Wat. Sci. Tech. Vol. 21, Brighton, pp. 567–577, 1989.

0273–1223/89 $0·00 + ·50

GENERALISED MODEL OF THE EFFECT OF DIFFERENT CONTROL MEASURES IN REDUCING HEALTH RISKS FROM WASTE REUSE

U. J. Blumenthal*, M. Strauss**, D. D. Mara*** and S. Cairncross*

**Department of Tropical Hygiene, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, U.K.*
***International Reference Centre for Wastes Disposal, Ueberlandstrasse 133, CH-8600 Duebendorf, Switzerland*
****Department of Civil Engineering, The University, Leeds, LS2 9JT, U.K.*

ABSTRACT

Health risks from wastewater and excreta reuse are assessed using an epidemiological definition of attributable risk instead of the presence of a microbiological hazard. Measures for health protection need not rely on total pathogen removal by waste treatment processes but may include ways to prevent direct human exposure to the wastes. The range of possible options for health protection includes: waste treatment, crop restriction, localised application methods, control of human exposure, and combinations of the different methods. A generalised model is used to show the effectiveness of each option in reducing health risks to agricultural workers and consumers of the crops grown. Three different regimes are available for rendering waste reuse 'safe' to both workers and consumers, and several regimes are capable of reducing but not eliminating health risks. Case studies are given of the application of the model to wastewater and excreta reuse in agriculture and aquaculture in 6 different countries. The model can be used to aid decisions by planners and engineers to ensure that health protection measures are targetted towards specific exposed groups in the population, within their local context.

KEYWORDS

Waste reuse; wastewater irrigation; health; epidemiology; waste treatment; localised irrigation; helminths; bacteria; viruses.

INTRODUCTION

The use of wastewater and excreta in agriculture and aquaculture is a widespread practice, throughout the world. The use of sewerage in urban areas has increased over the past few decades, and the desire to use the effluent productively has rapidly increased, particularly in arid and semi-arid areas. The impetus for the use of wastes comes from a shortage of fresh water for irrigation, together with a need to increase agricultural production and, in some cases, shortage of cash needed to purchase mineral fertilizers. Thousands of wastewater use schemes exist worldwide, but only relatively few have been designed and set up deliberately to provide good health protection for both agricultural workers and the consumers of the crops grown. There is a need to upgrade existing practices to incorporate measures for protecting the health of exposed groups of people, and a need to help those designing new waste use schemes to include appropriate health protection measures. This must be based on an accurate knowledge of the risks to human health posed by the use of wastes.

Measures of health risks

In the past, assessment of the risk to health from the use of human wastes was based on microbiological criteria. A **'potential risk'** was said to occur when pathogenic microorganisms were detected in wastewater or on crops, even if no cases of disease due to these microorganisms were detected. However, this uses the lay concept of risk, which is defined as the exposure to the chance of infection that might occur, but that does not at present occur. This is in contrast to the epidemiologist's definition of risk, which is the probability of an individual developing a given disease over a specified period. An epidemiological approach to risks associated with use of wastes has been advocated (Feachem and Blum, 1984) in which decisions are based on **"actual risks"** rather than potential risks.

It is possible that a 'potential risk' may not become an 'actual risk' due to factors including pathogen survival, minimum infective dose, human behaviour, and host immunity. In addition, a particular infection may have other routes of transmission in the community, so that some of the disease observed may not be associated with waste use. Therefore, the most useful measure is that of **'attributable risk'** or 'excess risk', which is a measure of the amount of disease associated with a particular transmission route within a population; in this case, the amount associated with waste reuse. This can only be measured by comparison of two populations, one exposed to wastes, and one not exposed to wastes (the control population). The difference in disease between the exposed and control populations, and not simply the amount of disease in the exposed population, is a measure of the risk attributable to waste use. Epidemiological studies are thus the only type of studies which can measure actual risks associated with waste reuse.

