WASTEWATER IRRIGATION AND GROUNDWATER RECHARGE

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PROJECT SUMMARY

Using wastewater for groundwater recharge is an attractive way for seasonal storage and additional water quality improvement through soil-aquifer treatment. The efficacy of soil-aquifer treatment for removal of organic carbon including pharmaceutically active compounds will be studied with soil columns in a greenhouse. Soil columns will also be used to study the fate of organic compounds in soil where crops are irrigated with sewage effluent. Additionally, samples of the upper groundwater below fields and urban areas (parks, golf courses, landscaping) with a long history of sewage irrigation will be taken and tested for organic agricultural compounds and pathogens.

Long-term storage of water via artificial recharge of groundwater (water banking) in times of water surplus provides a valuable source of water for use in times of water shortage. We plan to expand the potential of this technology, which is now pretty well restricted to permeable soils, to finer-textured "challenging" soils that need to be managed to minimize reductions in infiltration rates due to clogging.

OBJECTIVES

1. termine the fate of organic compounds, such as pharmaceuticals and pharmaceutically active chemicals and disinfection byproducts, in vegetated soil columns (grass and alfalfa) in a greenhouse irrigated at various efficiencies with chlorinated secondary sewage effluent. The columns will also be used to determine fate of pathogens in sewage irrigated soil under a companion project under National Program 208, Food Safety (Protecting Groundwater Quality Below Waste-Water Irrigated Fields).

2. Analyze samples of the upper groundwater below agricultural fields and urban irrigated areas (golf courses, parks, landscaping) with a long history of sewage irrigation for pharmaceuticals, disinfection byproducts and other chemicals to evaluate effects of sewage irrigation on groundwater quality. The samples will also be analyzed for pathogens under a companion project.

3. Carry out field and laboratory research to develop optimum management procedures for basins that infiltrate secondary or tertiary sewage effluent for recharge of groundwater and water quality improvement through soil-aquifer treatment. Focus will be on relatively fine-textured soils where clogging, crusting, and fine-particle movement can seriously reduce infiltration rates, and hence, recharge capacities.

NEED FOR RESEARCH

Description of the Problem to be Solved

Increasing populations and finite water resources necessitate more water reuse (Asano, 1998; Bouwer, 1993 and 1999). Also, increasingly stringent treatment requirements for discharge of sewage effluent into surface water make water reuse more attractive. The present focus in the U.S. is on sustainability of irrigation with sewage effluent and of soil-aquifer treatment, particularly the long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment (Lim et al., 2000; Bouwer, 2000; Drewes and Shore, 2001). The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used to treat sewage for reuse. These methods include lagooning, groundwater recharge, and intermittent sand filtration (Bouwer, 1993). While most standards or guidelines for irrigation with sewage effluent focus on indicator organisms and pathogens, other water quality aspects must also be considered (Bouwer and Idelovitch, 1987).

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation of phosphate, metals, and strongly adsorbed organic compounds to the soil matrix, and of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms in groundwater. Water reuse for irrigation is a good practice, however, care should be taken to prevent deterioration of groundwater quality (Bouwer et al., 1999; Bouwer, 2000). Typical concentrations of some potentially endocrine disrupting chemicals in sewage effluent are shown in Table 1, taken from Lim et al., (2000). Other pharmaceuticals such as lipid regulators, antiepileptics, analgesic/anti-inflammatory drugs, and antibiotics can also be present. The microbiological safety of water reuse is also an important issue, particularly when wastewater is used for the irrigation of fruits and vegetables that are eaten raw or brought raw into the kitchen, as discussed in a companion project under National Program 108. It is of utmost importance to understand the risks associated with wastewater used for irrigation and the factors affecting the deterioration of wastewater effluent after it leaves the treatment plant. There is growing concern about the potential for microbial regrowth in the conveyance /distribution systems where the effluent is transported over long distances to the irrigated areas (mostly with pipelines). The aim of this research is to develop technology for optimum water reuse, to evaluate the role that groundwater recharge and soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent (Bouwer, 1985) and to determine the safety of tertiary effluent used for irrigation of foods, particularly where effluent is transported for relatively long distances in pipes or open channels where regrowth of pathogens and other processes can occur.

