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Wastewater Use in Agriculture

Review of Impacts and Methodological Issues in Valuing Impacts

Intizar Hussain, Liqa Raschid, Munir A. Hanjra, Fuard Marikar and Wim van der Hoek

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International Water Management Institute

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[With an Extended List of Bibliographical References]

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Acronyms

As	Arsenic
B	Boron
BOD	Biochemical oxygen demand
Ca	Calcium
Cl^-	Chloride
COD	Chemical oxygen demand
Cd	Cadmium
EC	Electrical conductivity
Hg	Mercury
K	Potassium
Mg	Magnesium
Na	Sodium
N	Nitrogen
Ni	Nickel
P	Phosphorus
Pb	Lead
pH	Hydrogen ion concentration
SS	Suspended solids
TDS	Total dissolved solids
TKN	Total kjeldahl nitrogen
TP	Total phosphorus
Zn	Zinc

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Introduction

With increasing global population, the gap between the supply and demand for water is widening and is reaching such alarming levels that in some parts of the world it is posing a threat to human existence. Scientists around the globe are working on new ways of conserving water. It is an opportune time, to refocus on one of the ways to recycle water—through the reuse of urban wastewater, for irrigation and other purposes. This could release clean water for use in other sectors that need fresh water and provide water to sectors that can utilize wastewater e.g., for irrigation and other ecosystem services. In general, wastewater comprises liquid wastes generated by households, industry, commercial sources, as a result of daily usage, production, and consumption activities. Municipal treatment facilities are designed to treat raw wastewater to produce a liquid effluent of suitable quality that can be disposed to the natural surface waters with minimum impact on human health or the environment. The disposal of wastewater is a major problem faced by municipalities, particularly in the case of large metropolitan areas, with limited space for land-based treatment and disposal. On the other hand, wastewater is also a resource that can be applied for productive uses since wastewater contains nutrients that have the potential for use in agriculture, aquaculture, and other activities.

In both developed and developing countries, the most prevalent practice is the application of municipal wastewater (both treated and untreated) to land. In developed countries where environmental standards are applied, much of the wastewater is treated prior to use for irrigation of fodder, fiber, and seed crops and, to a limited extent, for the irrigation of orchards, vineyards, and other crops. Other important uses of wastewater include, recharge of groundwater, landscaping (golf courses, freeways, playgrounds, schoolyards, and parks), industry, construction, dust control, wildlife habitat improvement and aquaculture. In developing countries, though standards are set, these are not always strictly adhered to. Wastewater, in its untreated form, is widely used for agriculture and aquaculture and has been the practice for centuries in countries such as China, India and Mexico.

Thus, wastewater can be considered as both a resource and a problem. Wastewater and its nutrient content can be used extensively for irrigation and other ecosystem services. Its reuse can deliver positive benefits to the farming community, society, and municipalities. However, wastewater reuse also exacts negative externality effects on humans and ecological systems, which need to be identified and assessed.

Before one can endorse wastewater irrigation as a means of increasing water supply for agriculture, a thorough analysis must be undertaken from an economic perspective as well. In this regard the comprehensive costs and benefits of such wastewater reuse should be evaluated. Conventional cost benefit analysis quite often fails to quantify and monetize externalities associated with wastewater reuse. Hence, environmental valuation techniques and other related tools should be employed to guide decision-making. Moreover, the economic effects of wastewater irrigation need to be evaluated not only from the social, economic, and ecological standpoint, but also from the sustainable development perspective.

Pakistan is a case which illustrates this problem. Both treated and untreated municipal wastewater in the vicinity of large cities like Faisalabad is used for vegetable production. But, how safe is this practice? How does one tradeoff between the obvious benefits of this use and the costs associated with it?

1.1 *Objectives and organization of the paper*

The objective of this paper is to provide a review of the characteristics of wastewater used for irrigation, and the reasoning behind the international guidelines presently used in regulating wastewater reuse for agriculture. This paper presents various systems of wastewater treatment available and discusses their benefits and shortcomings. A selective review of recent empirical studies identifies major impacts both positive and negative impacts of wastewater irrigation. Finally, the paper provides the review of environmental valuation techniques for analyzing impacts of wastewater uses in agriculture, and suggest a framework for application of some of these techniques. This framework will be applied to a developing country case study (Faisalabad area in Pakistan), in the ongoing IWMI research program.

An explicit objective of this exercise is to identify areas of concern in the valuation of the impacts of wastewater irrigation and suggest ways to improve these covets. Although there are shortcomings, we believe that this methodological framework, supplemented with the framework presented in another related paper by Hussain et al.(2001) presents the most comprehensive framework for analyzing wastewater use in agriculture in a developing country. An extensive bibliography on the subject area, including references used here is annexed to the paper (Annex 1).

2. Wastewater Characteristics

2.1 *Sources of Wastewater*

In general, municipal wastewater is made up of domestic wastewater, industrial wastewater, storm water, and by 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, a large proportion of municipal wastewater from some sections of the city consists of industrial wastewater discharges. Unlike in some developed cities where the systems are separate, here, the municipal sewage network also serves as the storm water sewer. Due to defects in the sewerage system, there is groundwater seepage as well, adding to the volume of sewage to be disposed.

2.2 *Characteristics of Wastewater flow*

In general, domestic wastewater entering municipal wastewater systems tend to follow a diurnal pattern (Asano et al. 1985). This flow is low during the early morning hours and a first peak generally occurs 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. Peak flows may also be generated during festive occasions, and at times of religious rituals, such as the Friday prayer in Pakistan, during business hours, tourist seasons, and in areas with large university campuses etc.

Industrial wastewater flows, closely follow the processing pattern of local industries, which depend on the processes involved, the number of shifts operated, and the water requirement of the industry. Variations from established patterns are minimal and occur during shift changes or stoppages. Flow variations may also occur due to processing of seasonal products. Therefore, seasonal fluctuations in the industrial wastewater discharges are more significant. In cities where, industrial wastewater constitutes a major component of the total municipal wastewater flow, fluctuations in industrial wastewater discharges are likely to be of significant importance in water cycle management.

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

2.3 *Composition of Wastewater*

Though the actual composition of wastewater may differ from community to community, all municipal wastewater contains the following broad groupings of constituents:

- Organic matter
- Nutrients (Nitrogen, Phosphorus, Potassium)
- Inorganic matter (dissolved minerals)
- Toxic chemicals
- Pathogens

A brief overview of the wastewater constituents, parameters, and possible impacts are given in table 1.

Table 1. Pollutants and contaminants in wastewater and their potential impacts through agricultural use.

Pollutant/ Constituent	Parameter	Impacts
Plant food nutrients	N, P, K, etc.	- 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 species. (eutrophication) - nitrogen leaching causes groundwater pollution with adverse health and environmental impacts
Suspended solids	Volatile compounds, settleable, suspended and colloidal impurities	- development of sludge deposits causing anaerobic conditions - plugging of irrigation equipment and systems such as sprinklers
Pathogens	Viruses, bacteria, helminth eggs, fecal coliforms etc.	- can cause communicable diseases (discussed in detail later)
Biodegradable organics	BOD, COD	- depletion of dissolved oxygen in surface water - development of septic conditions - unsuitable habitat and environment - can inhibit pond-breeding amphibians - fish mortality - humus build-up
Stable organics	Phenols, pesticides, chlorinated hydrocarbons	- persist in the environment for long periods - toxic to environment - may make wastewater unsuitable for irrigation
Dissolved inorganic substances	TDS, EC, Na, Ca, Mg, Cl, and B	- cause salinity and associated adverse impacts - phytotoxicity - affect permeability and soil structure
Heavy metals	Cd, Pb, Ni, Zn, As, Hg, etc.	- bio accumulate 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 ion concentrations	pH	- especially of concern in industrial wastewater - possible adverse impact on plant growth due to acidity or alkalinity - impact sometimes beneficial on soil flora and fauna
Residual chlorine in tertiary treated wastewater	Both free and combined chlorine	- leaf-tip burn - groundwater, surface water contamination (carcinogenic effects from organochlorides formed when chlorine combines with residual organic compounds) - greenhouse effect

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

The final composition of raw wastewater depends on the source and its characteristics. In the case of mixed municipal wastewater this depends on the types and numbers of industrial units and the characteristics of the residential communities. The composition of typical raw wastewater for selected countries is given in table 2.

Table 2. Composition of raw wastewater.

Parameters	Composition of raw wastewater (mg/l)				
	India	USA	France	Morocco (Boujaad)	Pakistan (Faisalabad)
BOD	196-280	110-400	100-400	45	193-762
COD	-	250-1000	300-1000	200	83-103
SS	200-985	100-350	150-500	160	76-658
TKN	28.5-73	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 IUCN, 1994.Shuval et al. (1986).
World Bank Technical Paper Number 51.
Note: NA = not available

3. Existing Approaches for Regulating Wastewater Reuse in Agriculture

3.1 *Microbiological Guidelines for Wastewater Reuse*

Wastewater contains high concentrations of excreted pathogens such as viruses, bacteria, helminths eggs, and fecal coliforms. These excreted pathogens have the potential to cause disease if present in a human host in sufficient quantities. Intestinal nematodes pose the highest degree of risk of infection while bacteria pose a lower risk. Viruses exhibit the lowest risk. To minimize the potential risk of infection, the World Bank, World Health Organization and International Reference Centre for Waste Disposal at Engelberg, Switzerland, convened a group of experts comprising of epidemiologists, social scientists and sanitary engineers in 1985, to review recent epidemiological evidence, and make recommendations. This report was the basis for the WHO guidelines on the safe use of water for agriculture and aquaculture. The rationale behind the WHO guidelines outlined below, was to develop criteria that would prevent the transmission of communicable diseases while optimizing resource conservation and recycling.

Restricted irrigation: no more than one viable human intestinal nematode egg per liter.
Unrestricted irrigation: above criteria, plus no more than one thousand fecal 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), also known as Category A; and fruit trees, fodder crops and pastures, known as Category B.

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, known as Category C.

The human intestinal nematodes include, roundworm (*Ascaris lumbricoides*); hookworm (*Ancylostoma duodenale* and *Necator americanus*); and whipworm (*Trichuris trichiura*) Mara (2000).

Recent evidence (Blumenthal et al. 1996) suggests that these guidelines are used only to protect crop consumers but not necessarily farmers, farm workers and their families, thereby making these guidelines debatable. Presently, researchers are divided between two schools of thought on the question of appropriate level of nematode and fecal coliform in wastewater that should be used for irrigation. The two schools of thought are: the less stringent epidemiological evidence school led by the WHO, and the "no risk school" led by the US.