EPIDEMIOLOGICAL ASSESSMENT OF HEALTH RISKS

Reviews of available credible epidemiological studies of wastewater use (Shuval et al., 1986a) and excreta and sludge use (Blum and Feachem, 1985) led to an assessment of health risks associated with the use of untreated wastewater and excreta in agriculture and aquaculture (Table 1) which was also consistent with theoretical considerations (Shuval et al., 1986b; IRCWD, 1985). In this assessment, the parasitic worms that are often grouped together under the term helminths, are referred to separately. The nematodes are roundworms, the trematodes are flatworms, and the cestodes are tapeworms. The intestinal nematodes have a worldwide distribution, whereas the trematode and cestode infections have more localised distributions.

The high excess of intestinal nematode infections and lower excess of bacterial and viral infections is in contrast to previous expectations. The intestinal nematodes are among the most common of human infections; for example, about 1 in 4 of the world's population is infected with Ascaris, which is found worldwide where conditions of environmental hygiene are low. The intestinal nematode infections are most prevalent in developing countries and generally have symptoms which are more chronic than acute, and this may have contributed to their being overlooked in the past.

Guidelines for wastewater quality and measures for health protection

Acceptance of the epidemiological assessment of health risks led to a proposed change in the guidelines for the quality of treated wastewater, to include a guideline for helminthic quality (IRCWD, 1985; Shuval et al.,1986b) for the protection of both agricultural workers and crop consumers, as well as a reduction in the guideline for bacteriological quality. These changes were first agreed by a group of specialists meeting at Engelberg, Switerland in 1985 and have recently been confirmed by a Scientific Group of the World Health Organization. It was felt that the new guidelines could be readily achieved through a variety of treatment technologies but that, in many cases, a waste stabilisation pond system would be most appropriate. Where no restrictions were made on the types of crop grown, a pond series with a longer retention time would be required than where crop restrictions were enforced. Use of conventional secondary treatment technologies was not recommended, since these are not effective against helminth eggs, of which several hundred may be found in every litre of domestic wastewater.

TABLE 1 Relative health risks from the use of untreated excreta and wastewater in agriculture and aquaculture

Class of pathogen	Relative amount of excess frequency of infection or disease
1. Intestinal nematodes:	High
Ascaris	
Trichuris	
Hookworm	
2. Bacterial infections:	Lower
bacterial diarrhoeas (e.g. cholera)	
typhoid	
3. Viral infections:	Least
viral diarrhoeas	
hepatitis A	
4. Trematode and cestode infections:	From high to nil, depending upon the particular excreta use practice and local circumstances
schistosomiasis	
clonorchiasis	
taeniasis	

FURTHER OPTIONS FOR HEALTH PROTECTION

In protecting the health of those exposed to wastes, the focus of attention in the past has been on the use of waste treatment as the only feasible and fully effective measure for the reduction of health risks. However, this places most emphasis on microbiological criteria, and an absence of 'potential' risks by pathogen removal, and does not fully incorporate the concept of excess or attributable risk. Moreover, there are some situations where full treatment of wastes is not feasible or even desirable, due mainly to economic constraints. It is therefore necessary, as well as possible, to consider ways for the protection of human health other than waste treatment, especially where economic constraints are felt. This approach was taken by the World Health Organization and the United Nations Environment Programme in their Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture, prepared by Mara and Cairncross (1987) and reviewed at Adelboden, Switzerland in 1987. Four options for health protection must be considered. These are:

- waste treatment;
- restriction of the crops grown;
- choice of methods of application of the wastes to the crops; and
- control of human exposure to the wastes.

The points at which these four health protection measures can interrupt the potential transmission routes of excreted pathogens are shown in Fig 1. While full treatment stops excreted pathogens from even reaching the field or fishpond to which the wastes are applied, crop restriction and human exposure control act later in the pathway, preventing excreted pathogens from reaching the persons concerned, the crop consumers and the agricultural workers.