Relevance to ARS National Program Action Plan

This research directly addresses national and global problems dealing with safety of food produced in fields that have been irrigated with sewage effluent or with effluent contaminated water. It also addresses water conservation and integrated water management through water reuse. These issues occur or emerge in many parts of the U.S. and the rest of the world wherever there is not enough water to meet all demands for municipal, industrial, and agricultural (irrigation) purposes. All objectives fall under National Program 201, Water Quality and Management. Objectives 1 and 2 fall under Problem Area 2.5 (Waste Water Reuse), Goal 2.5.3 (Waste Water Standards). They address water conservation and integrated water management through water reuse. Objective 3 addresses Problem Area 2.3 (Water Conservation Management), Goal 2.3.1 (Water Conservation Technologies).

Table 1. Typical concentrations of some EDCs in treated sewage effluent (Lim et al., 2000).

Compound	Secondary Treatment	Tertiary treatment
Estrogen (ng/L)	38	3
Testosterone (ng/L)	50	2
Estrone (ng/L)	1.4 - 76	1.8 - 3.6
17**$**-estradiol (ng/L)	<5 - 10	2.7 - 6.3
Estriol (ng/L)	<10 - 37	
Ethyinylestradiol (ng/L)	<0.2	<0.2
Nonyl-phenol (µg/L)	<0.02 - 330	
2,4-dichlorophenol (µg/L)	0.061 - 0.16	
Alkylphenols (total)(µg/L)	27 - 98	
Bisphenol A (µg/L)	0.02 - 0.05	
Arsenic (µg/L)	1.3 - 23	
Cadmium (µg/L)	<0.02 - 150	
Lead (µg/L)	0.1 - 44	

Sources: Shore et al. 1993a, Desbrow et al. 1998, Lee & Peart 1998, Blackburn & Waldock 1995, Rudel et al. 1998, Johns & McConchie 1995, Feigin et al. 1991, Bahri 1998.

Potential Benefits

Benefits from attaining the objectives include safe reuse of sewage effluents for irrigation from the standpoint of food safety and groundwater quality protection. Control measures and actions or activities that can be used to prevent, reduce, or eliminate the microbial and chemical food safety hazard will be developed. Water reuse will be more common and the practices will be safer for public health. Such reuse will help in production of adequate food and fiber for growing populations.

Anticipated Products

1. Improved techniques of sewage treatment and system management for safe and sustainable water reuse with minimum adverse effects and in environmentally acceptable ways.
2. New guidelines for irrigation with wastewater to protect groundwater and surface water quality.

3. New procedures for managing groundwater recharge basins to improve their effectiveness, especially where soils are relatively fine-textured.

Customers

Customers of the research include the public, farmers and farm workers, water planners and managers, government regulators, consulting engineers, water districts and municipalities, wastewater treatment plant operators and managers, and the turf, landscape, and golf-course industries.

SCIENTIFIC BACKGROUND

In groundwater recharge, the quality improvements obtained as the effluent water moves downward through the vadose zone to underlying aquifers, and then through the aquifer to recovery wells for irrigation and/or potable use of the water are very important, as are the aesthetic aspects and public acceptance of water reuse. The lead scientist has been at the U.S. Water Conservation Laboratory for more than 41 years where a greater part of his research has been devoted to artificial recharge of groundwater, especially with sewage effluent. Field studies (Flushing Meadows and 23rd Avenue projects), supported by EPA grants, were conducted in the period 1967-1985, as well as numerous laboratory studies on soil columns, focusing on nitrogen transformations and virus transport. At that time, the effluent recharge team consisted of two engineers, a soil chemist, a microbiologist, and for a short period a soil physicist. This work has been published in numerous articles in peer-reviewed journals and book chapters (Bouwer et al., 1980; Bouwer et al., 1984; Bouwer and Rice; 1984) and has put the U.S. Water Conservation at the forefront of institutions in artificial recharge of groundwater and water reuse. However, new concerns have risen over the years, including sustainability issues, food safety issues involving the presence of pathogens in effluent directly used for irrigation, artificial recharge and soil aquifer treatment, trace organic compounds, and groundwater quality issues (Lim et al., 2000; Drewes and Shore, 2001; Bouwer, 2000).