The no risk philosophy cannot be adopted by many countries specially developing countries, which cannot find financial resources for expensive treatment systems, but badly require wastewater for irrigation (Marecos do Monte et al.1996). 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.

Differentiating between the potential risk and actual risk of contracting a disease is another issue in developing appropriate guidelines. The actual health risk depends on three more factors namely:

1. time of survival of pathogens in water or soil,
2. infective dose, and
3. host immunity.

In order to evaluate the financial feasibility of WHO and USEPA microbial health guidelines, Shuval et al. (1997), developed a risk assessment approach to conduct a comparative risk analysis. 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, for disease prevention. This is a major additional cost as the technology required to treat wastewater, to rigorous USEPA standards, is very expensive. An interesting research question arises in the context of developing countries whether the additional treatment expenditure is justifiable especially, if the risk of contracting the disease is negligible or, if alternative methods can be used to safeguard the health of the exposed communities. On the other hand, WHO guidelines can be achieved using low-cost, efficient, land-based treatment systems such as, waste stabilization ponds, which can achieve consistently reliable and very high microbial standards. Studies conducted in Morocco show that properly designed and operated waste stabilization ponds achieve almost complete removal of fecal coliforms, and helminth eggs. Thus, for the developing countries, WHO guidelines present a more technologically attainable and financially feasible alternative, than the USEPA guidelines.

Most European countries, with the exception of Germany and France, have not established any guidelines for the use of wastewater for irrigation. The EU guidelines, when formulated, propose to cover both agronomic aspects, of soil and groundwater protection, yield maximization, and the sanitary aspects, relating to public health protection.

3.2 *Chemical Guidelines for Wastewater Reuse*

With many guidelines dealing with water quality for irrigation purposes, the microbiological aspects have always predominated perhaps, because of their immediate human health consequences. Chang et al.(1996), notes that, few of the irrigation water quality criteria were developed specifically for wastewater irrigation. Also, the guidelines and manuals (e.g., US.EPA 1992) dealing with reclaimed wastewater reuse for irrigation *do not* address human health and safety issues relating to the introduction of toxic pollutants into the ecosystem through wastewater irrigation.

3.3 *Religious Perspective on Wastewater Irrigation in the context of Pakistan*

While investigating wastewater irrigation in Haroonabad, a small town in Pakistan which is predominantly Islamic, it was observed that although wastewater was used for crop cultivation by Muslim farmers who handled the produce, tasks related to sewage and wastewater handling were reserved for persons who were non-Muslim. In the light of these findings it was thought as essential, that the religious perspective be briefly reviewed in this desk study.

Islam, the religion of about 96 percent of the population of Pakistan, emphasizes cleanliness. Water is the main medium for achieving this cleanliness. According to the teachings of Islam, water becomes unclean when used by mankind. Only pure water (*Tahu¯r)* may be used for religious rituals and ablutions. Water that has changed its natural properties such as color, odor, and taste significantly, as a result of mixing pollutants or, used by humans, as when used for personal cleanliness, becomes unclean (*mutanajjis*) or wastewater, and cannot be used for “any religious mundane purpose.”

In 1979, 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. The Fatwa allowed the reuse of treated wastewater (water that is non-turbid, and has been sufficiently diluted with clean water or has been exposed to the natural elements for sufficient periods) for all purposes even for religious washings (Farooq and Ansari 1983; Ali 1987; Mara 2000).

4. Choice of (Cost-Effective) Wastewater Treatment Systems for 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 marginal costs are very high at higher levels of treatment. (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 concern. Cost minimization should remain an overriding objective of wastewater treatment plants in the absence of any binding constraints, such as environmental quality standards. However, studies show that enhancement of water quality is preferred over cost minimization (Schwarz and McConnell 1993).

In practice, most developing countries use untreated wastewater for agriculture for a variety of reasons, least of which are the cost of treatment and the loss of precious nutrients. However, treatment of wastewater prior to agricultural use, is believed to be essential: first, from the point of view of public health protection, and second, to respect local social and religious beliefs (Mara 2000). In view of these requirements, water scarcity, dry land farming, hot climatic conditions, and the high economic value of fresh water resources, a great deal of research and development effort has been undertaken particularly in Israel, for the reuse of wastewater.

Municipal wastewater treatment is a well-developed engineering science and various processes and techniques are available to efficiently treat the waste (Asano et al. 1985; NRC report 1996). In the absence of too high a concentration of waste from industrial sources, an efficient treatment option for conventional wastewater treatment is to use primary sedimentation followed by secondary biological treatment using high-rate biological processes. But, high energy costs, technology requirements and frequent maintenance problems render it ineffective for use in most developing countries.

4.1 *Wastewater Treatment Using Land-Based Systems—Quality and Cost Considerations*

When regulations require that wastewater is treated before reuse for crop cultivation in developing countries, cost considerations become essential in the choice of a suitable system. Land-based systems are considered to be one of the best wastewater treatment processes, especially for arid and semi-arid regions (Young and Epp 1980), as they are capable of achieving comparable nutrient removal levels for a considerably low cost, provided land is available at reasonable prices. Additional benefits include recovery and reuse of wastewater and plant food nutrients for crop production. Waste stabilization ponds are a popular form of land-based treatment systems. A classical configuration of such a system comprises anaerobic, facultative, and maturation ponds. Studies in Egypt (Shereif et al. 1995), Morocco (Yagoubi et al. 2000), and Israel (Juanico 1995), describe different configurations of these land-based systems and their performance.

These studies conclusively show that wastewater treatment using waste stabilization ponds, is very efficient, and inexpensive in terms of capital and maintenance costs. The quality of the effluent produced is a result of the configuration used. Anaerobic and facultative ponds in series, produce effluent which is suitable only for restricted irrigation (i.e. for some types of crops) according to WHO Guidelines. Further treatment in maturation ponds (or chlorination) is required for unrestricted irrigation. Mara (2000), shows that the land requirement for acceptable treatment levels for unrestricted irrigation, is more than twice that required for restricted irrigation. It is therefore recommended that unrestricted irrigation should only be selected if it is financially viable. More simply, one should choose unrestricted irrigation only if the difference in net present value of unrestricted crops, and net present value of restricted crops grown, is greater than the discounted costs of maturation ponds. The use of wastewater storage and treatment reservoirs, after pretreatment in anaerobic ponds, is advantageous as it permits the wastewater flow of an entire year to be used for irrigation. This would enable a much larger area to grow crops. Therefore, the high land requirement for land-based natural treatment systems is compensated.

Two disadvantages of waste stabilization ponds often cited in literature are high land requirements, and high water loss through evaporation. The high land requirement becomes a constraint only if land is in short supply and becomes expensive. Appropriately designed waste stabilization reservoirs permit the entire year's wastewater to be used and thus enable 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).

An alternative to using tertiary treatment with conventional municipal waste treatment (non-land-based systems) is to use floating aquatic plants in constructed wetlands. They can either be used as single species or multi-species constructed wetlands that feed on nutrient rich wastewater and reduce pathogenic bacteria. Recently, several major works have been published in this area. Two recent studies, one focusing on the nutrient removal efficiency (Bramwell and Prasad 1995) and the other focusing on microbiological efficiency of these aquatic plants (Karpiscak et al. 1996), show that the system is low cost, has a low land requirement (0.27 m^2 per head for single species systems) and is well suited to the needs of small communities. 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 are attracted to these wetland sites. Thus, this aquatic, multi-species wetland system also has a positive ecosystem impact on habitat quality and biodiversity

It is important to emphasize here that the use of waste stabilization ponds, in the form of anaerobic, facultative, and maturation ponds, is a substitute for a full-blown tertiary treatment process including disinfection. However, disinfection can be achieved by using either chlorine or ozone or Ultra Violet (UV) light. Chlorine is an ozone depleting substance and is believed to have severe negative environmental impacts. Hence, when calculating costs 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 require a very high degree of treatment integrity and consumer education, which unfortunately is very costly in developing countries.

5. Review of Potential Impacts of Wastewater Use in Agriculture

This section provides a review of selected literature on the potential impacts of wastewater use in agriculture. The review covers:

1. Public health
2. Crops
3. Soil resources
4. Groundwater resources
5. Property values
6. Ecological impacts
7. Social impacts

5.1 *Public Health*

As mentioned earlier, wastewater contains pathogenic microorganisms such as bacteria, viruses, and parasites, which have the potential to cause disease. In particular, human parasites such as protozoa and helminth eggs are of special significance in this regard as they prove to be most difficult to remove by treatment processes and have been implicated in a number of infectious gastrointestinal diseases in both developed and developing countries. However, in evaluating health impacts it must be remembered that it is the actual risk that make people fall ill that must be quantified and not the presence of pathogens in water. Whilst the potential risk may be quite high, the actual risk depends on many other factors. A summary of empirical evidence on public health impacts of wastewater reuse is given in annex 2.

The use of untreated wastewater for irrigation, no doubt, pose a high risk to human health in all age groups. However, the degree of risk may vary among the various age groups. Untreated wastewater irrigation leads to relatively higher prevalence of hookworm (Feenstra et al. 2000), and Ascariasis infections among children (Cifuentes et al. 2000; and Habbari et al. 2000).

Heavy metals in wastewater pose a health risk if they are ingested in sufficient concentrations, and can be dangerous. In principle, uptake of heavy metals by crops and the risk posed to consumers may not be an issue as plants cannot resist high concentrations of these pollutants and die off before they become a threat to humans. Shuval et al. (1986), made an extensive study of health effects of pathogens but there is no comprehensive study which assess the impact of heavy metals and the real risks posed to human health.

These findings have important implications for the valuation of public health risks associated with wastewater irrigation. First, they indicate that valuation of public health risk is an important decision variable in wastewater irrigation and both adult population as well as children should be considered as potential exposure group. Second, the entire population, living within and outside the wastewater irrigation zone, should be considered as the potential exposure groups for economic valuation purposes.