Some of these health protection measures may not be considered fully efficient in preventing transmission of pathogenic micro-organisms, and some

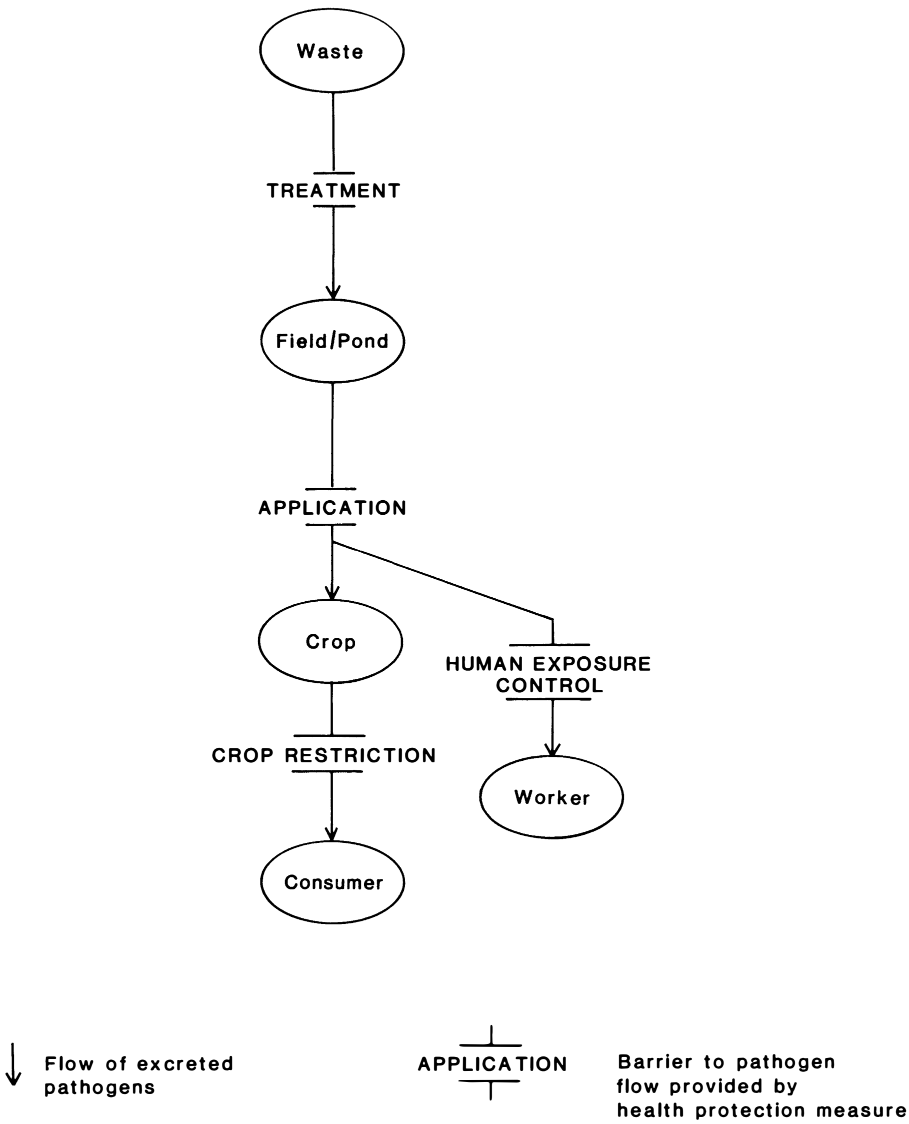

Fig. 1. Flow diagram to show the potential transmission of excreted pathogens and points at which different health protection measures can interrupt the pathogen flow

do not act on both the consumers and the workers. The purpose of the generalised model (Fig 2) is therefore to demonstrate that there are ways to combine the various options for health protection to achieve the same reduction in health risks as achieved by full treatment of the wastes. The model is intended to be an aid to thinking and to decision making. It demonstrates that there is a range of options for protecting agricultural workers and the crop-consuming public, and allows a flexibility of response to different situations. Each situation can be considered separately, and the most appropriate option chosen for that situation, taking into account economic, cultural and technical factors. Measures for health protection can be 'targetted' towards the specific exposed groups in the population, rather than being aimed at protecting unspecified groups, who may or may not actually be exposed.

