leaching of excess nitrogen and phosphorous from wastewater application sites has serious environmental consequences. Such degradation of water resources can result in loss of their component species, loss of amenity and ecosystem services, and economic loss through resource degradation (*ibid*).

Effects of eutrophication can be classified into:

- Effects on lakes and reservoirs
- Effects on stream ecosystem
- Effects on estuarine and coastal ecosystem
- Effects on terrestrial ecosystems.

As the environment of Faisalabad closely resembles to a terrestrial ecosystem, effects of eutrophication on terrestrial ecosystems are summarized in Table 8.

Table 8: Effects of Nitrogen Enrichment on Terrestrial Ecosystems

<ul style="list-style-type: none">◆ Increased total production of vascular plants◆ Increased susceptibility of some plant species to disease, cold stress and herbivory◆ Changes in soil chemistry◆ Nitrate leaching and accumulation in groundwater◆ Changes in plant and microbial community structure<ul style="list-style-type: none">-Decreased dominance by legumes-Increased dominance by grasses-Decreases in symbiotic nitrogen fixing bacteria◆ Changes in animal community structure<ul style="list-style-type: none">-Increase in deer, wild boar, winter geese and swans, wood pigeons, and ducks-Decrease in quail, partridge, rabbit, hare, and open vegetation birds.

Source: Smith *et. al.* (1999) as modified from Tamm, 1981.

The impact of wastewater irrigation depends on the quality of the baseline ecosystem and quality of the wastewater. The quality of the receiving ecosystem can be assessed using biological indices or biomarkers. For the quantification of harmful components of wastewater, Isnard (1998) describes the following approach:

- *Conventional approaches*: based on the measurement of physiochemical, ecotoxicological, and microbiological parameters. Parameters used for WHO health Guidelines, and EU chemical guidelines for wastewater use are good examples.
- *Chemical specific approaches*: based on the ratio predicted environmental concentration (PEC) to predicted no effect concentration (PNEC) of harmful compounds in the environment, i.e., PEC/PNEC. This approach is useful when some specific compounds may be particularly toxic to the environment, e.g., B, Cd etc.
- *Integrated approaches*: based on the fact that wastewater is a mixture of compounds, this approach relates the characteristics of the wastewater to that of the specific compounds. From an applied policy perspective an integrated approach may be more useful as it enables to tailor situation

specific solutions to address particular environmental problems posed by wastewater irrigation. A thorough discussion of the approaches used for the assessment of environmental impacts of wastewaters, however, is beyond the scope of this report.

Though the economic valuation of ecosystem services is prone to controversy, economists have attempted to place dollar values on ecosystem services. Such approaches use non-market based instruments, such willingness to pay estimates, for assessing the benefits of restoration of ecosystem services to the community. Loomis *et. al.* (2000) use contingent valuation method to measure the total economic value of restoring five ecosystem services viz: dilution of wastewater, natural purification of water, erosion control, habitat for fish and wildlife, and recreation along 45 miles of South Platte river, USA. Their value estimates show that aggregated value of willingness to pay is sufficient to pay for the cost of provision of these services through water leasing and conservation easement on agricultural land. Thus, the policy to provide ecosystem services qualifies economic efficiency criteria, that is, benefits exceed costs of service provision.

Social Impacts

As noted earlier, often the fine line between social and economic impacts of wastewater irrigation does not exist and thus the localized economic impacts or environmental impacts may either have social dimensions or they may assume strong social dimensions if they affect a large proportion of population. For example, if wastewater irrigation had a negative effect on a farmers health and productivity, it must be considered as an economic impact. But if an overwhelming majority of the farmers in the area are negatively affected, it becomes a social problem because of its consequences for income levels, health, productivity etc for the whole community.