Concern is growing with regard to the refractory natural and synthetic organic materials present in the sewage effluent, both for irrigation and potable use of the reclaimed water. Potable use normally involves release and dilution in natural streams and rivers or a groundwater recharge cycle after conventional primary and secondary sewage treatment. This is done for aesthetic and public acceptance aspects (indirect potable use without toilet-to-tap connection) and for additional quality improvements of the water through soil-aquifer treatment (removal or reduction of suspended solids, nitrogen, phosphorus, synthetic and natural organic carbon compounds, metals, and pathogenic microorganisms). However, not all organic compounds are biodegradable or adsorbed, leaving a residual or refractory total organic carbon concentration (TOC) of 2 to 5 mg/L (Bouwer, 1985). California guidelines for potable use of the water without additional treatments require that this concentration be reduced to less than 1 mg/L. This concentration can be achieved by treating the effluent with activated carbon or membrane filtration before infiltration for groundwater recharge, or by blending with natural groundwater in the aquifer so that the wells yield a water with not more than 1 mg/L of effluent TOC. Several studies have been conducted to identify the composition of the residual TOC (Bouwer et al., 1984; Drewes and Fox, 1999 and 2000; Schoenheinz et al., 2000). Typically, these show a wide spectrum of aliphatic and aromatic, halogenated and non-halogenated compounds, almost all at about the parts per billion (ppb) level. In one study the pharmaceutical clofibric acid was also found (Bouwer et al., 1982). However, perhaps less than 10% of the TOC has been characterized, and there is more concern about what is not known about the residual TOC than what is known about it, even though two major health effects studies in California have not shown adverse health effects in populations where well water with less than 1 mg/L sewage TOC was used for municipal water supply (Nellor et al., 1984; Sloss et al., 1996).

When effluent is used for irrigation, all the chemicals in the effluent, not taken up by the plants and not biodegraded adsorbed or otherwise attenuated or immobilized in the root zone, are leached out of the root zone with the deep percolation water that is necessary to keep a salt balance in the root zone (Bouwer, 2000). This deep percolation water can be produced by irrigation applications in excess of evapotranspiration, or by natural rainfall. In dry climates, the volume of deep percolation water will be considerably less than the irrigation water applied, so that the concentration of salts and other chemicals not attenuated in the root zone will be higher than in the irrigation water. In dry climates, an irrigation efficiency of 80% would produce a deep percolation water with salts and other unattenuated chemicals concentrations that are five times those in the irrigation water. For irrigation with sewage effluent the sewage chemicals of concern are salts and nitrates, natural and synthetic organic compounds (including pharmaceutically active compounds), disinfection by-products (DBPs) including the potent carcinogen nitrosodimethyl amine (NDMA), and humic and fulvic acids that can act as DBP precursors when affected groundwater is pumped up again and chlorinated for potable use. Thus, it is important to study more about chemicals in deep percolation water below sewage irrigated fields so that the potential long-term effects on groundwater can be better predicted and the sustainability of water reuse for irrigation can be better assessed. Membrane filtration of the effluent before irrigation, or of the underlying groundwater where needed for potable use, may eventually become necessary. Irrigation efficiency may play a role in this because while higher concentrations of organic compounds in the deep percolation water may be undesirable, they can also be an advantage if the concentrations become high enough to trigger enzyme expression required for biodegradation by indigenous microorganisms. However, when sewage effluent is used for groundwater recharge, evaporation normally is negligible compared to infiltration, so that concentrations of refractory organic compounds are not increased which may keep them below threshold concentrations for enzyme expression and biodegradation by bacteria.