DESCRIPTION AND USE OF THE MODEL

The model is made up of 5 concentric bands, each representing steps on the pathway from the waste itself to the human consumer or worker. Pathogen flow is from the wastewater or excreta on the outside towards the workers and consumers in the centre. The thick black circle between the crop band and the worker band therefore represents a barrier beyond which pathogens should not pass if health is to be protected. The level of contamination of the wastewater or excreta, the field or fishpond to which it is applied, and the crop (plant or fish) which is being fertilized, is shown by the type of shading employed. A white area indicates no contamination. In the centre, the level of risk to the agricultural worker and the crop consumer is also shown by the level of shading: a white area in the centre indicates no risk to human health and therefore indicates that the strategy employed leads to the 'safe' use of the wastewater or excreta. The model is a simplification of reality, and although it should apply to most situations of reuse of wastewater or excreta in agriculture and aquaculture, there will be some cases where it does not accurately represent the level of risk involved.

From the top sector of the model, it is clear that when no protective measures are used (that is, with the use of raw wastewater or excreta applied directly onto the field or the fishpond) then contamination is present throughout and both agricultural workers and consumers of the crops are at high risk. On the other hand, when **full treatment** is given to the waste (regime H), pathogenic microorganisms are removed at source, no contamination remains, and there is no risk to either workers or consumers. In this case, full treatment is used to describe treatment of wastewater to meet the guideline for unrestricted irrigation in terms of both helminthological and bacteriological quality, or treatment of excreta which would make restriction of the crops grown unnecessary. Wastewater of the required quality could be achieved by several means; firstly, by waste stabilisation ponds of about 25 days' total retention time; secondly, through upgrading existing secondary (mechanical or biological) treatment plants by addition of maturation ponds; and, thirdly, through the use of well designed and operated tertiary treatment plants including filtration and chlorination. The efficiency of the second and third options is less well known than that of the first, and more research is needed into pathogen (especially helminth) removal by these methods.

Moving around the model clockwise, and considering the options for health protection singly at first, it is clear that **crop restriction** by itself (regime A) is a good measure for the protection of consumers since either consumable crops are not grown, or the crop grown is cooked before consumption. A wide range of crops is allowed under this regime, including cereal crops, industrial crops, fodder crops, pasture and trees, including fruit trees. Under some circumstances vegetables growing well above the ground (such as chillies, tomatoes and green beans) or vegetables eaten cooked (such as potatoes) may also be allowed. Although crop restriction protects the health of consumers, it does nothing to protect agricultural workers who remain at high risk since they are still exposed to pathogens in the waste.