5.2 *Crops*

Generally speaking, wastewater (treated and untreated) is extensively used in agriculture because it is a rich source of nutrients and provides all the moisture necessary for crop growth. Most crops give higher than potential yields with wastewater irrigation, reduce the need for chemical fertilizers, resulting in net cost savings to farmers. If the total nitrogen delivered to the crop via wastewater irrigation exceeds the recommended nitrogen dose for optimal yields, it may stimulate vegetative growth, but delay ripening and maturity, and in extreme circumstances, cause yield losses. Crop scientists have attempted to quantify the effects of treated and untreated wastewater on a number of quality and yield parameters under various agronomic scenarios (reference bibliography, and annex 3 on “Empirical Evidence of Impacts of Wastewater Irrigation on Crops”). An overview of these studies suggest that treated wastewater can be used for producing better quality crops with higher yields than what would otherwise be possible.

The use of untreated municipal wastewater, as is the practice in many countries, pose a whole set of different problems. Nevertheless, the high concentration of plant food nutrients becomes an incentive for the farmers to use untreated wastewater as it reduces fertilizer costs, even when the higher nutrient concentrations may not necessarily improve crop yields. Most crops, including those grown in peri-urban agriculture, need specific amounts of NPK for maximum yield. Once the recommended level of NPK is exceeded, crop growth and yield may negatively be affected. For example, urea plant effluents are a rich source of liquid fertilizer but in concentrated forms they have adverse effects on rice and corn yields (Singh and Mishra 1987).

The composition of municipal wastewater also has to be taken into account. Predominance of industrial waste brings in chemical pollutants, which may be toxic to plants at higher concentrations. Some elements may enter the food chain, but most studies indicate that such pollutants are found in concentrations permitted for human consumption. On the other hand, predominance of domestic wastewater may result in high salinity levels that may affect the yield of salt sensitive crops.

The above discussion shows that the economic impacts of wastewater on crops may differ widely depending upon the degree of treatment and nature of the crops. From an economic viewpoint, wastewater irrigation of crops under proper agronomic and water management practices may provide the following benefits: (1) higher yields, (2) additional water for irrigation, and (3) value of fertilizer saved. Alternatively, if plant food nutrients delivered through wastewater irrigation result in nutrient over supply, yields may negatively be affected.

5.3 *Soil Resources*

Impact from wastewater on agricultural soil, is mainly due to the presence of high nutrient contents (Nitrogen and Phosphorus), high total dissolved solids and other constituents such as heavy metals, which are added to the soil over time. Wastewater can also contain salts that may accumulate in the root zone with possible harmful impacts on soil health and crop yields. The leaching of these salts below the root zone may cause soil and groundwater pollution (Bond 1999).

Prolonged use of saline and sodium rich wastewater is a potential hazard for soil as it may erode the soil structure and effect productivity. This may result in the land use becoming non-sustainable in the long run. The problem of soil salinity and sodicity can be resolved by the application of natural or artificial soil amendments. However, soil reclamation measures are costly, adding to economic constraints resulting in losses to crop productivity. Moreover, it may not be possible to restore the soil to the original productivity level, by using these soil amendments. Hence, wastewater irrigation may have long-term economic impacts on the soil, which in turn may affect market prices and land values of saline and waterlogged soils.

Wastewater induced salinity may reduce crop productivity due to general growth suppression, at pre-early seedling stage, due to nutritional imbalance, and growth suppression due to toxic ions (Kijne et al. 1998). The net effect on growth may be a reduction in crop yields and potential loss of income to farmers.

Wastewater irrigation may lead to transport of heavy metals to soils and may cause crop contamination affecting soil flora and fauna. Some of these heavy metals may bio-accumulate in the soil while others, e.g., Cd and Cu, may be redistributed by soil fauna such as earthworms (Kruse and Barrett 1985). 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 up to 31percent of soil surface metal accumulation and lead to heavy metal uptake by alfalfa. However, heavy metal concentrations in alfalfa pose no risk to animal or human health.

In a critical assessment of USEPA heavy metal guidelines, McBride (1995), argues that heavy metals applied through sewage use can harm sensitive plants with possible loss of soil productivity in the long run, if available in sufficient quantities. In general, heavy metal accumulation and translocation is more a concern in sewage sludge application than wastewater irrigation, because sludge formed during the treatment process consists of concentrations of most heavy metals.

The impact of wastewater irrigation on soil may depend on a number of factors such as soil properties, plant characteristics and sources of wastewater. The impact of wastewater from industrial, commercial, domestic, and dairy farm sources are likely to differ widely. The use of dairy factory effluents for 22 years in New Zealand shows that nearly all applied P is stored in the soil while nitrogen storage is minimal, implying nitrogen leaching and consequent nitrate pollution of the groundwater (Degens et al. 2000).

5.4 *Groundwater Resources*

Wastewater application has the potential to affect the quality of groundwater resources in the long run through excess nutrients and salts found in wastewater leaching below the plant root zone. However, the actual impact depends on a host of factors including depth of water table, quality of groundwater, soil drainage, and scale of wastewater irrigation. For instance the quality of groundwater would determine the magnitude of the impact from leaching of nitrates. If the groundwater is brackish the leaching of nitrates would be of little concern as the water has no valuable use attached to it. The proximity of wastewater irrigation to sources of potable water supplies such as wells or tubewells will influence how we evaluate the severity of groundwater pollution effects.

Groundwater constitutes a major source of potable water for many developing country communities. Hence the potential of groundwater contamination needs to be evaluated before embarking on a major wastewater irrigation program. In addition to the accretion of salts and nitrates, under certain conditions, wastewater irrigation has the potential to translocate pathogenic bacteria and viruses to groundwater (NRC report 1996).

Farid et al. (1993), report that in Gabal el Asfar farm in the Greater Cairo region, where untreated or primary treated wastewater has been used for irrigation since 1915, the long-term use of wastewater for crop irrigation has interestingly led to an improvement in the salinity of the groundwater. This was offset by evidence of coliform contamination of groundwater which was also observed in Mexico (Downs et al. 1999, Gallegos et al. 1999). A companion study (Rashed et al. 1995), reveals that in the wastewater irrigated Gabar el Asfar region, concentrations of chloride, sulfate, TDS, and dissolved oxygen in groundwater is much higher than average concentrations in sewage effluents. The leaching and drainage of wastewater, applied for crop irrigation, to groundwater aquifer may serve as a source of groundwater recharge. In some regions, 50-70 percent of irrigation water may percolate to groundwater aquifer (Rashed et al. 1995). The influence of percolated wastewater on groundwater quality and its recharge is thus likely to be substantial. Despite poor quality, groundwater recharge through wastewater application can be a vital environmental and economic service in regions where freshwater supplies are limited and groundwater removal rates exceed replenishment rates. In this context it may be viewed as a benefit under some circumstances. Thus, there is an obvious trade off between groundwater recharge benefits and groundwater pollution costs.

5.5 *Property Values*

In discussing the effects of environmental pollution on property values, we must distinguish between two types. The first is the discomfort from a pollution source associated with, nuisance, noise, odor, hazards, and unsightliness, have been studied extensively. The costs may include health, clean up costs and legal liability (Page and Rabinowitz 1993). Properties located along a polluted stream had significantly lower market prices than properties located along clean streams (Epp and Al-Ani 1979). Pollution-related beach closures have been known to reduce property values in New Jersey by about 23 percent (Polhemus et al. 1985).

The second type is the eventual use one might make of a polluted resource associated with property. Residential, commercial or industrial areas that use groundwater as a source of water may reduce in property value as opposed to areas with clean ground-water because the resource cannot be used for the designated purpose. If on the other hand, other sources of water exist, then the only effect on property value that should be accounted for is the first type.

Wastewater induced salinity and sodicity may also have negative affects on soil productivity, which in turn may affect land prices and lease revenues. On the other hand, given the resource value of wastewater, lands irrigated with wastewater may also appreciate in value. Thus, we can assume that wastewater irrigation has the potential to influence property values depending on the circumstances, and will affect property values positively or negatively. It should, therefore, be accounted as a cost and benefit item in analyzing the impacts of wastewater irrigation.

5.6 *Ecological Impacts*

When drainage water from wastewater irrigation schemes drains particularly into small confined lakes and water bodies and surface water, and if phosphates in the orthophosphate form are present, the remains of nutrients may cause eutrophication. This causes imbalances in plant microbiological communities of water bodies (Smith et al. 1999). This may in turn affect other higher forms of aquatic life and influence the presence of waterbirds and reduce biodiversity. Insofar as these water bodies serve local communities for their needs, the ecological impacts can be translated into economic impacts, which can be quantified. For example, overloading of organic material resulting in decreases in dissolved oxygen may lead to changes in the composition of aquatic life, such as fish deaths and reduced fishery. The eutrophication potential of wastewater irrigation can be assessed using biological indices or biomarkers, which in turn can be quantified in monetary units using appropriate economic valuation techniques.

The likelihood of heavy metals from wastewater affecting the food chain is addressed under soil resources. Soil usually acts as a filter and retains heavy metals in the soil matrix. An ongoing IWMI study of cadmium in irrigation water applied to rice fields indicates that cadmium concentration decreases as water passes through the fields. This may have an impact with respect to concentrations of heavy metals in drainage water. The effects of these concentrations on the ecosystem may thus be reduced.

5.7 *Social Impacts*

In the context of this analysis social impacts are the concerns/doubts expressed by the public about wastewater irrigation. These concerns can be classified as follows:

General concerns such as nuisance, poor environmental quality, poor hygiene, odor, noise, higher probability of accidents, etc.

Social concerns such as food safety, health and welfare, impaired quality of life, loss of property values, and sustainability of land use.

Natural resource concerns such as pollution of vital water resources, loss of fish, wildlife, exotic species, etc.

Public concerns about the perceived or real risks of wastewater irrigation may create business risks, which have to be addressed adequately to avoid exploitation by lobby groups. Business risks and potential liability can be covered by obtaining appropriate levels of insurance. The premium for general risk assurance against wastewater irrigation is likely to be high at the beginning because, most developing countries, including Pakistan, do not have experience in agriculture sector insurance. Moreover, premium and indemnity structures are likely to vary significantly among crops and regions.

6. Economics of Wastewater Irrigation—a Selective Review of Empirical Information

To date, in relation to wastewater irrigation, economic analyses have been conducted with specific perspectives in mind viz that of a municipality optimizing treatment costs, or that of farmers or a regional entity maximizing income, or that of evaluating environmental impacts. A selected number of studies are reviewed here to highlight these dimensions.