Where soils are fine-textured and limit the rate of recharge to groundwater, larger infiltration areas that can be combined with wetlands or stream channels may be used to recharge the groundwater. This approach, however results in additional freshwater losses to evaporation and transpiration. Maintaining maximum recharge rates may help to improve the effectiveness of these systems and could extend the benefits of artificial recharge of groundwater and long-term underground storage (water banking) to desert and agricultural areas where sands and other permeable soils are not available (Bouwer 1998). In general, groundwater recharge and soil-aquifer treatment (SAT) systems are fairly robust. From a practical standpoint, we want to avoid very tight soils, very coarse soils, very shallow or very deep groundwater tables, low transmissivity aquifers, geochemical incompatability between infiltrated water and aquifer, and situations with vadose zone or groundwater pollution problems, or where the recharge will cause “unreasonable” harm to other land owners or users, such as land subsidence or damaging high groundwater levels.

A CRIS search of active projects on groundwater recharge identified 22 projects, of which 2 are from this research unit. A majority of the rest deal with natural recharge or return flows from irrigation, and not with artificial recharge systems. Several project dealing with conjunctive use, primarily in the Great Plains, deal with issues that are closely related to this project. Of particular interest is recharge along the South Platte River in Colorado. Conjunctive use is being studied there by Colorado State University. Their results would likely have an impact on our assessment of the value of groundwater recharge. There are 9 CRIS projects on irrigation with wastewater, 2 of which are at the U.S. Water Conservation Laboratory. The project at Mississippi State University with swine effluent is of interest to the microbiologist aspects, including survival of pathogens in the soil. Foliar damage to tree species is studied in Reno, Nevada (2 projects). Effects of irrigation with paper mill effluents on soil are studied in Flagstaff, Arizona. Enhanced pesticide transport in soils irrigated with sewage effluent is studied at Purdue University. Swine waste treatment is studied at Honolulu, while the group at Fresno develops management practices to minimize adverse effects of irrigation with normal water on soils and groundwater. These are all considered complementary to the research proposed herein.

APPROACH AND RESEARCH PROCEDURES

Objective 1 - Fate of Organic Compounds

Experimental Design

Technologies based on previous research at the U.S. Water Conservation Laboratory (USWCL) and other more recent research will be applied to new and existing groundwater recharge and water reuse principles and projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. Ten soil columns in 2.4m x 0.3m stainless steel pipes have been set up in a greenhouse at the USWCL to study movement of pathogens and chemicals (including trace organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and recharge and irrigation with Colorado River water. The columns were filled with a sandy loam from the McMicken Flood Control reservoir northwest of the City of Surprise. This is a desert soil in the Mohall-Laveen Association that has had no agricultural use. The hydraulic conductivity of the soil was determined with a laboratory permeameter test as 280 mm/day, using a disturbed sample. To avoid particle segregation, the soil was placed in the columns in air-dry condition, lowering it in a container and tipping the container when it rested on the bottom of the pipe and then on the top of the soil as the column was filled. The new soil was then compacted with a rod.

The sewage effluent to be used in the column studies should be representative of typical treatment for irrigation. As a minimum, the effluent should have had primary and secondary treatment followed by chlorination. Coagulation and granular medium filtration before chlorination should makes this so-called tertiary effluent suitable for unrestricted irrigation. This includes irrigation of lettuce and other crops consumed raw or brought raw into the kitchen, and of parks, playgrounds, golf courses and residential yards. Also the effluent should primarily be of residential origin with not much industrial input. Proposed irrigation and recharge studies of the 10 columns are shown in Table 2 (Columns 9 and 10 are discussed under Objective 3). Initially, there will be no replications since variability issues theoretically do not exist. Because of space and other physical limitations, only ten columns could be set up. Thus, the schedule in Table 2 was developed so as to include as many different treatments as possible, including different crop and soil conditions (legume, non-legume, and bare soil), different modes of water application (irrigation and recharge, different irrigation efficiencies, and different sources of water (effluent and Colorado River water). The irrigation efficiencies in Table 2 will be determined as ET divided by amount of water applied and expressed as a percentage. ET will be calculated from the weight loss of the column as measured with load cells on which the columns are resting. Estimates of irrigation efficiency will also be obtained from EC values of irrigation water and leachate. Depending on the results, however, some replicated treatments may be used in the future to firm up some of the conclusions.