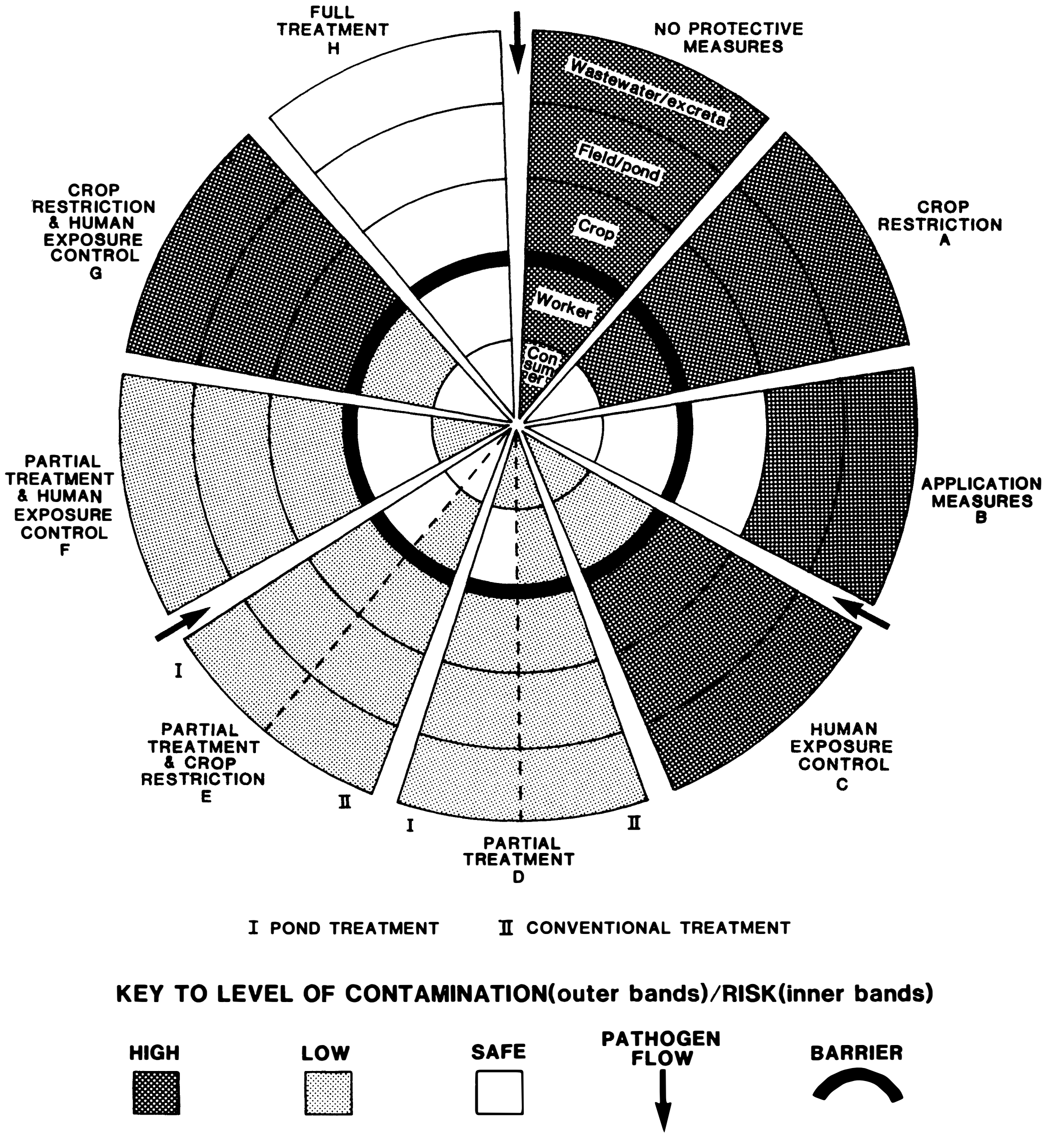

Fig. 2. Generalised model of the effect of different control measures in reducing health risks from waste reuse

Careful choice of the method and timing of **application** of the waste can be very effective (regime B): if it is applied directly to the roots of the crop, then no contamination remains where the workers walk and none reaches the edible part of the crop, so both workers and consumers are safe. In excreta use, this could occur when excreta are applied to the field in covered trenches before the start of the growing cycle. In wastewater use this could occur through the use of localised drip or bubbler irrigation where row crops (eg. fruit trees) are grown. This method of application has the advantage of using water more efficiently and often producing higher crop yields, as well as giving the greatest degree of health protection. At present, however, effluent used in drip irrigation generally requires some mechanical treatment, to remove the settleable solids before application, even though treatment to provide pathogen removal is not a requirement. A lower grade effluent can be used in bubbler irrigation.

Methods of **human exposure control** (regime C) can be used for both workers and consumers. These methods aim to prevent people from coming into direct contact with the pathogens in the wastes, or to stop contact with the pathogens from leading to the manifestation of disease. Measures to protect workers include the wearing of protective clothing (to prevent contact with pathogens), increased levels of hygiene (to remove any pathogens present), and possibly immunisation or chemotherapeutic control of selected infections which could be used as a temporary palliative measure (to prevent infection leading to disease). Measures to protect consumers include increased levels of hygiene and thorough cooking of the food concerned. In practice, such measures are rarely fully effective on their own, and a reduced level of risk to both groups remains.