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) undertook a simulation study of the costs of land application of municipal wastewater and its effect on crop selection. Their analysis show 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. They found that crop selection strongly affect costs, through revenue effects, and performance of the 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 evaluated the effect of crop selection on cost and revenue streams and system efficiency by selecting three cropping patterns viz. reed canary grass, alfalfa, corn and forest plantations. Their analysis suggests that, as reed canary grass allows year round use of wastewater, it is a more efficient and economical system. Alfalfa and corn become more cost-effective than reed canary grass if wastewater can be used for longer durations. 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 water year round and are more acceptable to the public than crop irrigation. This finding has important policy implications. It implies that wastewater can be used for producing rapidly growing pulpwood, such as eucalyptus, on public lands, along canal banks, roads and greenbelts etc. These plants can be harvested every 8 to 10 years to generate revenue, along with the added advantage of working as natural air conditioners and greenhouse gas sinks, for ameliorating the highly polluted urban environments.

Dinar and Yaron (1986) used 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. The results suggest that if a subsidy, which had a high transportation cost was provided for wastewater irrigation, the participating farmers optimized their income. The regional benefit optimized at a subsidy level of 50 percent when all wastewater was treated and all farmers engaged in wastewater irrigation. All participating entities, both direct and indirect, such as farmers, town, environment and water ecosystems benefited from participating in a regional cooperative solution.

The study assumed that 'inter-farm transfer of fresh water quota is not permitted' or more simply, farmers cannot trade their water entitlements (as is the case in Israel). Hence, in the absence of water markets, the model estimates a sub optimal 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) 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 results show that profit maximizing options in ascending 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.

Segarra et al. (1996), also uses 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 estimates suggest that alfalfa, wheat-corn, wheat-grain sorghum, and cotton are optimal crop combinations to maximize net revenue. The selection of economically optimal cropping patterns reduce 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.

A recent IWMI study (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 applied and validated the integrated River Aquifer Simulation Model to predict changes in water quality under various wastewater management scenarios. Field surveys and simulation results showed that land application of raw wastewater resulted in relatively higher levels of salinity and coliform concentrations.

The study used an opportunity cost or replacement value approach to estimate dollar values for water and nutrient contents of wastewater. Regional estimate of added value 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 crop requirements, nutrient content value approach result may overestimate actual economic worth of nutrients. Hence, cost savings on fertilizer bill plus fertilizer application charges were considered as a more appropriate measure of nutrient value by the 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. However, the study recognizes that there could be negative health and environmental impacts of wastewater use, and that these impacts should be evaluated.

7. Techniques for Economic Valuation of Impacts

A variety of valuation techniques may be used to quantify socioeconomic, health and environmental impacts of wastewater use, classified essentially into market-based and nonmarket-based techniques.

Tools of conventional cost benefit analysis can be used for decision making when the inputs and outputs of alternative projects, policies or programs can be bought and sold in the market, i.e., costs and benefits can be evaluated in monetary units. However, when the project inputs and outputs are not traded in the market, conventional cost benefit analysis needs to be modified. This is particularly true in the case of programs with environmental dimensions, such as wastewater irrigation, because environmental goods and services are not sold in the market place. They possess attributes of public goods such as non-rivalry and non-excludability and as such, market prices do not exist for these goods and services.

In the case of projects or programs with environmental externalities, economists have developed other nonmarket-based techniques for evaluating the costs and benefits of such projects. These techniques evaluate the change in consumer welfare, under "with" and "without" project scenarios. If the project leads to a positive change in consumer or community welfare, the consumers should be willing to pay for the project. Thus, the consumer willingness to pay for an environmental resource or service[1] becomes the basis for judging the economic feasibility of the project in the absence of market prices and marketable outputs.

All economic and environmental valuation techniques, whether market-based or nonmarket-based, measure the change in consumer/producer welfare, using "with" and "without" project scenarios to evaluate socioeconomic and environmental feasibility. Table 3 below gives an overview of environmental valuation techniques. The valuation methods can be categorized according to: (a) the type of market they rely upon; and (b) how they make use of actual or potential behavior of economic agents.

[1] Measuring the demand for conventional goods and services is rarely easy, and the problems are even more complex in the case of environmental goods. An environmental good is defined as having at least one of the two characteristics: either it is negative good - a "bad" which carries no price and thus is inefficiently allocated by the market; or it is public good endowed upon the society (rather than purchased) such as biodiversity. In these cases, the aggregate quantity of good or bad supplied is observable but the individual or aggregate expenditures or valuation of the good are not. Thus in general, the researcher knows the cost of supply of public goods and trade off monetary costs with benefits, but they don't know the cost of environmental goods. In these cases environmental goods all that can be observed is how the consumption of private goods change with the level of the environmental goods. Thus the challenge is to recover the underlying demand for the environmental good. Alternatively, artificial or hypothetical markets may be constructed to elicit implicit prices or values for environmental goods and services. In the latter, demand estimation is easier although eliciting preferences becomes harder.

Table 3. Taxonomy of economic valuation techniques.

Conventional Market	Implicit Market	Constructed Market
Based on Revealed Preferences		
Private goods sold in the market (conventional price and quality analysis) • The Productivity Approach • Effect on Health or Earnings • Defensive Expenditures • Averting Expenditures	Public goods/Government services (collective choice analysis) • Hedonic Pricing • Travel Cost Analysis • Hedonic Property Values Approach • Proxy Marketed Goods or Supply and Demand Analysis of Related Goods	Artificial Market
Based on Stated Preferences		
Potential Market Goods (experimental economics, conjoint analysis) • Repair / Replacement Cost • Shadow Project Analysis	Indirect or Passive Use of Environmental Resources • Contingent Valuation Method Conjoint Analysis • Habitat Equivalency Analysis Direct Use of Environmental Resources • Contingent Valuation Method, Conjoint Analysis • Habitat Equivalency Analysis	• Contingent Valuation Method, Bidding Games Trade off Games

Source: Partly Adapted from Munasinghe (1993). A brief description of these techniques is given in annex 4.

The valuation method has been categorized into two broad groups:

1. Surveys of willingness to pay, like the Contingent Valuation Method and

2. Production function-based approaches. The second category is further divided into two subcategories;

   (2a) Output measurable in markets (corresponding to second column-conventional markets-in table 3); and

   (2b) Output not measurable in markets (corresponding to column two and three-other techniques in table 3).

Some environmental valuation techniques are generally applicable while others are potentially applicable and still others may be selectively applicable. Table 4 gives a summary of different techniques that may aid in specific environmental and resource valuation issues.

Table 4. Applicability of valuation techniques to environmental impacts.

Valuation Method	Health impacts		Aesthetic impacts	Ecosystem impacts	Recreational impacts	Production impacts
	Illness	Mortality				
Productivity approach	Yes		Yes	Yes	Yes	Yes
Opportunity cost	Yes		Yes	Yes		Yes
Preventive Expenditure/ replacement cost	Yes	Yes	Yes	Yes		Yes
Hedonic pricing		Yes	Yes		Yes	
Travel cost			Yes		Yes	
Contingent valuation	Yes	Yes	Yes	Yes	Yes	Yes

Source: Based on EPA, NSW, 1993.

7.1 *Limitations of Valuation Techniques*

Each of the environmental valuation techniques has advantages and limitations related to reliability, cost of implementation, and amount of experience gained. Table 5 presents a comparative overview of advantages and limitations of various valuation techniques.

Table 5. Comparisons of valuation methodologies.

Valuation method	Reliability of results	Data requirement	Ease of application	Technical development	Accumulated experience
Special features: based on market transactions—assumes no distortions in market prices					
Productivity approach	High	Medium	High	High	High
Opportunity cost	High	Medium	High	High	High
Preventive expenditure/ replacement cost	High	Medium	High	High	High
Special features: assumes mobility and perfect information					
Hedonic Pricing	High	High	Medium	High	Medium
Special features: use limited to recreation benefits					
Travel Cost	Medium	Medium	High	High	High
Special features: the only technique that measures existence values can suffer from a lot of biases					
Contingent Valuation	High	Medium	Low	High	High

8. Economic Valuation in Practice

8.1 *Approach to date and its limitations*

As seen from section 7, to date, the general approach to evaluate costs and benefits of wastewater irrigation has been to take into account the cost savings in irrigation water and fertilizer inputs based on:

1 the market value of water, and

2 market value of wastewater nutrients.

IWMI utilized this approach in attempting to value wastewater reuse in Haroonabad, a small town in southern Punjab (forthcoming IWMI Research Report). The study used the market value of water and fertilizer as the yardstick for evaluating the benefits of savings in freshwater (when replaced by wastewater) and for valuing the nutrients found in the water.

The study was carried out in Haroonabad town of Bahawalnagar district in the southern Punjab. Haroonabad, located at the edge of the Cholistan Desert, had a population of approximately 63,000 (Population Census Organization 2001). Rainfall averaging 160 mm a year is quite scanty, and is limited to the monsoon periods of July and August. Groundwater is brackish and therefore water supply to the town is dependent on irrigation water from the nearby Hakra-4/R Distributary Canal. The main disposal scheme has two pumps operating for 12 hours. The effluent was mainly used to irrigate an area of 120 hectares. There are two smaller schemes that irrigate an additional area of 25 hectares. The total discharge from these stations approximated over 4,600 m^3 of raw sewage a day.

The study adopted the 'with' and 'without' approach ie. comparison of vegetable production (cauliflower) with wastewater and with canal water. The results of the study show that gross margins with wastewater were significantly higher (Rs.8,369/ha) compared to those with canal water (Rs.1,786/ha). This was mainly due to much higher yields on wastewater farms (13,170 kg/ha) compared to those using canal water (9,720 kg/ha), and savings on cost of fertilizer use (which was Rs 2,420/ha for wastewater farms and Rs. 5,008/ha for canal water farms). The main limitation of the study is that it focuses on only production aspects of a single crop, and does not account for other aspects of wastewater use.

Using price of water as a yardstick for evaluating the benefits of saving fresh water resources through wastewater irrigation will yield suboptimal estimates. This is because water is considered a public good and hence it is rarely priced and allocated at its opportunity cost in most developing countries, including Pakistan. In most countries water allocation is determined by a host of legal, political, and historical factors. Endemic social problems, for example water theft, can create additional constraints to efficient working of water markets (Ray and Williams 1999). The absence of well-functioning competitive water markets can create two problems: loss of efficiency gains due to difficulty in allocation, and lack of price signals to assist allocation. Thus, even in the presence of formal and informal water markets, water prices at best may reflect only sub-optimal opportunity cost of water.