Table 2. Schedule of irrigation and recharge studies for soil columns in greenhouse.

Irrigation			
COLUMN	**COVER**	**IRRIGATION EFFICIENCY**	**WATER SOURCE**
1	grass	50%	effluent
2	grass	70%	effluent
3	grass	90%	effluent
4	alfalfa	50%	effluent
5	alfalfa	70%	effluent
6	alfalfa	90%	effluent
7	bare soil	70%	effluent
8	grass	70%	Colorado River
Groundwater Recharge			
9	bare soil	maximum loading	effluent
10	bare soil	maximum loading	Colorado River

Since U.S. Water Conservation Laboratory and ARS do not have analytical capability for the detection of trace amounts at the part per trillion (ppt) levels of synthetic organics such as pharmaceuticals and pharmaceutically active chemicals contributed to the effluent by human and industrial waste, preliminary tests have been conducted by the Civil and Environmental Engineering Department at the University of California at Berkeley, California, where Dr. David L. Sedlak has an active research program on pharmaceuticals in sewage effluent. The first sample was taken from the Goodyear treatment plant because the effluent there was also used for landscape irrigation and artificial recharge of groundwater. The treatment process consisted of primary and secondary treatment, sand filtration, and UV disinfection. The sample was taken in mid-August in the late morning when the sewage flow was still relatively small. The results showed very low concentrations of pharmaceuticals (Table 3), about an order of magnitude less than what is found in San Francisco Bay area sewage effluents, and close to detection limits, which are normally in the 5-10 ng/L range.

Table 3. Concentrations of selected pharmaceuticals in Goodyear effluent.

Pharmaceuticals	**Concentrations**
ibuprofen	17 ng/L
naproxen	22 ng/L
gemfibrozil	24 ng/L
ketoprofen	12 ng/L
diclofenac	30 ng/L
indomethacine	<3 ng/L
metoprolol	20 ng/L
propranolol	7 ng/L

A better effluent for the column studies may be from the Tolleson sewage treatment plant, which also receives mostly residential sewage and gives only the more typical conventional primary and secondary treatment and chlorination. A sample was sent to the University of California Berkeley for analysis of pharmaceuticals, which showed that the concentrations were more in line with typical values (Table 4). Hence, Tolleson effluent will be used in the column studies. In a companion project, the secondary effluent and the drainage water from the columns will also be analyzed for pathogens using PCR technology since viruses are not always retained by the soil matrix and have a higher potential to migrate to underground aquifers. Overall, these studies will help determine the factors affecting microbial and chemical contamination of groundwater in order to protect our future water resources.

Table 4. Concentrations of selected pharmaceuticals in Tolleson effluent.

Pharmaceuticals	**Concentrations**
ibuprofen	247 ng/L
naproxen	699 ng/L
indomethacine	55 ng/L
metoprolol	133 ng/L

Contingencies

Arrangements were made with the Central Arizona Water Conservation District to obtain Colorado River water from the Central Arizona Project (CAP) Aqueduct at a point where the canal has 100% Colorado River water. The CAP water has been applied in a recharge mode to one column, starting February 10, 2000. This research also relies on cooperation with local municipalities to obtain wastewater and with various collaborators to conduct some chemical analyses. Studies on groundwater recharge rely on field sites of water purveyors. Alternative collaborators may be easily be found.

Collaborations

- Necessary (within ARS); collaboration with microbiologist, Norma Duran, at the U.S. Water Conservation Laboratory is required for the study of pathogens, as described in her Project Plan under National Program 108.

- Necessary (external to ARS); Collaboration with the U.S. Geological Survey is being developed to analyze the water samples for the column and field studies for pharmaceuticals. The USGS has several laboratories and analytical equipment (GC with MS-MS in tandem) for detection levels of 1 to 100 part per trillion (ppt). The USGS has applied for a District Special Initiative Fund to help pay for the analyses, which will also be partly funded by ARS. The analyses will cover a wide spectrum of chemicals, including pharmaceuticals, antibiotics, hormones and hormonally active compounds, disinfection byproducts, and synthetic organic compounds (Table 5). General collaboration will be established with the National Center for Sustainable Water Supplies in the Civil and Environmental Engineering Department of Arizona State University, Tempe, Arizona.