National Research Council (1996) identified four type of people generally most concerned about the potential risk of wastewater irrigation include: farmers, food processing industry, affected community, and general public (discussed later). From a social standpoint, public concerns regarding wastewater irrigation projects can be summarized as:

- Concerns over nuisance, poor environmental quality, reduced hygienic conditions, odor, noise, and poor visibility etc
- Concerns about food safety
- Effect on property values
- Impaired quality of life

- Effect on natural resources such as vital water supplies, fish, wildlife, and exotic species
- Social aspects such as sustainability of the land use, and
- Lack of public confidence.

The public concerns about the perceived or real risk of wastewater irrigation may create business risks and thus should be addressed adequately to avoid exploitation by lobby groups working against wastewater irrigation. Such public concerns can be addressed through specifically targeted public education and awareness programmes and involvement of public at early project planning and implementation stages. Opinion leaders, particularly in developing country situations, can play an important role in informing and motivating the public about potential benefits of wastewater irrigation projects. Moreover, private sector forces such as common law liability, voluntary self regulation and insurance, and market forces of supply and demand and product loyalty can be used to address some of these public concerns if the country has a strong institutional and legal system. However, the ability of the private sector to deliver is doubtful in developing countries and some form of government regulation may be inevitable.

7. ECONOMICS OF WASTEWATER IRRIGATION

Cost Benefit Analysis

The potential benefits of wastewater irrigation can be considered from the following perspective:

- From the view point of wastewater treatment and disposal agency with a cost minimization framework
- From the view point of a farmer with a profit maximization objective
- From the perspective of a country with national welfare maximization objective
- From environmental perspective with the objective of minimization of environmental impacts
- From ecosystem perspective with the objective of minimization of holistic ecosystem impacts

For the purpose of evaluating farm level benefits of wastewater irrigation, the World Bank (1986) adopted a cost benefit analysis framework. The cost benefit analysis framework, along with other nonmarket valuation techniques (to incorporate externality aspects of wastewater irrigation) is employed for evaluating the economic feasibility of wastewater irrigation in this report. The detailed analytical framework along with the valuation techniques used is given in a companion research report.

The cost benefit analysis is preferable to financial analysis firstly because often some benefits of wastewater irrigation can not be valued in monetary terms and secondly, the potential benefits possess attributes of 'common good' with freeriding and benefit sharing. The inherent difficulty with existing valuation techniques make it impractical to place monetary values on all benefits and costs associated with direct, indirect, and passive use of wastewater as an irrigation resource. Hence, these valuations can not be used as input values for conducting a financial analysis..

Like all other development projects, however, economic analysis of wastewater irrigation projects can be conducted using measure of economic value that are readily comparable under various scenarios. A survey of project analysis literature suggests that most commonly used measure of economic value is net present value. The net present value represents the discounted value of the net project benefits over the entire life of the project. Although, issue of appropriate level of discount rate is contentious, most infrastructure development projects, including irrigation projects, use a discount rate of 10 percent. An adjustment can be made

for the inflation because high rate of inflation, a common phenomenon in developing countries, can lead to cost over run with serious economic and financial implications. Often, a sensitivity analysis is performed assuming various scenarios for cost over run and benefit reduction. The sensitivity analysis enable risk minimization in estimating net present worth of the project.

In view of the long gestation period of the irrigation projects and their strong ecological and environmental impacts, it is often argued that the use of positive discount rate discriminates against the welfare of the future generations. Hence, in order to assure intergenerational equity, the use of zero discount rate is advocated, that is, the net projects benefits should not be discounted. The counter arguments suggests that discounting is appropriate because future generations benefit from having a larger and superior stock of infrastructure resources, built by the previous generation, and hence their income and welfare levels would be higher than they would have been without those projects. Hence, future generations should pay for some of those benefits, that is, discounting. Notwithstanding the controversy surrounding the discount rate, wastewater irrigation projects should have a positive net present value in order to be economically viable. Now, we return to a farm level perspective and consider the benefits and costs of wastewater irrigation.