Partial treatment of wastewater (regime D) causes a reduction in the level of contamination, but the effects of this vary between treatment technologies. Treatment in a waste stabilisation pond system for about 8-10 days (regime DI), or equivalent methods, removes helminth eggs sufficiently to protect the health of agricultural workers and consumers. However bacteria removal is only sufficient to reduce but not eliminate the risk to consumers of vegetable crops. Conventional secondary treatment, (regime DII), does not guarantee sufficient helminth egg removal and a reduced level of risk remains for both workers and consumers.

Moving further around the model, the effect of combinations of different methods is shown. A combination of **partial wastewater treatment**, using waste stabilisation ponds (or equivalent), **and crop restriction** (regime EI) provides full protection to both workers and consumers. This is particularly useful in situations where there is demand for the type of crops in the restricted range, but where full treatment of the wastes is not possible. Crop restriction plus conventional treatment to secondary level (regime EII), however, may still leave the workers at some risk, particularly concerning intestinal nematode infections. This emphasises the need to be careful in the choice of treatment technology when the effluent is intended for reuse. **Partial waste treatment** combined **with human exposure control** for both workers and consumers (regime F) would provide full protection for workers, whichever type of treatment technology was employed, since human exposure control would provide an additional barrier. However, it would be difficult to produce sufficient human exposure control in consumers in the absence of crop restriction, and so a low level of risk to consumers may remain. In situations where there is no possibility of treating the wastes, a combination of **crop restriction and human exposure control** (regime G) could be used. In this regime the risk to workers would be considerably reduced, though not eliminated, and the consumers would be fully protected.

Choice of health protection measures

It is easy to see from the model that three regimes are available for rendering waste reuse 'safe' to both agricultural workers and the crop consuming public. These are:

1. Localised application of wastes to the crops (regime B)

2. Partial treatment using waste stabilisation ponds, combined with crop restriction (regime EI).

3. Full treatment (regime H).

Several regimes are available where health risks are much reduced although full 'safety' has not been achieved. Measures providing partial protection could be used within an incremental approach to reducing health risks until it is possible to use a regime providing full protection. Full protection of consumers and a reduced (but low) risk to agricultural workers may be acceptable in some situations, for example where the economic and nutritional returns to farming families from the use of wastes are seen to outweigh the low level of risk from infectious diseases.

The choice of the measure or combination of measures to be used would depend on an analysis of important factors in the local situation. The factors to be considered would include economics, technical factors, socio-cultural factors, institutional capacity and personnel constraints and also existing patterns of excreta-related diseases. In some situations it may be that economic and technical factors make it infeasible to adopt the 'blanket' approach of full treatment of all wastes to protect all potential workers and consumers. In such a situation cultural factors (for example, the type of staple food crops), good institutional capacity and availability of personnel could create good conditions for the enforcement of crop restrictions together with either human exposure control or partial treatment of the wastes. This would be a more 'targetted' approach, focusing the resources on protecting the specific exposed populations and not all potentially exposed populations.

CASE STUDIES OF THE APPLICATION OF THE MODEL

The following examples show current reuse practices where full treatment of wastes does not occur but where other means of health protection are used. In some cases, full health protection of both workers and consumers is not at present achieved, but the model can be used to aid decision-making on suitable additional measures to adopt.