There are two main alternatives to derive shadow price of wastewater: using hedonic price analysis to reveal implicit price of water, or using the cost of energy required to deliver a unit of water to the farm. Using hedonic price analysis of irrigated farm property sales is advantageous because the implicit price of market will be based on market transactions rather than estimates of crop-yield, prices, and costs. Nevertheless, hedonic analysis reveals market value of water rather than agricultural production value (Faux and Perry 1999). Moreover, if the property markets are imperfect, as is the case in developing countries, market value of water will be a gross estimate only.

Using the cost of energy required for delivering a unit of water, (pumping, transport, storage, delivery, and application) to the farm outlet, as an approximation of the opportunity cost of water, to estimate its market value, may be a better option. However, even this estimate is partial, first, because its does not assign any cost for depletion of water resources (buffer value). Second, energy prices, especially for agricultural tube- wells in Pakistan are highly subsidized, and therefore do not reflect actual market values. Third, negative externalities of fossil fuel energy (green house gas emissions) or hydropower (sedimentation, waterlogging and salinity), are rarely reflected in the market prices of energy in developing countries. Fertilizer prices are also highly subsidized in Pakistan. Hence, the use of cost savings in irrigation water and chemical fertilizer as a measure of benefits of wastewater irrigation can at best give only suboptimal values or, result in the undervaluation of the benefits.

Another problem with the use of the value or price of water or value of fertilizer approach is that it does not take into account off-farm effects (negative and positive externality effects) such as effects on public health, soil resources, groundwater resources, property values, ecosystem impacts, and social concerns. Given these shortcomings, we develop a simple, systematic, comprehensive, and theoretically consistent approach to evaluate the impacts of wastewater use in agriculture from a holistic ecosystem perspective.

8.2 *A suggested framework for valuing impacts*

For the purpose of analyzing the socioeconomic and environmental impacts of wastewater irrigation, impacts and proxies have to be first identified and a suitable valuation technique determined. The dollar value estimates are then generated and the various economic value measures are aggregated. The approach therefore, attempts to estimate the economic, social, and ecological sustainability of wastewater irrigation in terms of its aggregate costs and benefits to society.

Impacts include both actual and potential impacts of wastewater irrigation. The change in productivity is the first measure used in the analysis. If the impact leads to a measurable change in productivity and non-distorted market prices are available, the impact can be monetized using the change in productivity approach. However, if the market prices are distorted, shadow prices may be used to measure change in productivity.

However, if the identified impact does not lead to a measurable change in productivity, then the change in environmental quality is identified and valued using appropriate proxies and valuation techniques. The proxies are not the exact variables rather they are quasi-variables that can be used as “near representations” of the actual variable to quantify the change in economic terms.

In order to keep with the convention of cost benefit analysis, the impacts can be classified into costs and benefits and discounted to a single period to calculate the net present value of programs, wastewater irrigation in our case. As wastewater irrigation in one period generates impacts in the next period or over certain future periods, the impacts should be estimated in a dynamic analytical framework to address equity and sustainability concerns.

The first convention followed in this analysis is that expenditure saved is a benefit, and benefit foregone is a cost item. For example, wastewater is a rich source of plant food nutrients and therefore, wastewater irrigation eliminates the need for inorganic chemical fertilizers, that is, wastewater irrigation saves fertilizer costs. Therefore, the nutrient contents of wastewater represent a benefit item. An appropriate numerator for the fertilizer cost savings is the market value of fertilizer. On the other hand, wastewater contains pathogenic microorganisms, which pose a potential risk to human health. The morbidity caused by the wastewater pathogens results in loss of earnings and extra healthcare expenditure, an inconvenience cost for the affected population. The earnings forgone due to illness caused by wastewater pathogens would therefore represent a cost item. The appropriate numerator for the loss of earnings is the market or shadow price of labor. The second, convention is that costs or benefits identified and valued under one impact are not valued under another impact to avoid the possibility of double counting.

8.3 *Public Health*

In evaluating the costs, one can attempt to quantify public health impacts of wastewater pathogens by looking at morbidity and mortality associated with them. The degree of risk to cause disease with wastewater irrigation, as has been observed, is higher with untreated wastewater than with treated wastewater.

The morbidity or illness caused by wastewater pathogens may result in:

- loss of potential earnings,
- medical costs, and
- inconveniences such as loss of leisure and sleep disturbances.

The loss of potential earnings can be evaluated using *human capital approach* to which medical or healthcare costs and inconvenience costs can be added (opportunity cost principle). The approach assumes that earnings represent the value of marginal product of labor, and medical and other costs are well defined. Productivity or earnings loss can be quantified in economic terms by using the information on occurrence of disease (on number of sick days, both full time and part time off-work called restricted activity days in literature), and daily wage rate.

The medical costs include the:

- cost of medical consultation(s),
- cost of medication,
- transport costs,
- cost of defensive expenditure (continued use of medicine, protective measures etc., to avert the disease risk ex-post), and
- any other out-of-pocket illness-related expenses.

Private treatment cost can be used as proxy (opportunity cost) for medical costs as public healthcare is highly subsidized in most developing countries. Sickness-related leisure and sleep disturbances may cause inconvenience and suffering to human beings. The value of inconvenience caused by leisure and sleep disturbances may, however, be difficult to quantify in economic terms, because of the low value people may attach to such losses in developing countries (costs are not well defined). Nevertheless, as leisure and sleep disturbances have the potential to impact on labor productivity, they should not be dropped out of the analysis on account of technical difficulties. Two possible alternative approaches to obtain monetary values of time lost through leisure and sleep disturbances are, by using consumers willingness to pay, to avert any inconvenience caused by sickness or by using appropriately deflated wage rate (around 25%), to work out the Opportunity Costs.[2]

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[2]The averting expenditure approach has been used by Dickie et al. (1991) to estimate the benefits of reduced morbidity such as skin cancer. The stated willingness to pay for an imaginary product that would reduce lifetime cancer risk by one percent ranges between $2.70 to $4.44 per head–a willingness to pay (WTP) value considered very small by any conservative estimate.

As cost of education is an investment in human capital formation, absence from school due to water-borne diseases can be considered as a loss of productivity. The amortized expenditure on schooling per student can be used as a 'shadow price' for estimating the monetary value of loss of schooling, due to sickness. Since a large proportion of children in developing countries drop out of school to engage in labor, the loss of productivity caused by child labor should also be valued in economic terms. The opportunity cost of child labor can be evaluated by using appropriately deflated market wage rate (around 25%, 50% and 75% depending upon age), on the assumption that the marginal product of child labor is less than that of adult labor. Alternatively, one can state that the social cost of child labor is much higher than the actual value added in developing countries. The productivity loss and cost of inconvenience of the unemployed and underemployed and unfit individuals can be estimated using the above methodology though the wage rate may require some adjustment.

The economic value of mortality (deaths), if any, caused by wastewater irrigation can be evaluated in terms of net productivity of an individual over the expected life span. The mortality-related productivity loss is thus net present value of difference between production and consumption of an individual over the remaining period of life (in case of premature deaths). For adults, the net present value of productivity lost by the society is, the difference between adult earnings and adult consumption, whereas for children, the net present value of productivity lost by the society is the difference between child's future production and household expenditure per capita (assuming that child would be the future head of family unit). The value of life estimates[3] along with the estimated change in mortality[4] for each population cohort, attributable to wastewater pathogens, can be used to generate population wide measures of economic cost of mortality.[5]

Although the value of human life approach is contentious, it is more appropriate to combine willingness of individuals to pay to save their own lives and also the lives of others (altruistic motive) as the inclusion of the latter may significantly increase the value of life estimates.

8.4 *Crops*

Wastewater is a rich source of plant food nutrients. Empirical studies, presented in an earlier section of this paper, show that the impact of wastewater irrigation on yield, varies from crop to crop. If the crops are undersupplied with essential plant food nutrients, wastewater irrigation will act as a supplemental source of fertilizer thus increasing crop yields. Alternatively, if plant food nutrients delivered through wastewater irrigation result in over supply of nutrients, yields may negatively be affected. In the absence of any chemical fertilizer application, wastewater nutrients will act as a sole source of fertilizer, delivering savings in fertilizer cost. Thus, from an economic standpoint

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[3] Although considerable controversy exists over the value of life estimates, one commonly used value in the US studies is US$300 for 0.0001 reduction in death risk. Thus, the reduction in risk equals US$3 million per death avoided. Some UK studies, e.g., Meng and Smith (1990) estimate the value of life at 3.84 million pounds. However, as the value of life estimates are country specific, a regional estimate would be more appropriate to use.

[4] Change in mortality (persons per year) = mortality coefficient x crude mortality x population exposed. The value of mortality coefficient estimated by empirical epidemiological studies on wastewater pathogen risk can be used. For example, based on the available empirical evidence, WHO guidelines assume a risk factor of 10^{-6}.

[5] Shuval et al. (1997), use a risk assessment model to evaluate additional cost of wastewater treatment from WHO standards to USEPA standards.

wastewater irrigation may have a three-fold effect on crops: (1) higher yields, (2) source of irrigation water, and (3) fertilizer value.

The economic approaches that may be used to evaluate the yield effects of wastewater irrigation are; traditional models, optimization models and econometric models (Hanley and Spash 1993).

The *traditional model* uses a simple approach to evaluate monetary value of yield changes. The dollar value estimates can be generated, by using information on crop yield changes, acreage and current prices. This is a static type basic model, which assumes that resource use or crop response functions, prices, and consumer surplus remain constant. As the information requirements are quantitative and relatively small quick and inexpensive measurements can be made. The results of the model may provide a quick insight into the effects of policy changes such as wastewater irrigation. Under these conditions the major benefits of wastewater irrigation accrue in the form of fertilizer cost savings. Nevertheless, constant price assumption may easily be violated in practice, and it is an unrealistic abstraction.

This traditional model is unable to quantify such changes in regional welfare due to changes in input use (fertilizer and water economy), output(s), employment, secondary benefits of increase in income, and distributional impacts of income changes. Optimization models on the other hand are able to do so, as they can model complex interrelationships of an agricultural system and predict direct, indirect and distributional effects of yield changes. The simple mathematical optimization models include Linear Programming Models and Quadratic Programming Models.

For the estimation of benefits of wastewater irrigation, a linear programming model can be specified as a profit maximization model with constraints on inputs such as crop acreage and NPK use per crop. Along with the standard assumptions, the linear programming model will assume a perfectly elastic supply and constant returns to scale. As profit maximization is the objective function, prices will be exogenously fixed.