The major benefits of wastewater irrigation are: (1) the value of additional supplies of water, (2) the value of plant food nutrients, (3) labor cost savings associated with fertilizer application, low tillage requirements etc., and (4) (4) positive externality effects associated with water reuse and nutrient recycling.

Major costs of wastewater irrigation are: (1) costs of wastewater treatment, (2) infrastructure costs, if any, (3) negative externality effects associated with health, environment, and ecosystem.

As some from of treatment is always required before the municipal sewage can be disposed off to the natural environment, the *additional* cost incurred on the treatment of wastewater to achieve agricultural standard would be the cost component to be enumerated towards wastewater irrigation related treatment cost. Infrastructure cost may include the cost of pumping wastewater upstream, cost of earthworks, and protective clothing etc. A risk premium should be allowed to cover possible health, environment, and ecosystem risks.

If these cost are high, wastewater irrigation may be economically viable only for growing high value added cash crops such as fruits, vegetables, and marketable pastures. A careful crop selection may be warranted which in turn may induce changes to existing cropping patterns with possible income and employment effects.

A more reliable and low cost wastewater supply, on the other hand, can

supplement existing irrigation resources and thus can help to increase the land use intensity and cropping intensity of the cultivated area and bring new lands under the plough. Higher crop yields may translate into higher income, and hence, higher welfare levels for the farmers using wastewater as a supplemental source of irrigation. Labour and fertilizer cost savings in turn can be invested to generate on-farm or off-farm income. Farmer using wastewater as the only source of irrigation, unimaginably hard to find though as rain fall is every where, may, however, experience some decline, at least partial, in yield and thus lowers levels of return per unit of land.

Wastewater irrigation can also change existing land utilization patterns and land tenure systems. For example, if the available wastewater qualifies restricted irrigation quality criteria only, farmer may not be able to grow fruits and vegetables eaten raw (potential income loss). If, on the other hand, available wastewater qualifies unrestricted wastewater irrigation quality criteria, farmer may be able to grow both vegetable and commercial crops: he may thus be able to maximize profits by selecting a cropping pattern that suits his resource endowments and is consistent with market demand and supply situation. The cropping patterns in the restricted and unrestricted wastewater irrigation scenario are likely to be totally different with plausible consequences for revenue streams, land use, and tenure system.

Two most common forms of land tenure system, among others, that deserve special attention with respect to wastewater irrigation are: share cropping, and lease holding. Under the share cropping system, value of the produce and the variable costs, other than labor costs, are equally shared among the tenant and the landlord.

The cost of any off-farm purchases of irrigation water are also shared equally. Now, under this arrangement there is inherent tendency for the tenant to grow high value added, short duration, and labor intensive crops in order to maximize return to his labor. On the other hand, there is an incentive for the landlord to force the tenant to grow long duration commercial crops in order to maximize return to his fixed resources, that is, land and water entitlements. Under this share cropping scenario, there will thus be mixed or differing incentive for two parties to practice wastewater irrigation. Additional concerns for the landlord may arise due to negative externality effects, e.g., salinity, associated with wastewater irrigation.

Under lease hold tenure system, the farmers is free to grow whatever crops he wants in order to maximize his income during the period of tenure. There will clearly be an unhindered and unrparalled incentive for the farmer to supplement on-farm water resources with wastewater resources to grow short duration, labor intensive, high value added crops to maximize returns to his labor resources.

Clearly, this higher income incentive may bring changes to the cropping pattern and presumably to the land tenure system: possibly landless farmers looking for long term lease agreements to maximize the benefits from wastewater irrigation while landlords still caught up with the dilemma of not finding the share croppers of their choice!