Use of untreated wastewater in agriculture in Mexico

Part of the wastewater from Mexico City is used in semi-arid areas with low annual rainfall. Food production on a year round basis is only made possible by the use of wastewater to supplement scarce supplies of fresh water for irrigation. Crop restrictions are rigorously enforced by staff of the Ministry of Agriculture and Water Resources who run the irrigation system, thereby providing protection to consumers. In one district, wastewater is used to irrigate over 80,000 ha of mainly maize, alfalfa, barley and oats. Prohibited crops include lettuce, cabbage, beetroot, coriander, radish, carrot, spinach and parsley, and some tomatoes and chillies are permitted, since they grow above the ground. No purposeful treatment is given to the wastewater, although some occurs during its passage through over 60 km of channels, and in one case, further 'treatment' occurs in a large storage reservoir. Therefore in some of the areas of reuse, regime (A) applies, involving crop restriction alone, while in other places regime (E) applies, giving partial protection to the health of workers. In some districts, however, it may be necessary to consider the introduction of either partial waste treatment or of human exposure control, to protect the health of the many thousands of agricultural workers involved.

Use of conventionally treated wastewater in agriculture in Tunisia

Wastewater from Tunis is used for irrigation of citrus trees, grown as a cash crop. The largest area is irrigated with wastewater treated in activated sludge plants (with no chlorination). The wastewater is distributed via a system of underground pipes, and the effluent reaches the trees along short furrows coming from wastewater valve outlets located near to groups of citrus trees. The method of application therefore is partially localised. This represents regime EII where partial (conventional) treatment is complemented by crop restriction, but with a further addition of partly localised application of the waste. This regime should provide good health protection to consumers and may provide good protection to the workers. The system works well in an area where fruit trees are a traditional cash crop, and wastewater is in demand since fresh water has become scarce due to increasing salinity of ground water resources. In an experimental area, the Health authorities are testing a refinement of localised irrigation using drip irrigation (regime B) for health protection of both workers and consumers. In this case, secondary treated effluent undergoes some filtration before distribution in overground pipes.

Use of pond treated wastewater in agriculture in Peru

The coastal zone of Peru is very arid, and without irrigation no agriculture can occur. Use of wastewater for irrigation is popular, and a policy of treating wastewater in waste stabilisation ponds has been developed. Wastewater from the town of Ica is partially treated in a waste stabilisation pond system and used to irrigate principally maize and cotton. The area used to be a wine growing area and later switched to cotton as a cash crop. The ponds only provide partial treatment since the retention time is relatively short. The regime adopted is therefore EI on the model, providing protection for consumers and probably also for the farm workers. The enforcement of crop restrictions is assisted by two factors: firstly, the desire to grow cotton and maize as cash crops, and secondly, the availability of fresh water (wells) for the growing of vegetables so that farmers are not forced to use wastewater for vegetable growing. In areas of Peru where fresh water is short and where the growing of non-vegetable crops is less traditional, the enforcement of crop restrictions is more difficult.

Use of treated excreta in agriculture in Guatemala

The introduction of DAFF (dry alkaline fertilizer-producing family) latrines into villages in the volcanic areas of Guatemala has led to the use of the fertilizer in crop production. Most families have only small plots of land of poor quality, which require conditioning and fertilizing for good crop production, so they welcome the fertilizer produced from the double pit DAFF latrines. Investigations in progress will reveal whether the DAFF latrine provides full or partial treatment of the excreta, that is, whether all helminth eggs are rendered non-viable. If the treatment is found to be only partial (regime DII), then it may be necessary to advise farmers to adopt localised application of the fertiliser, some human exposure control (regime F) or some restrictions of the crops grown (regime E) in order to provide full protection to the farmer and the consumer.

Use of wastewater in aquaculture in India

The use of wastewater in aquaculture occurs in the wetlands east of Calcutta. Untreated wastewater is used to fertilize very large fishponds which together cover an area of 4,400 ha, and supply about 10-20 per cent of the fish consumed in Greater Calcutta. The ponds appear to act in a similar manner to waste stabilisation ponds and a process of pathogen removal occurs within them. The fishpond worker, who wades into the pond dragging a net through the water to catch the fish, may therefore be exposed to the equivalent of partially treated wastewater. The consumers of the freshwater fish in this area cook the fish thoroughly before consumption. The regime is therefore similar to regime F, partial treatment and human exposure control. The health of the consumer is probably safeguarded, but the extent of protection of the fishpond worker will depend on how much 'treatment' has occurred in the pond where contact takes place.