By changing the biological relationships between inputs and output, the quantities of output produced can be estimated. The advantage of the model is that it can be a very helpful tool in crop selection subject to the land and variable resource constraints, when profit maximization is the overriding objective. However, optimization models are complex with high data requirement, and their use as a predictive tool is limited.

Among the *econometric models*, production function approach models can be used for evaluation of yield effects of wastewater irrigation. The functional form most commonly used in the agriculture sector is the Cobb Douglas production. However, as the prior specification of production function imposes unrealistic assumptions on crop supply and input demand functions, the ‘dual approach’ offers a better alternative.

The dual approach uses both a production function, to quantify the maximum output as a function of inputs, and a transformation function, to quantify the maximum net output vector (Varian 1992). The transformation function describes the production possibilities and measures the technical inefficiency of farm with multiple outputs. The duality approach can be set as a profit function with wastewater quality as an input so that it directly determines the loss in farmer profits and how other inputs are adjusted in response to a change in wastewater quality. The dual approaches can be modeled as cost function and profit function for the estimation of effect of wastewater irrigation on crops. This dual approach is advantageous to estimate cost, revenue, and profit function in a systematic and theoretically consistent manner (see Mjeldle et al. 1984, for an application of duality).

Whatever the model used, the empirical valuation of the effects of wastewater irrigation on crops should include both direct and indirect effects estimated within a dynamic framework.

8.5 *Soil Resources*

In addition to plant food nutrients, wastewater contains high concentrations of dissolved salts and some heavy metals and trace elements. Salinity-related impacts of wastewater irrigation on soil resources can be expressed in economic terms by: (1) potential yield and income loss; (2) loss of soil productivity; (3) depreciation in market value of land; and (4) cost of soil reclamation measures. Depending on the degree to which soil is affected, we can use one or other of these measures as proxy.

The potential yield loss due to salinity constitutes the loss of potential income for the farmers practicing wastewater irrigation. Yield losses can be evaluated in economic terms by using productivity loss approach as described earlier. However, as yield loss may be affected by several factors simultaneously, the yield loss due to salinity alone may be difficult to isolate and quantify in absolute terms. Moreover, the extent of poor agricultural market performance may distort crop prices. Hence, potential yield loss as a measure of income foregone may at best be a gross approximation of the actual impact on salinity of soil resources induced by wastewater. Expert opinion regarding salinity-related crop yield loss could serve as a proxy for estimating such income loss.

Similarly, the economic value of soil productivity may be measured in terms of the ability to produce crops. The loss in productivity may be difficult to quantify and evaluate in economic terms because the general measure of soil productivity is land price (more fertile and productive land command higher prices). But, land prices for similar parcels, not related to soil productivity like proximity to canal or residential area, may differ significantly due to a variety of reasons. Unless, an elaborate hedonic price analysis is conducted, the true price of land productivity difference attributable to salinity parameter may be difficult to quantify and evaluate in economic terms.

The depreciation in market value of land has two dimensions: decline in sale value of land (investment depreciation), that is market price per acre, and land rent, that is, annual lease revenue per acre under lease hold arrangement.[6] The net present value of differential in market price or annual lease per acre over a common period, say 20 years, may be used as a measure of opportunity cost of wastewater induced salinity. The extent of resources, perfect market performance and the use of sale value or annual lease differential should yield same results if discount period is based on actual time required for reclamation. However, for all practical purposes, sale value differential may be used as a proxy if the impact of salinity is long-term and severe (irreversible). Alternatively, annual lease differential may be used as a proxy if the impact of salinity is moderate.

A more consistent and practical measure of opportunity cost of wastewater-induced salinity is the cost of soil reclamation measures such as application of gypsum or green manure. As the application of gypsum or green manure is a recurring and ongoing expenditure, it represents a better proxy for evaluating the cost of wastewater irrigation induced salinity. Moreover, it does not require the selection of discount period based on level of salinity because wastewater irrigation

[6]Even under sharecropping, the tenant may require soft terms for salinity-affected land there by reducing the annual return to landlord.

project or policy period itself sets the discount period. Ideally, soil sodium absorptive ratio, a measure of salinity, and corresponding cost of reclamation measures, if supported by available empirical literature, should be used for the valuation of wastewater irrigation induced salinity. If wastewater induced soil salinity is insignificant or damage to the soil productivity is minor, cost of soil reclamation measure will be a good proxy for all economic valuation purposes (though some upward adjustments would be required as gypsum prices are highly subsidized in Pakistan).

In summary, as the impact of salinity varies from severe to moderate to minor, the appropriate proxies for the valuation of wastewater induced salinity damage are sale value differential, annual lease differential, and cost of soil reclamation measures respectively.[7]

8.6 *Groundwater Resources*

Two principle effects of wastewater irrigation that require economic valuation are groundwater recharge (a benefit item), and nitrate contamination of groundwater resources (a cost item) through leaching and drainage.

The annual contribution of wastewater irrigation towards groundwater recharge in volumetric terms can be estimated, based on the amount of wastewater applied and the leaching fraction. The recharge volume can be converted into economic terms by using market prices of water. Since, water resources are not priced at their true opportunity cost in Pakistan, appropriate proxies can be used to estimate a dollar value of the benefits of groundwater recharge. The suggested proxies are:

- cost of domestic water supply per capita, and
- cost of irrigation water supply per cubic meter.

The economic rationale behind using these proxies is that the groundwater is a major source of domestic and agricultural water supplies, and the depletion of groundwater resources in the absence of recharge, may have serious economic, social, and ecological consequences. Hence, the relevant measures of economic value of water is the cost of domestic water supply per capita, (for example in Faisalabad, water is supplied by a pipeline from river Chenab located some 30 km away from Faisalabad.)

Literature has cited two health problems associated with excess nitrate levels in drinking water. The first- methaemoglobinaemia, that is caused in bottle-fed infants due to oxygen starvation, the second- stomach cancer caused by the formation of carcinogenic compounds. While the evidence on stomach cancer is inconclusive, cases of methaemoglobinaemia have been reported in UK and elsewhere (Hanley and Spash 1993). Health concerns associated with excess nitrate levels have therefore, prompted WHO to recommend an upper limit of 50 mg/l in drinking water.

If the groundwater survey reveals excess nitrate levels in drinking water in Faisalabad, the nitrate risk to human health should be evaluated and incorporated into economic analysis of wastewater irrigation. The evaluation of risk from contaminants migrating by groundwater, for example nitrates, however is a complex and difficult task. The general evaluation of nitrate

[7]Two other proxies for economic valuation of salinity are: (1) cost of desalinization or removal of saline content per acre inch of wastewater, (2) cost of regulation and community-based initiatives to reduce salt enrichment of domestic sewage.

pollution risk involves the identification of risk agent, its fate and transport through soil, estimation of human exposure, and conversion of this exposure into the risk level. The risk level can be quantified on the basis of risk factor (risk per unit of intake) and total potential intake. In view of the uncertainty in consuming nitrate polluted water and dose response functions, the total risk level can be expressed as a distribution rather than a single estimate from which mean risk factor affecting a population cohort can be estimated.

Alternatively, a simpler method to estimate the amount of nitrates added to groundwater, is to use wastewater nitrogen application rates, nitrogen leaching fraction and base level nitrate concentrations in groundwater, to calculate the concentrations leaching annually. Leaching fraction can be calculated as the concentration of available nitrogen minus nitrogen required by the crop. If nutrients are undersupplied than crop requirements, leaching fraction can be assumed as a fraction of supplemental fertilizer dose (for example, 30%, though it will be advisable to use the estimate developed by regional irrigation and drainage studies).

The nitrate-related risk to human health can be evaluated using human capital approach and opportunity cost principle as described under the valuation of health impacts earlier. Assuming that nitrate pollution already exists in the study area, an alternative approach would be to use contingent valuation method, to ask households to state their maximum willingness to pay per annum to enable the reduction of nitrate concentrations in drinking (ground) water to WHO limit of 50 mg/l. In a follow up questionnaire, respondents can be given additional information that high nitrate levels can lead to a higher cancer risk, in order to assess their risk valuation and willingness to pay for changes. The mean bids, with full information, can be aggregated over the entire population of Faisalabad to estimate regional benefit (or alternatively cost) of averting nitrate pollution of groundwater resources.

8.7 *Property Values*

Groundwater quality, public health risk, and discomfort associated with odor, nuisance, and poor hygiene caused by wastewater irrigation, has a negative impact on property values. Hedonic pricing studies show that people discount the risk of proximity to polluted streams and waterfront when placing values on properties. Moreover, there is documented evidence in literature that depreciation of property values may sometimes be solely due to belief that risks persist. Thus both, actual and potential risk to property values due to wastewater irrigation should be evaluated in economic terms.

Hedonic price models can be used to place monetary values on property attributes. For example, attributes such as size, location, proximity to roads, markets and major population centers, productivity and fertility index, land rent and annual lease revenue, availability of canal/ groundwater, agroforestry, earthwork investments, and more importantly proximity to wastewater irrigation sites, can be valued using this method. If the effect of income and other demographic variables remain constant, the proximity risk premium for properties located near sources of wastewater-related pollution might be estimated. The problem of paucity of data in itself should not arise since empirical data on real estate sales are recorded on a regular basis, (notwithstanding the difficulty in accessing these data) by The Revenue Department, Punjab, Pakistan.

8.8 *Ecological Impacts*

Ecological impacts would be those related to eutrophication of water bodies from nutrient rich drainage water, in the vicinity of wastewater agricultural areas and those related to buildup of heavy metals and toxic contamination of ecosystem components. Eutrophication affects fish species and fish populations and thereby commercial fishing at such places (income loss). Another consequence of eutrophication is the disappearance of popular fish species important for recreational fishing (welfare loss to general public). The loss of potential income to commercial fish farms and loss of welfare to recreational fisherman can be evaluated using contingent valuation method. For this purpose, the respondents can be divided into: (1) those who go fishing and (2) those who do not go fishing. A willingness to pay (and willingness to accept) question can be asked to solicit bids for management programs for controlling wastewater related eutrophication problems so as to maintain current levels of fish in the ecosystems. A positive willingness to pay, even by non-fishing population, would indicate that people disregard the risk of eutrophication-related fish destruction.

The bids for fishing and non-fishing populations can be used to generate estimates of welfare loss to the general public and this estimate in turn can be added to income loss to aquaculture and commercial fishing to generate an aggregate eutrophication economic loss to regional fisheries.