Table 5. Target compounds for USGS National Reconnaissance of Emerging Contaminant US streams

Veterinary and Human Antibiotics	
Tetracyclines	**Sulfonamides**
Chlortetracycline	Sulfachlorpyridazine
Doxyclycline	Sulfamerazine
Oxytetracycline	Sulfamethazine
Tetracycline	Sulfathiazole
Flouroquinolones	Sulfadimethoxine
Ciprofloxacin	Sulfamethiazole
Enrofloxacin	Sulfamethoxazole
Norfloxacin	**Others**
Sarafloxacin	Lincomycin
Macrolides	Trimethoprim
Erthromycin	Carbadox
Erthromycin-H20 (metabolite)	Virginiamycin
Tylosin	Amoxicillin
Roxithromycin	Spectinomycin
	Ivermectin
	Roxarsone

Human Drugs	
Prescription	**Non-Prescription**
Metformin (antidiabetic agent)	Acetaminophen (analgesic)
Cimetidine (antacid)	Ibuprofen (anti-inflammatory, analgesic)
Ranitidine (antacid)	Codeine (analgesic)
Enalaprilat (antihypertensive)	Caffeine (stimulant)
Diltiazem (antihypertensive)	Paraxanthine (caffeine metabolite)
Fluoxetine (antidepressant)	Cotinine (nicotine matabolite)
Paroxetine (antidipressant, antianxiety)	
Furosemide (diuretic)	
Warfarin (anticoagulant)	
Salbutamol (antiasthmatic)	
Gemfibrozil (antihyperlipidemic)	
Dehydronifedipine (antianginal metabolite)	

Industrial and Household Wastewater Products	
Insecticides	**Polycyclic aromatic hydrocarbons (fossil fuel and fuel combusion indicators)**
Diazinon	Napthalene
Carbaryl	Phenanthrene
Chlorpvrifos	Anthracene
cis-Chlordane	Fluoranthene
N,N-diethyltoluamide (DEET)	Pyrene
Lindane	Benzo(*a*)pyrene
Methyl parathion	
Dieldrin	
Plasticizers	**Antioxidants**
bis(2-Ethylhexyl)adipate	2,6-di-tert-Butylphenol
Ethanol-2-butoxy-phosphate	5-Methyl-1H-benzotriazole
bis(2-Ethylhexy)phthalate	Butylatedhydroxyanisole (BHA)
Diethylphthalate	Butylatedhydroxytoluene (BHT)
Triphenyl phosphate	2,6-di-tert-Butyl-p-benzoquinone
Detergent metabolites	**Others**
p-Nonylphenol	Tetrachloroethylene (solvent)
Nonylphenol monoethoxylate (NPEO1)	Phenol (disinfectant)
Nonylphenol diethoxylate (NPEO2)	1,4-Dichlorobenzene (fumigant)
Octylphenol monoethoxylate (OPEO1)	Acetophenone (fragrance)
Octylphenol diethoxylate (OPEO2)	*p*-Cresol (wood preservative)
Fire retardants	Phthalic anhydride (used in plastics)
Tri(2-chloroethyl)phosphate	Bisphenol A (used in polymers)
Tri(dichlorisopropyl)phosphate	Triclosan (antimicrobial disinfectant)

Sex and Steroidal Hormones	
Biogenics	**Pharmaceuticals**
17*b*-Estradiol	17*a*-Ethynylestradiol (ovulation inhibitor)
17*a*-Estradiol	Mestranol (ovulation inhibitor)
Estrone	19-Norethisterone (ovulation inhibitor)
Estriol	Equilenin (hormone replacement therapy)
Testosterone	Equilin (hormone replacement therapy)
Progesterone	**Sterols**
cis-Androsterone	Cholesterol (fecal indicator)
	3*b*-Coprostanol (carnivor fecal indicator)
	Stigmastanol (plant sterol)