Use of excreta in aquaculture in Indonesia

The use of excreta in small scale fish ponds occurs in West Java. The excreta are diluted in all fishponds and may undergo partial treatment in the larger fish ponds, but possibly not in smaller ponds. Fish are cooked thoroughly before eating. The situation is therefore a cross between regime C and F and it is not certain whether there is a low level of risk to aquaculture workers, though there is probably none to consumers.

These examples of current reuse practice have shown how combinations of different protection measures are being used, and how the model can be used to identify exposed groups who may require further protection. Another implication of the model, though, merits attention. Where full treatment is given to wastes, both workers and consumers are 'safe', and there is no need for further protection measures. However, there are countries which not only require treatment of wastewater to a very high quality but also impose crop restrictions before it can be used in irrigation. In one reuse project in the Middle East, domestic wastewater is treated in high-rate plastic biological filters, followed by tertiary treatment in a storage pond and chlorination before reuse in irrigation of cereal crops. In another country, effluent from activated sludge plants is treated by rapid sand filtration and chlorination, and ozonation has been added as a further disinfecting step. Such a series of health protection measures provides a very large safety margin, more than is justified by epidemiological evidence, and more than can be afforded by most countries.

CONCLUSION

In many countries where fresh water sources are scarce, the use of wastewater for irrigation is becoming imperative, to liberate first use water for domestic use. In addition, the use of excreta and excreta-derived products such as sludge, septage and compost is increasingly attractive to poor communities, as the cost of mineral fertilizers rises. Yet, in many of these countries, there is no possibility of providing full-scale central treatment for the wastes, before releasing them for use by farmers. All those involved in making decisions about the use of wastes in agriculture or aquaculture should be aware of the range of options and combinations of measures that are available for health protection, and the effects of the different measures on different sub-groups in the community, as shown in the model presented here. This will enable them to consider the most appropriate option for their particular situation, taking into account cultural, institutional and economic aspects, as well as technical factors. In future, health risks should be assessed using the epidemiologists' concept of attributable risk, and health protection measures or combinations of measures should be targetted towards specific exposed groups in the population, within their local context.

ACKNOWLEDGEMENTS

This work was supported by the International Reference Centre for Wastes Disposal, Switzerland, the World Health Organization and the United Nations Environment Programme. The model was developed during the meeting at Adelboden to review the WHO/UNEP Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture. We appreciate the stimulating suggestions of other participants, particularly Donald Sharp, International Development Research Centre, Canada.

REFERENCES

Blum, D. and Feachem, R.G. (1985). Health aspects of nightsoil and sludge use in agriculture and aquaculture: an epidemiological perspective. Report no. 05/85. International Reference Centre for Wastes Disposal, Duebendorf, Switzerland, 66 pp.

Feachem, R.G. and Blum, D. (1984). Health aspects of wastewater use. In: Proceedings of the International Symposium on Re-use of Sewage Effluent. Institution of Civil Engineers, London, October 30-31. pp. 237-247.

International Reference Centre for Wastes Disposal (1985). Health aspects of wastewater and excreta use in agriculture and aquaculture: The Engelberg Report. IRCWD News, 23, 11-18, December.

Mara, D.D. and Cairncross, S. (1987). Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture: measures for public health protection. United Nations Environment Programme/World Health Organization, Geneva.

Shuval, H.I., Adin, A., Fattal, B., Ramitz, E. and Yekutiel, P. (1986a). Wastewater irrigation in developing countries: health effects and technological solutions. World Bank Studies in Water Supply and Sanitation. The World Bank, Washington DC, 480 pp.

Shuval, H.I., Yekutiel, P. and Fattal, B. (1986b). An epidemiological model of the potential health risk associated with various pathogens in wastewater irrigation. Water, Science and Technology, 18(10), 191-198.