8.9 *Social Impacts*

The social concerns about the potential risk of wastewater irrigation originate from general concerns regarding impacts on environmental quality, public health and safety, and concerns about the non-sustainability of natural resources. These concerns may be addressed with appropriate educational and public awareness programs. Thus, the cost of public education, awareness and demonstration programs can be used as a proxy for the valuation of social impacts of wastewater irrigation programs, using adult learning and educational models cost estimates may be developed.

The agribusiness risk and potential liability concerns can be addressed by seeking insurance against these potential risks. The insurance premium to cover the risk of wastewater irrigation can be used as a ‘near proxy’. The underlying premise is that insurance providers are profit seeking commercial firms who would set the premium over and above the true cost of risk involved in wastewater irrigation. Hence, the risk premium should be adjusted downwards before using it as a proxy for the cost of wastewater irrigation risk to agribusiness. In summary, the cost of public education programs and insurance premium, can be regarded as an opportunity cost of addressing social and agribusiness concerns about the potential risks of wastewater irrigation

8.10 *Indirect Impacts*

As with irrigation systems, wastewater irrigation may also have secondary impacts at a regional or national level. These indirect effects are the creation of employment opportunities and improvements in living standards. For instance, peri-urban areas that use wastewater for crop production for immediate or on-site markets, can become employment centers for labor and open up opportunities for commercializing crops. Landless farmers, who lease agricultural properties as horticultural nurseries, will be able to afford higher standards of living for their families or communities. Thus, the indirect effects of wastewater irrigation such as effects on employment, income levels and its distribution, and social effects such as equity implications, should be assessed.

Secondary effects of wastewater irrigation can be assessed by using input-output models or by applying general equilibrium analysis. However, given the high data requirements and complexity of these models, a simpler method to compare income levels would be to value the secondary effects of wastewater irrigation (a function of employment or resource rents), and use measures of income distribution such as Lorenz curve and Theil entropy change index. Educational attainment index of communities practicing wastewater irrigation and those not utilizing wastewater resources can be compared to assess relative human capital formation.

A review of existing literature on the subject of wastewater irrigation and its impacts has shown that an extensive information base is available on the impacts associated with wastewater reuse on crop production (mainly forage and non-consumable crops). Other impacts have been addressed to a lesser degree. There is a definite need to quantify and value public health impacts and impacts on the resource base. It is also imperative to develop a framework for quantifying and valuing these impacts using economic and noneconomic parameters, where necessary. This should be done with the eventual objective of helping governments to decide the options they choose, when permitting wastewater reuse for agricultural purposes.

As a follow-up to the present report, the authors have developed such a framework.

[For details and actual application including data requirements, please refer to the companion paper on “Framework for analyzing socioeconomic, health and environmental impacts of wastewater use in agriculture in developing countries” (Hussain et al. 2001)].

Annex 1. Note on Environmental Valuation Techniques

Generally speaking, environmental valuation techniques are of two types: those relying on revealed preferences or what humans *actually do* in the markets; and those relying on stated preferences or what humans say they *would do* in a hypothetical market context. Thus both of these approaches attempt to evaluate human behavior in economic terms but they differ in the sense that the former is based on actual or observed behavior while the latter is based on potential or likely behavior. As the revealed preference methodologies are based on actual expenditures, they, however, are better able to predict the underlying human preference structure though data difficulties and statistical problems can affect the quality of results.

The revealed preference techniques include production cost analysis (applied to a wide range of impacts including crops, livestock, forest, and ecosystem), travel cost method (applied mainly to recreation demand studies), defensive/averting cost analysis (applied to healthcare studies) and hedonic price analysis (used for property prices and attribute analysis).

Where wastewater irrigation leads to a measurable change in quantity, quality or cost of production, the resulting change can be measured in monetary units using market or shadow prices. This is called production cost analysis. The travel cost method seeks to quantify the value of travel time and out of pocket or actual travel expenses to provide a measure of the value people place on leisure activities such as angling and sight-seeing. The health effects resulting in morbidity and mortality can generally be quantified by using human capital approach and defensive/ preventive cost analysis. The value of output foregone due to mortality (pre-mature death) or morbidity (sickness) is a proxy for human productivity loss to which actual cost of medical visits, defensive expenditures, and inconvenience cost can be added to derive a cumulative measure of health effects. The mortality-related productivity loss or the value of human statistical life is estimated to be 120 times GDP per capita (Miller 2000). Sickness-related expenses could be calculated from clinical and personal records.

The hedonic price analysis seeks to decompose property prices into: component attributable to property characteristics such as size of the plot, number of rooms, parking spaces, type of heating, north/south aspect, land tax, utility rates, and proximity to civic facilities; and component attributable to environmental variable such as proximity to a landfill or hazardous waste site. Thus the willingness to pay higher property price for being located away from the waste site, for comparable property characteristics, represents the price premium of discomfort associated with proximity to waste site.

The stated preference methodologies, commonly called contingent valuation techniques, are based on surveys where humans are directly questioned by the researchers to place monetary values on goods and services normally not sold in the common market place. Thus, contingent valuation method seeks to replicate hypothetical market conditions to elicit consumer preferences about non-marketed goods: that is, how would they behave if the goods in question *were actually* sold in market. The consumer preferences are sought either in terms of willingness to pay (WTP) or willingness to accept (WTA). Sometimes, a variant of the contingent valuation method, such as Delphi technique, is used for valuation purposes where experts, instead of consumers, are approached to seek their opinion about a particular environmental resource or issue (Edward-Jones et al. 1995). Contingent valuation techniques can be used to evaluate a number on nonmarketed public or environmental goods such as water quality and quantity improvement projects, natural resource conservation projects, assessment of natural resource injuries such as water pollution due to hazardous waste or oil spills, enhancement of environmental quality, ecosystem change, and endangered species conservation etc.

The environmental valuation techniques seek to place monetary values on both marketed and non-marketed goods and services and environmental resources: that is; e*verything* in dollars. Hence, the ensuing ethical concerns with the use of contingent valuation method have, lead to the evolution of two *nonmonetary* approaches to valuation: conjoint analysis; and habitat equivalency analysis (Braden 2000). The habitat equivalency analysis seeks to identify which bundle of natural resources are considered equal to the other damaged resources for example, by the public. No attempt is made to determine their relative importance to the humans, even in physical terms. The conjoint analysis, on the other hand, goes a step further and seeks to: (1) quantify the equivalence in terms of physical units; and (2) assign relative importance in terms of human preference structure. However, both habitat equivalency analysis and conjoint analysis do *not* attempt to translate physical units into monetary terms.

The prohibitively high costs of conducting a contingent valuation study has lead researchers to look for existing studies in literature that are sufficiently comparable to the case under question and use the findings of these studies to make inferences about the new situation. This technique called Benefit Transfer, presents a promising valuation alternative in situations where data are hard to come by and public agency has to make strategic policy decisions.

A detailed description of the valuation techniques, their application, and problem areas can be found in appropriate text such as James (1994), Hanley and Spash (1993), and Pearce and Turner (1990).

Annex 2. Summary of Empirical Evidence on Public Health Effects of Wastewater Reuse

RECENT EMPIRICAL EVIDENCE ON PUBLIC HEALTH IMPACTS OF WASTEWATER REUSE

Year and Author(S)	Main Objective	Methodology	Major Findings	Implications
Shuval et al. (1986)	A comprehensive review of credible epidemiological studies on waste-water irrigation.	Health risk assessment model and empirical evidence.	• Pathogenic microbes in high to low disease risk order are: helminths, bacteria, and viruses. • Epidemiological evidence suggests that prevailing wastewater irrigation standards were overly restrictive.	• Proposed guidelines for unrestricted wastewater irrigation viz: 1 nematode egg/l and 1000 coliform per 100 ml. • Basis for WHO health guidelines.
Brosnan and O'Shea (1996)	Impact of cumulative abatement of untreated waste-water discharges on coliform concentrations (concs.) in lower Hudson-Raritan Estuary.	Water sampling and analysis to monitor concentrations of total coliforms and fecal coliforms.	• Decline in coliform conc as the results 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. • Abetment of illegal connections, wet weather overflows, and reduced discharge.	• Water quality improvements. • Enhanced recreational resource value. • Cost savings on bathing advisories.
Olivieri et al. (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.	• Secondary treatment using water hyacinths plus advanced treatment generates reclaimed water of acceptable potable quality. • Health risk associated with. • Potable use of reclaimed water is < existing water supply	• Water Hyacinth system as treatment alternative. • Community attitude to potable reuse? • Financial and economic feasibility . in San Diego.
Downs et al. (1999)	Risk screening from exposure to contaminated surface water and groundwater due to untreated waste-water irrigation in Mexico.	Risk assessment based on detection of pathogens, ingestion, and morbidity patterns	• High total coliforms in surface water and lower levels in groundwater. • Fecal contamination of water resources as a potential risk of gastrointestinal disease irritation reported. • Infants and children at risk from. • Frequent diarrhea and skin nitrate pollution. • Risk exists outside and inside irrigation district.	• Pathogenic risk intervention should be a priority. • Nitrate pollution risk determination and possible treatment.
Cifuentes et al. (2000)	Risk factor affecting giardia infections in agri. population in Mexico.	Household exposure to untreated wastewater vs rain-fed agri. villages.	• Children have highest prevalence of infection. • Risk of infection corelated to unprotected drinking water and lack of faeces disposal facilities. • Untreated wastewater exposure has no excess risk. • No risk from agri activities.	• Provision of primary health care and • W/water treatment facilities. • Equity and human capital formation issues.
Habbari et al. (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 behaviors and demographic factors	• Ascariasis prevalence five times higher in wastewater-impactedregions. • 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.	• Adequate treatment of wastewater for irrigation. • Water supply and sanitation program. • Exposure control. • Public health education program.