Technical Analysis

Like economic feasibility, technical feasibility of the wastewater irrigation projects is also important. A computer based water balance model has been developed by IWMI for analyzing the utilization of water from surface irrigation and rain fall within an irrigation project (Perry, 1996). This water balance model can be manipulated to work out the technical feasibility of wastewater project in conjunction with the existing irrigation project. Moreover, the IWMI's water balance model along with IWMI's set of indicators for comparing the performance of irrigated agricultural systems in the world (Molden et. al., 1998) can be used to evaluate and compare the performance of various irrigation projects across various basins.

Major Economic Issues

The National Research Council (1996) noted that potential barriers to wastewater irrigation are:

- Lack of economic incentive for the farmer
- Agribusiness risk for the processor
- Public health and general concerns
- Concerns of affected community.

There is essentially economic incentive for the municipality, and the society, for the reuse of wastewater due to potential cost savings and mitigation of negative environmental externality effects. However, there may not be a comparable economic incentive for the farmer to adopt wastewater irrigation especially if the cost of irrigation water is low, i.e., water not priced at its marginal opportunity cost, and fertilizer is low, i.e., if the fertilizer cost constitutes only a small proportion of the total variable cost of crop production. While the notion of water resource underpricing is true for Pakistan, high cost of fertilizer, seasonal shortages, and black marketing should provide enough incentive for the farmer for wastewater irrigation. The wide spread use of untreated wastewater for crop irrigation in various parts of Faisalabad, an Haroonabad, as shown in the pictogram flyer on IWMI Home Page (Nov., 2000) negates the lack of economic incentive argument at least in case of Pakistan.

The food processors concern originate from the risk of potential liability, negative public attitude towards wastewater grown produce, and consequent fall on consumer demand. In Pakistan, fruits and vegetables are rarely processed or canned for marketing and other industrial crops, like maize, wheat etc. undergo necessary processing. These marketing/consumption practices allow sufficient margin of safety to minimize the concerns of agribusiness and processor.

Whatever concerns remain, they can be addressed by enforcing appropriate code of conduct, worker training, audits, certification, monitoring and evaluation of the wastewater irrigation projects.

Strategies for addressing concerns of general public and affected community have been discussed elsewhere in the report.

State of Knowledge

Economic analysis of wastewater irrigation can be performed from the perspective of the disposal agency, farmer, region or nation, environment, or ecosystem as noted earlier. In view of the time and resource constraints, a selected number of studies focusing on the economic of wastewater irrigation from the above perspective are briefly reviewed here under.

Land treatment of partially treated wastewater has been used as a low cost method of wastewater disposal for a very long time. Young and Epp (1980) provide a simulation of the costs of land treatment of municipal wastewater and its effect on crop selection. Their analysis shows that land treatment costs are affected by numerous factors such as degree of pretreatment, pumping costs, land costs, annual application rate, type of crops, and regulation governing wastewater use.

Of these, crop selection is an important item which can strongly affect the cost, through revenue effects, and performance of land treatment system. If the delta of water is high, wastewater can be used more efficiently while maximizing crop yield and maintaining the renovation capacity of the system. The researchers evaluate the effect of crop selection on cost and revenue streams and system efficiency by selecting three cropping patterns viz: reed canarygrass, alfalfa and corn, and forest plantations. Their analysis suggests that as reed canarygrass allows year round use of wastewater, it is more efficient and economical system. Alfalfa and corn become more cost effective than reed canarygrass if wastewater can be used for longer duration. Nevertheless, due to comparably short growing season and low water requirements, alfalfa and corn remain high cost alternative. Forest plantation may have comparably lower nutrient removal rates (long growth cycle and low harvests) and lower revenue but they are more efficient as they can utilize year round supply of water and are more acceptable to public than crop irrigation. This finding has important policy implications. It implies that

wastewater can be used for producing rapidly growing pulpwood, such as popular and eucalyptus, on public lands, along canal banks, roads, greenbelts etc. These plants can be harvested every eight to ten years to generate revenue along with the added advantage of working as natural air conditioners and greenhouse gas sinks for ameliorating the highly polluted environment of Faisalabad, Pakistan.