Objective 2 - Upper Groundwater Samples

Experimental Design

This is a reconnaissance-type project. Sites for sampling upper groundwater below agricultural fields and golf courses and other urban green areas with a long history of sewage effluent irrigation will be selected on the basis of depth to groundwater (preferably shallow), availability of wells that pump primarily upper groundwater, and cooperation with farmers, irrigation districts, and municipalities. The USGS already has several wells which were sampled for pesticides and industrial contaminants, and which can be used for our studies as well. In addition to natural and synthetic organic compounds (pharmaceuticals, pesticides, etc.), samples will also be analyzed for EC, DOC, and nitrate and possibly other forms of nitrogen. As much information as possible will be obtained about cropping patterns, fertilizer applications, irrigation practices, EC of irrigation water and groundwater, irrigation efficiency, use of herbicides and pesticides, and other agronomic practices.

Contingencies

Arrangements will be made with irrigation districts, municipalities, and landowners to permit sampling water from existing wells. There is enough interest in the effect of sewage irrigation on groundwater that adequate cooperation should not be a problem.

Collaboration

- Necessary (within ARS); collaboration with microbiologist, Norma Duran, at the U.S. Water Conservation Laboratory is required for the detection of pathogens, as described in her Project Plan under National Program 208.

- Necessary (external to ARS); collaboration with the U.S. Geological Survey (USGS) is being developed for chemical analysis of the groundwater samples. The USGS is interested in this because it would be an extension of their NAWQA (National Water Quality Assessment) Program. Focus will be on synthetic and natural organic compounds such as pharmaceuticals, hormones, and hormonally active compounds. General collaboration will also be established with the National Center for Sustainable Water Supplies in the Civil and Environmental Engineers, Department of Arizona State University, Tempe, Arizona.

Objective 3 - Optimum Management Procedures

Experimental Design

Management of groundwater recharge basins: Groundwater recharge of surplus waters (excess river flows, municipal wastewater, etc.) provides an alternative to surface reservoirs for storing water and also provide a mechanism for treating water. A number of unanswered questions are faced with projects that artificially recharge groundwater, including; How much of the recharged groundwater can be recovered? What reduction in quality of the reclaimed water results from the recharge project? Does the recharge water degrade existing groundwater supplies?

Laboratory and field studies will be initiated to develop best management practices for groundwater recharge basins in relatively fine-textured soil where reductions in infiltration rates must be minimized. Emphasis will be on crusting and fine-particle movement (wash out-wash in) in the upper soil profile. Laboratory studies will use 10-cm diameter columns to study basic aspects of wash out-wash in processes such as fine particle movement and accumulation for different soil types and different simulated soil management practices (drying, disking, rolling, etc.). Studies will also be done on small field plots ranging in size from 1 m^2 to about 10 m^2, and on small experimental basins (about 10 x 100 m) which are to be installed as part of a larger recharge system for the effluent of the City of Surprise South Wastewater Treatment plant. The City of Surprise received a research grant from the Arizona Department of Water Resources for this project, with our research unit as a cooperator. Various tillage and management practices will be tested to see how fine particle movement occurs, how it can be minimized, and how infiltration rates can be maximized. The standard practice is to have roughly 30 cm water on the basins for 5 days (wet) followed by 3 to 4 days dry and disking the basins every 8 to 12 months. Modified practices include; extending or reducing the wet period, extending the dry period, varying the water depth, disking more or less often, ripping, scraping, and rolling. The number of basins and treatments will be decided as the project unfolds. The basins will be narrow and long to allow disking and other management practices with regular farm equipment. About 10 such basins will be constructed. The basins will be calibrated as to their infiltration potential, so that results of various treatments can be expressed relative to the original infiltration rates. Infiltration rates will be determined from inflow rates or as fall of the water level at zero inflows, corrected for evaporation. Hydraulic gradients in the soil to indicate surface or deeper clogging of the soil will be measured with tensiometers at different depths. The work will be cooperative with City of Surprise personnel. Construction is expected to begin in August 2001. This is essentially a two-year project (which has been delayed a year and a half because of water rights issues). Depending on the results of this study, we will pursue further projects of this kind.