Annex 3. Summary of Empirical Evidence on Effects of Wastewater Irrigation on Crops

EMPIRICAL EVIDENCE ON EFFECTS OF WASTEWATER IRRIGATION ON CROPS

Year and Author(s)	Main Objective	Methodology	Major Findings	Conclusions/ Implications	* ESD Assessment
Day et al. (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 fiber 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 fertelizer. • 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∅
Sidle et al. (1976)	Uptake of heavy metals by reed canary-grass and maize over time.	Wastewater irrigation for 11 years. Base year as control.	• Higher Cu and Zn conc. and total uptake in reed canary-grass. • Lower Cu and Zn conc. and total uptake in Maize than reed canary-grass. • 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.	• Animal feed program (Cu level in w/w irrigated r-grass may be a problem for sheep feed). • Loadings+ removal @ modeling to evaluate life of a land disposal sys.	+ve$$ -ve♠♠ -ve♣♣ -ve∅
Day and Tucker (1977)	Effect of treated municipal wastewater irrigation on sorghum growth, yield and quality parameters.	Well water+ normal NPK dose vs. well water+ simulated NPK dose vs treated wastewater, no fertilizer.	Wastewater irrigation lead to: • Higher leaf length (more forage) and maturity period. (low cropping intensity). • Higher sorghum grain yields. • Similar protein content, but • Less amino acid content in grains. • Wastewater 'has something in addition to fertilizer elements' that simulated grain production thus more giving higher yield than control(s).	• Treated w/w: a potential source of irrigation water plus a rich source of fertilizer. • Fertilizer cost savings. • Higher potential yields.	+ve$$ +ve♠♠ NA♣♣ +ve∅
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 canary-grass, brome-grass, wild rye, and tall wheat-grass.	• Higher alfalfa yields than other grass sp. • Double N-yield of alfalfa. • N uptake by all grass, except wheat-grass, exceeds w/w N supply. • P supply in w/w exceeds plant uptake.	• 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	+ve$$ +ve♠♠ -ve♣♣ +ve∅

			• For optimal utilization of waste-water, alfalfa is most suitable forage crop (max. N and water uptake). Alfalfa can optimize 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.	utilization and disposal of w/water.	
Marten et al. (1980)	Effect of municipal waste-water irrigation on feed quality and yields of maize vs reed canary-grass.	Parameters: feed quality, dry matter, digestible . Dry matter 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 decline progressively with higher amounts of w/w applications in maize. • Higher crude protein in r-grass, and • Higher crude protein yield per hectare. • Differences increase 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$$ +ve♠♠ -ve♣♣ +ve∅
Ajmal and Khan (1985)	Effect of textile factory effluents on soil chemistry, and germination and growth of two vegetables viz kidney beans and lady's fingers.	• Untreated textile effluent in dilutions of v/v 25, 50, 75, and 100% vs • Normal irrigation water as control • Effect on kidney beans and lady's fingers	• Textile effluent rich in BOD, COD, Cl, SO_4, and trace metals such as Ns, K, Ca, Mg and highly alkaline. • Higher dilution applications led to higher conc. of these elements in soil with top-soil conc. higher than subsoil. • Plant Na increased correspondingly (absorption and translocation). • Irrigation with 100 and 75% textile effluents inhibited germination, and retarded growth. • Irrigation with 50% effluent enhanced growth.	• Diluted textile effluent may be used for crops without affecting soil quality • Textile effluent. as a source of water and nutrients • Industrial policy design	+ve$$ +ve♠♠ NA♣♣ +ve∅
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 by effluent conc. of >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. > 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$$ -ve♠♠ -ve♣♣ +ve∅
Misra and Behera (1991)	Effect of paper industry effluent on growth, carbohydrates, and protein content of rice	Untreated paper industry effluent Various dilutions vs distilled water Effect on rice seedlings as a function of effluent con and exposure time.	• Germination %, growth, and pigment, carbohydrate, and protein contents decline with increase in effluent conc. and exposure time. • Protein content most sensitive to effluent conc. • Protein and protein enzymes as bioindicators of effluent phyto-toxicity. • Pulp and paper industry effluent not suitable for irrigation.	• Pollution regulation for pulp and paper industry. • Evaluation of phytotoxicity and pollution risk. • Point source. pollution control. • Eutrophication control.	-ve$$ -ve♠♠ NA♣♣ -ve∅
Aziz et al. (1995)	Effect of crude oil refinery wastewater irrigation on growth and yield parameters of four varieties of wheat.	Treated oil refinery wastewater vs ground-water 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 long-term impact evaluation. • Industrial pollution abatement policy. • National food security policy.	+ve$$ -ve♠♠ -ve♣♣ -ve∅
Aziz et al. (1996)	Long-term effects of petrochemical refinery wastewater irrigation on heavy metal accumulation in soil and grain and yield parameters of six cereals and legumes viz. wheat, triticale, chickpea, lentil, pigeon pea, and summer moong.	Treated oil refinery wastewater vs. Lake water as control for 8 years Same dose of commercial fertilizer Effect on soil Effect on seed yield of crops	• Treated oil refinery w/w met irrigation standards, hence suitable for crop irrigation. • Negligible accumulation of heavy metals in soil and grains • Grain metal content below permissible limit, thus seed fit for human consumption. • Higher seed yield for all crops, except moong, with w/w irrigation.	• With out crops, fixing of heavy metals in soil may pose future threat of food chain transfers. • Industrial pollution abatement policy. • National food security policy.	+ve$$ -ve♠♠ -ve♣♣ -ve∅
Howe and Wagner (1996)	Effect of paper mill 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: waste-	• 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	• Problem: Na accumulation in paper mill effluent irrigated soils; Management action: gypsum application. • Role of Ca amendment in sodic	+ve$$ -ve♠♠ -ve♣♣ -ve∅

		water pH and gypsum application rate Dep. variables for cottonwood: biomass, stem Na, and Ca, K, and Na in leaves	• 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.	w/w irrigation management . • Potential long-term effects need attention.	
El Hamouri et al. (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, zucchini, beans, tomato) crops.	Domestic origin waste-water with: Raw wastewater vs waste stabilization. Pond treated w/w vs groundwater. Four irrigation methods (surface, 2 sy. drip, sprinkler). Fecal coliform and helminth eggs on crop and in soil.	• WSP treatment produces effluent of WHO's guidelines quality for unrestricted irrigation. • 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 . • High salinity of w/w affects yield negatively. • For salt tolerant crops: small differences in yield among w/w types and groundwater, thus. • Much lower salinity effect. • No helminth eggs found on treated w/w irrigated crops and soils. • Helminth eggs found on raw w/w irrigated crops and soils. • Raw wastewater not suitable for irrigation. • Drip irrigation gives highest performance and crop yield.	• 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. • Arid and saline zone development policy. • Wastewater treatment technology.	+ve$$ +ve♠♠ -ve♣♣ +ve∅
Shahalam et al. (1998)	The suitability of wastewater irrigation for alfalfa, tomato, and radish crops and its effect on soil, and health and groundwater pollution risk.	Treated wastewater below WHO standard vs standard freshwater. With and without fertilizer sub-trt. Effect on crop growth and yields. Soil porosity, pH, sodicity and alkalinity, and drainage. Fecal coliform conc. On vegs and environment.	• Yield trends: • Alfalfa: freshwater with fert. > w/w with fert. • Radish: w/w use insignificant effect. • Tomato: w/w only > w/w with fert. • Wastewater irrigation with fertiilzer gives yield at least comparable to freshwater with fertlizer. • Higher porosity, lower pH with wastewater irrigation. • Higher salinity with w/w irrigation though EC value < limit, inconclusive effect in the short run. • Subsurface drainage analysis: no contaminants • Tomatoes free of FC after 24 hours. • Hygienic quality: no odor or aesthetic effects.	• No risk to crops, soil, humans or environment from below guidelines wastewater irrigation, however, chlorination is recommended. • Wastewater irrigation: a way forward to solve Jordan's water scarcity problem. • National water security policy.	+ve$$ +ve♠♠ NA♣♣ +ve∅
Parames-waran (1999)	The agro-economic feasibility of wastewater irrigation for growing Jerusalem artichoke (helianthus tuberosus) in Australia.	Furrow irrigation using raw urban wastewater. Various cultivars of artichoke. Plant biomass-tops and tuber- yield -and nutrient analysis. Soil pH and salinity. Long-term impacts of w/w irrigation.	• Artichoke 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 • Higher nutrient conc. in tops than tubers. • Higher yield of atrichoke using wastewater irrigation than otherwise.	• wastewater as a resource • Artichoke production, an alternative for land disposal of municipal w/w. • Artichoke biomass may be used for many products including ethnol. • Ethnol- pollution	+ve$$ +ve♠♠ -ve♣♣ +ve∅

			• High unit cost with channel water and low with w/w irrigation. • Unit cost of products sensitive to yield-economies of scale. • Sensitivity of production costs needs investigation. • Slight change in soil microclimate. • No change in soil pH • Slight increase in salinity due to Na accumulation as artichoke needs large amount of Ca. • No measurable change in soil nutrient content. • Long-term w/w irrigation lead to nutrient build up and iron accumulation.	free renewable biomass fuel for cars. • Commercialization needs high yields > 70 t/ha. Biomass Fuels Program.	
Reboll et al. (1999)	Effect of wastewater irrigation on citrus growth, leaf minerals and yield. 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 detrimental effects on citrus trees.	Flood irrigation with w/w from sewage plant (treated) vs groundwater Growth: height, trunk and canopy diameter Yield: fruits/tree Fruit quality: fruit weight, diameter, color, acidity, ripeness index, TSS, and juice, peel, and flesh % Soil N, and Na, Cl, and B	• Plant height and diameter not affected by w/w irrigation. • Higher canopy dia. with w/w irrigation. • Higher nutrient content in w/w may cause excessive veg. growth and late ripening. • Fruit yield not affected by w/w irrigation. No effect on fruit quality due to higher B content in w/w irrigation. • Overall fruit quality not affected by w/w irrigation. • No detrimental effects on citrus plants after 3 years of w/w irrigation. • High B content in w/w but no effect on soil B and no B-toxicity in plants. • Soil N and Cl content not affected by w/w irrigation. • Higher soil Na content due to w/w irrigation (low permeability).	• Reclaimed wastewater a suitable alternative source of water supply for citrus production. • Wastewater irrigation for citrus can reduce fertilizer costs. • Citrus is an economically important crop in Spain, therefore w/w irrigation has economy wide implications.	+ve$$ -ve♠♠ -ve♣♣ +ve∅

* Ecologically sustainable development (ESD) criteria are used for evaluating the impacts of wastewater irrigation. These criteria are preferable to conventional economic analysis criteria, as argued by the World Bank (Pezzy 1992; Munasinghe 1993),[8] as they allow the assessment of holistic impacts against a common yardstick in a dynamic framework. The ESD criteria are:

($$) 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. NA means not assessed and represents a situation where a clear opinion cannot be established by the authors.

[8]Similar criteria have recently been used by Sydney Water (Australia) for the development and evaluation of its "Draft 2000-2005 Environment Plan."

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