Dinar and Yaron (1986) use a long run mathematical programming model to maximize the regional income subject to constraints such as wastewater treatment technology, agricultural production technology, prices, and environmental regulations. Wastewater treatment technology affects treatment capacity, treatment levels, and hence supply of effluents for irrigation. Agricultural production technology constraint manifests itself through resource endowments, ability of the farmer to utilize effluents effectively, and cropping pattern etc. Forces of supply and demand affecting prices alongwith regulatory compliance present over all binding constraint. The results suggest that the participating farmers optimize their income if a subsidy is provided for wastewater irrigation (high transportation cost). The regional benefit is optimized at a subsidy level of 50% with: all wastewater being treated and all farmers engaging in wastewater irrigation program. All the participating entities, both direct and indirect, such as farmers, town, environment, and water ecosystem benefit from participating in a regional cooperative solution.

The study assumes that 'interfarm transfer of fresh water quota is not permitted' or more simply, farmers can not trade their water entitlements (as is the case in Israel). Hence, in the absence of water markets, the model estimates a suboptimal solution only. In general, substantial efficiency gains can be realized by trading water in a competitive market -though it may not be the case for Israel- (a quasi-water market exists in Faisalabad, Pakistan) and these gains in turn may eliminate the need for subsidy!

Darwish *et. al.* (1999) use a linear programming model to determine the optimal cropping pattern to maximize farmers income in Tyre region, Lebanon. The model is estimated using LINDO computer program as it is capable of solving linear, interactive, and discrete equations for simultaneous optimization. The results show that profit maximizing options, in their increasing order, are: sea disposal with no crop production (least profitable), using wastewater irrigation for existing cropping pattern, and introduction of new crops to existing cropping pattern (highly profitable). Supplemental irrigation and fertilizers are required for new cropping patterns to optimize farmer income. This implies that all available plant food nutrients and moisture content of wastewater are effectively recycled with the introduction of new crops. Thus, this study predicts that changes in cropping pattern are an essential element for optimal use of wastewater resources

for crop irrigation.

The results show that the main benefits from wastewater irrigation are effective water and nutrient recycling, higher crop yields, a diversified cropping pattern, and disposal cost savings. It is important to emphasize that wastewater irrigation for the existing cropping pattern brings net positive revenue as against zero revenue in case of sea based disposal. Hence, wastewater irrigation is preferable and environmentally benign option.

Segarra *et. al.* (1999) also use a dynamic optimization model to determine the optimal cropping system capable of using all effluent water, recycle nutrients, and maximize revenue under the agronomic and climatic conditions of Lubbock, Texas. Their estimation suggests that alfalfa, wheat-corn, wheat-grain sorghum, and cotton are optimal crop combinations to maximize net revenue. The selection of economically optimal cropping patterns reduces the treatment and disposal routinely incurred by the municipalities. It ,therefore, implies that municipalities can benefit from cooperative arrangements with neighboring farmers for wastewater irrigation.

Recently, a state of the art study by IWMI (Scott, et. al. 2000) evaluated the economic value and risks associated with long term use of urban wastewater for crop irrigation in Guanajuato, Mexico. The study develops and validates a risk assessment model to predict the changes in water and soil quality under various wastewater management scenarios. Both field survey and simulation results show that land application of raw wastewater results in relatively higher levels of salinity and coliform concentrations. The heavy metal accumulation in the soil, nevertheless, falls within Mexican and EU guidelines. Also, total nitrogen and phosphorous concentrations in potable water are within permissible limit indicating there by that nitrate pollution is not a problem in the study area. Due to data problems, the disease risk posed by high coliform concentrations can not be determined.

The study uses an opportunity cost or replacement value approach to estimate dollar values for water and nutrient contents of wastewater.