Water quality improvement through infiltration of sewage effluent for groundwater recharge and soil-aquifer treatment will be studied on 2 large soil columns in the greenhouse (columns 9 and 10 in Table 2). The Colorado River water column will primarily be used to study underground fate of organic carbon analyzed as total organic carbon in the water and its potential for disinfection byproduct formation (tribalomethanes, haloacetic acids, NDMA) when the water after soil-aquifer treatment is chlorinated or otherwise disinfected for potable use. The sewage-effluent column will be used to study the fate of pharmaceuticals in the vadose zone where sewage effluent is used for artificial recharge of groundwater.

Contingencies

Studies on groundwater recharge rely on field sites of water purveyors. Alternative collaborators may easily be found.

Collaborations

- Necessary (within ARS); No necessary collaborators.
- Necessary (external to ARS); City of Surprise AZ. (Letter of intent attached).

Physical and Human Resources

The wastewater irrigation group consists of a research engineer (LS) (100%) and a part-time technician support. Support for the column studies is also provided by a microbiologist and physical science technician on a related research project specifically studying pathogens. There is also general laboratory support including a water quality chemistry lab, a soils lab, and a machine shop. Field facilities include sewage treatment plants and sewage irrigated fields in Arizona and California, and shallow wells for sampling the upper groundwater in a sewage irrigated area west of Phoenix. Additional labor for the column studies is provided through a cooperative agreement with Arizona State University.

MILESTONES AND EXPECTED OUTCOMES

Milestone Time Line: Publication and presentation of results as significant outcomes arise. Demonstration and training programs will be held with potential users as required (Table 6).

Information should be available on the underground fate of sewage chemicals like synthetic and natural organic compounds below sewage irrigated fields and their potential effect on groundwater below sewage irrigated fields or infiltration basins used for artificial recharge of groundwater with sewage effluent. Depending on the results, these outcomes should have a significant effect on water reuse practices around the world, either giving them the green light or a warning about potential adverse effects on human health and underlying groundwater. If the latter is true, best management practices will be developed and tested. The pathogen aspects will be the responsibility of the microbiologist on a related project. The organic chemical aspects of recharge and soil-aquifer treatment systems, as well as principles and practices of water reuse and groundwater recharge in general will be the responsibility of the engineer and chemist.

Since the research addresses practical and real-world problems, it should not be difficult to translate the results into useful concepts. Additional investigations are needed and will be added to the project as funds become available.

National Collaboration

Depending on the results of the column studies and local field studies, the project will be expanded to other field sites in the U.S. and other countries. Preliminary contracts have already been established. This project is also relevant to projects within ARS that focus on manure handling and utilization and could lead to collaboration with other ARS laboratories such as the Natural Resources Institute, Beltsville Area.

ARS is in the process of establishing an initiative on the use of wastewater for irrigation, which is supported by the Irrigation Association. The initiative intends to establish related research projects at Bushland, TX and Florence, SC.

Table 6.

Research Study Components	**end of year 1**	**end of year 2**	**end of year 3**	**end of year 4**	**end of year 5**
Greenhouse soil columns	operation, management and sampling for irrigation and groundwater recharge procedures, chemical analyses, program completed	operation, continued results of chemical analysis interpreted changes in column management as indicated, consider applying animal manure and analyze inflow and outflow for pharmaceuticals	operation continued, manuscripts prepared, spiking infiltration water with tracers and specific chemicals	final reports and manuscript prepared, plan and perform future studies	final reports and manuscript prepared, plan and perform future studies
Field reconnaissance	select sites of wastewater irrigated fields and urban areas and sample water and groundwater for wastewater chemicals	include more sites in other parts of the U.S.	expand sampling program to other countries	prepare final reports for presentation and publication of papers, plan and perform future studies	prepare final reports for presentation and publication of papers, plan and perform future studies
Clogging research	set up laboratory and field studies for soil clogging and mitigation in recharge basins, study crusting and fine particle movement	continue laboratory and field studies for maximizing infiltration rates in fine-textured soils	continue laboratory and field studies for maximizing infiltration rates in fine-textured soils	write papers on best management practices, plan and perform future studies	write papers on best management practices, plan and perform future studies

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