Regional estimate of value added of water, developed by other IWMI studies, is used as a measure of water value of wastewater. Since, the nutrients are supplied in excess of the crop requirements, the nutrient content value approach result may overestimate the actual economic worth of the nutrients. Hence, cost savings on fertilizer bill plus fertilizer application charges are considered as a more appropriate measure of nutrient value by authors. The findings suggest that wastewater is a valuable resource for the community and wastewater reuse for irrigation is an economical alternative to expensive treatment. Under the new proposal, if a wastewater treatment plant is installed and water is sold to

commercial interests, the shortage of water resources for crop irrigation will lead to a welfare loss and may stimulate a chain of negative social impacts.

The study identifies that wastewater irrigation has negative environmental and ecological costs associated with eutrophication potential, and may be health risk, heavy metal accumulation and salinity etc. These negative externality effects can be incorporated into the dollar value estimates generated by the study by making an allowance for these externality costs. Nevertheless, the study presents an excellent example of the combination of theory and practice to evaluate real world problems associated with wastewater irrigation.

Problem Areas in Evaluating Benefits of Wastewater Irrigation

Over the past decade, the tools of conventional cost benefit analysis has been extensively used in conducting economic analysis of development projects with an environmental and ecological externality element. The tools of conventional cost benefit analysis were assisted largely with the development and application of new techniques, such as non-market based valuation techniques, in order to extend the analysis to the valuation of environmental and ecological externality effects and incorporate dimensions of intergenerational equity and ecological sustainability. Wastewater reuse particularly for irrigation purposes falls within the category of resource use problems with strong externality, equity, and sustainability dimensions. A holistic evaluation of the costs and benefits of wastewater irrigation poses problems of model specification and its estimation in real world setting. Additional difficulties may arise due to data deficiencies. Despite their shortcomings, the techniques of environmental economics are by now sufficient developed to address this challenge. A thorough discussion of these techniques along with their application to wastewater irrigation can be found in another IWMI study by the authors of this report (forthcoming).

8. ECONOMIC APPROACHES TO WASTEWATER REUSE

Environmental Economics Approaches

The general criteria for the economic feasibility of wastewater irrigation projects is that whether the value of benefits exceed the costs or not (i.e. marginal reuse benefits should exceed the marginal reuse costs). However, the social feasibility criteria requires that all social, environmental, and economic costs should be fully paid for by the project benefits (i.e. marginal social benefit should be greater than marginal social cost). A knowledge of the marginal costs and benefits of wastewater irrigation and/or other water pollution abatement projects may be used as a key decision tool for environmental policy making.

The current environmental policy is based mainly on market based instruments, such as taxes, and command and control type of regulation, for example, effluent standards. In developing countries, where resource markets perform poorly, however, the working of these environmental policy instruments poses peculiar issues for policy makers. Arguably, the regulation based standards, say inspections for Guidelines enforcement, perform poorly than the market based instruments, say wastewater subsidy/pollution levy, for the development and adoption of wastewater reuse or technology. The incentive based instruments rely on the role of market forces in determining the supply of and demand for wastewater reuse

Wastewater irrigation standards and other regulatory measures has already been discussed in detail under health Guidelines. In what follows, we present a unique market based incentive scheme that may be used for promoting wastewater irrigation as an economically viable and ecologically sustainable practice in our study area with the possibility of extension to other parts of the country and possibly to developing world.

Green Slip Program for Wastewater Irrigation

The use of wastewater for irrigation in areas where availability of water is factor limiting agricultural development could be significant benefit to the generator of the effluent, the farmer, and down stream water users. This premise is the basis of our Green Slip scheme structured as follows:

- ◆ Interested or practicing farmer can apply for a wastewater irrigation permit to the local municipality to secure their wastewater entitlements or rights
- ◆ A wastewater irrigation permit be issued keeping in view tech-economic feasibility and ecological sustainability of the proposal
- ◆ The permit should define the amount of wastewater to be used, crops to

be irrigated and irrigation schedule

- ◆ A monitoring and evaluation mechanism be provided by the local municipality
- ◆ Peri-urban farmers will use the fertilizer treated wastewater for irrigation thereby eliminating the need for expensive fertilizer, reducing land or river based disposal, and mitigating environmental consequences
- ◆ The farmers may be encouraged to pay low water rates for using nutrient rich wastewater over time (marginal cost rate design)
- ◆ Farmers can sell their canal water entitlements or part there off to other farmers in the local water market at commensurate prices
- ◆ In recognition of their use of wastewater in an ecologically sustainable manner, the participating farmers be issued a 'green slip' for recycling a specified volume of wastewater and nutrients annually
- ◆ The Green Slips can be deposited in a bank to earn interest, claim discount on farm loans, traded in the open (stock) market, or relinquished in lieu of cash payments from the Green Slip Fund
- ◆ Industrial effluent levy, higher household water rates, and wastewater irrigation tariff can be used to finance Green Slip Fund
- ◆ Municipal councils can pool their resources to float Green Slip Funds, with a limited liability, on the stock market.
- ◆ National and international industrial manufacturing firms looking to improve their environmental credentials or carbon credits can buy Green Slip Fund shares
- ◆ Customer loyalty can be promoted by granting special products labeling rights to the farmers participating in the wastewater irrigation scheme (e.g., 'green product' slogan symbolizing the use of environment friendly production techniques).

RESEARCH SUGGESTIONS

- A number of small studies be initiated to conduct socio-economic and environmental impact assessment of wastewater reuse in large industrial cities for urban and peri-urban agriculture
- A national level feasibility study should be conducted to evaluate socio-economic and environmental benefits of wastewater irrigation in Pakistan.
- Design mechanism for optimizing wastewater reuse in agriculture through a partnership between water pollution abatement regulator, farmer, and government
- Risk aversion strategies for wastewater reuse in irrigation and other related uses: theory versus practice and its policy implications
- Pricing of wastewater resources within the framework agricultural water markets: Infrastructure and institutional aspects
- ◆ In order to assure that municipal wastewater is used for irrigation only when environmentally acceptable and agriculturally beneficial, a wastewater irrigation *manual* should be produced with special reference to Pakistan.

Various wastewater irrigation manuals, such as Pettygrove and Asano (1985) and guidelines such as WHO (1989), and recent Canadian guidelines such as Pentland (1993), Ontario Ministry of Environment and Energy (1996), Alberta Environment (2000a), and Alberta Environment (2000b) can be useful starting point for this manual.

- ◆ IWMI now has the resources to fill a large gap in literature by publishing a state of the art *bibliography* on socio-economic and environmental impacts of wastewater irrigation. To satisfy the needs and expectations of globally wired community, an *Electronic Version* of bibliography will be highly desirable. This database will be a valuable resource for the research, development, and teaching community around the globe.

An extensive amount of literature has been collected for the compilation of this report, which, alongwith other internet resources, can be used to produce proposed electronic version of bibliography. IDRC has recently published a bibliography on public health aspects of urban agriculture (Flynn, 1999). IWMI can complement this effort by compiling *Bibliography of Socio-Economic And Environmental Impacts of Wastewater Irrigation: Electronic Version/ 2001/ 2002.....!*

9. GLOBAL HIGHLIGHTS IN WASTEWATER REUSE

Wastewater Reuse Markets

In addition to the wastewater reuse for irrigation, a number of potential recycled water markets exist in at least situations other than Faisalabad. Some of these additional opportunities are spread across a wide range of recycled water markets.

Water markets can be divided into two main categories viz: potable water markets and non-potable markets. Two forms of potable uses are: blending with water supply, and piped water supply. The non-potable water markets, existing and potential, mentioned in literature, can be further divided into following categories and uses:

Residential market:

- toilet flushing
- car washing
- garden use
- other outdoor use

Industrial and Commercial market:

- Process
- Boiler feed
- Cooling towers
- Air conditioning
- Snow making
- Quenching
- Dust control
- Heavy construction
- Mining
- Washing
- Toilet flushing
- Refuse compaction
- Soil compaction
- Fire protection

- Border safety(barrier) and psychological effects
- Oil field repressurization and oil recovery

Rural irrigation market:

- Pasture
- Horticulture
- Landscape
- Nurseries
- Turf grass
- Forest plantations
- State forest
- Game lands
- Wetlands and reserves
- Aquaculture
- Cemeteries *(may be objectionable in some countries)

Urban agriculture and irrigation market:

- Golf course
- Race courses
- Sports ground and ovals
- School yards
- Parks and gardens
- Freeway medians
- Green belts
- Commercial nurseries
- Cemeteries *

Environmental and ecological market:

- Stream flow augmentation
- Drought mitigation
- Marsh enhancement

- Artificial groundwater recharge
- Salt water intrusion control
- Subsidence control
- Fisheries
- Ecosystem services
- Wetland management, and
- Biodiversity and species conservation.

It is important to note that all potential recycled water markets are characterized by some degree of uncertainty. Whether or not any of these markets can be exploited for wastewater reuse depends on a host of factors including commercial considerations, economic feasibility, environmental regulations, public health concerns, and more importantly public acceptance of the practice.

In developing countries, agriculture sector represents major nonpotable use water market where as share of other nonpotable use water markets is very small. Not only non agricultural nonpotable use markets are very small at present, they are characterized by negligible marginal returns to additional water use. Thus, in developing countries, non agricultural non potable wastewater demand is unlikely to expand in near future. However, potential non potable reuse markets and opportunities exist in developed world where marginal water use commands very high returns.

Nevertheless, the size of these potential wastewater reuse markets, other than agricultural market, in Faisalabad region is likely to be small firstly because additional water use in industrial and commercial market has negligible marginal returns, and secondly, adequate water resources are available to meet water demand for industrial and commercial sector (Hussain, 2000). Thus, agriculture sector is the most likely candidate to create demand for wastewater reuse. This argument is consistent with ESD principle because agriculture is the only sector which presents opportunity for: (1) water reuse, (2) nutrient recycling, and (3) and pollution management on a sustainable basis. Other sectors, for example industrial and commercial sectors, either use water only or do not adequately recycle nutrients. Even if they do, water becomes more polluted and least reusable as the result of their activities. Thus water reuse argument, nutrient recycling argument, pollution management argument, and sustainability argument suggest that non potable wastewater reuse has:

- competitive disadvantage for nonagricultural sectors, and
- a comparative advantage for agricultural sector in developing countries.

Global Initiatives in Wastewater Reuse

(Unfinished Business)

Africa: Urban: Potential use of Treated Wastewater for Drought Mitigation

Australia: Cooling water make up

Australia: Rousehill: Dual nonpotable water supply source

Australia: South Queensland: Potable reuse options

Belgium and Italy: water recycling in textile industry

France: Sprinkling Goufcourses

Germany: Berlin: Groundwater Recharge

Greece: Athens: Multiple nonpotable urban use

Israel: Jerusalem: Dual distribution reuse

Japan: Fukuoka: Tokyo: Stream restoration and flow augmentation

Japan: Shinjuku: Tokyo: Toilet flushing in high rise buildings

Namibia: Windhoek: Supplementation of potable water

Tunisia: Landscape applications

Turkey: Istanbul: urban industrial and recreational augmentation

USA: San Deigo: Potable reuse possibilities

Literature Cited

To be sorted/finalized later depending on the final format.

For an extended list of bibliographical references, please see:

Hanjra, M. A. (2000) *Socio-Economic Aspects of Wastewater Use in Agriculture: A Bibliography*. Unpublished report. International Water Management Institute, Colombo, Sri Lanka

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