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## Environnement Canada

A review of water reuse and recycling with reference to  
Canadian practice and potential: 2 Applications

By:

K. Exall

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**A review of water reuse and recycling, with reference to Canadian practice and potential:  
2. Applications**

**K. Exall**

**Abstract**

Common water reuse applications include agricultural and landscape irrigation with treated municipal wastewater, industrial recirculation of process waters, rainwater collection, and groundwater recharge for non-potable and indirect potable reuse. As compared to other countries worldwide, water reuse is currently practised infrequently in Canada, with the focus of most of the water reuse effort within Canada on agricultural irrigation applications. Landscape irrigation and other non-potable urban uses are practised to some extent, but provide an opportunity for expanded application of reclaimed water. Similarly, while water recycling is practised to various degrees within specific industrial sectors, further industrial water reuse and recycling affords an opportunity to conserve large volumes of water. The Canada Mortgage and Housing Corporation (CMHC) has supported a great deal of research into treatment and reuse of domestic greywater for non-potable uses within individual buildings, as well as some work on rainwater collection and use. Groundwater recharge and potable reuse are practised to some extent in extremely dry regions of the world, but public health concerns with respect to emerging trace contaminants may limit the spread of these reuse applications. The main issues associated with each of the above applications are reviewed, and the state of Canadian water reuse and recycling is described.

**Aperçu de la réutilisation et du recyclage de l'eau en fonction  
des pratiques et des possibilités au Canada :**

**2. Applications**

**K. Exall**

**Résumé**

Parmi les applications courantes de la réutilisation de l'eau non potable et de la réutilisation indirecte de l'eau potable, on trouve l'irrigation des terrains et des terres agricoles au moyen d'eaux usées traitées provenant des municipalités, la recirculation des eaux de traitement industrielles, la collecte des eaux de pluie et l'alimentation des nappes d'eau souterraines. Comparativement à d'autres pays, la réutilisation de l'eau est une pratique peu courante au Canada, où la plupart des projets de réutilisation concernent l'irrigation agricole. Bien que certains projets d'irrigation des terrains et d'autres utilisations urbaines d'eau non potable soient en cours, de telles applications constituent d'excellentes occasions pour accroître l'utilisation de l'eau recyclée. De même, bien que l'on recycle l'eau à différents degrés dans certains secteurs industriels, une plus grande réutilisation de l'eau et un recyclage accru permettraient de conserver de plus grands volumes. La Société canadienne d'hypothèques et de logement (SCHL) a financé de nombreuses études sur le traitement et la réutilisation des eaux ménagères à des fins d'utilisation d'eau non potable dans des immeubles individuels; certaines études de la SCHL ont aussi porté sur la collecte et l'utilisation des eaux de pluie. Le réapprovisionnement en eau des nappes souterraines et la réutilisation de l'eau potable ont cours dans une certaine mesure dans les régions extrêmement sèches du monde, mais la présence de contaminants-traces dans ces eaux préoccupe les autorités de la santé publique et pourrait limiter les applications de la réutilisation de ces eaux. Les principaux enjeux liés à chacun des éléments ci-dessus sont examinés dans le document qui fait le point sur la réutilisation et le recyclage de l'eau au Canada.

## **NWRI RESEARCH SUMMARY**

### **Plain language title**

A review of water reuse and recycling, with reference to Canadian practice and potential: 2. Applications

### **What is the problem and what do scientists already know about it?**

In water reuse, treated municipal effluents are utilized to provide a new source for non-potable water supply, while at the same time reducing the discharge of polluted effluents into receiving waters, thus reducing their pollution. Applications of water reuse are increasing throughout the world, and are beginning to gain popularity in Canada, particularly in B.C. and the Prairie provinces. This paper served to review applications of water reuse, with reference to past and potential applications in Canada.

### **Why did NWRI do this study?**

While applications of water reuse are becoming more frequent around the world, the knowledge in Canada has not been compiled and reviewed. A literature review was done in preparation for the CCME Linking Science to Policy Workshop on Water Reuse and Recycling; this work arose from that review.

### **What were the results?**

Various applications of water reuse and recycling were reviewed, including agricultural irrigation, non-potable urban uses, greywater reuse, industrial reuse, rainwater/stormwater collection and use, surface water and groundwater recharge, and potable reuse. Associated with each application are specific water quality, public health and technical issues. Canadian experiences are described in the context of global practices.

### **How will these results be used?**

This review is intended to inform Canadian environmental professionals about the current and potential practices of water reuse; this information can be used as a starting point in planning and implementation of new water reuse projects or guidelines.

### **Who were our main partners in the study?**

N/A, although this work arose from the CCME Linking Science to Policy Workshop on Water Reuse and Recycling.

## **Sommaire des recherches de l'INRE**

### **Titre en langage clair**

Aperçu de la réutilisation et du recyclage de l'eau en fonction des pratiques et des possibilités au Canada : 2. Applications

### **Quel est le problème et que savent les chercheurs à ce sujet?**

Dans les projets de réutilisation de l'eau, les effluents municipaux traités sont utilisés comme nouvelle source d'eau non potable, ce qui permet de réduire les rejets d'effluents pollués dans les eaux réceptrices et, par conséquent, d'en réduire la pollution. Le recours à la réutilisation de l'eau augmente de par le monde et cette stratégie gagne en popularité au Canada, surtout en Colombie-Britannique et dans les Prairies. Le présent article a permis d'examiner certains aspects de la réutilisation de l'eau, notamment en ce qui a trait aux applications antérieures et aux possibilités de recourir à cette technologie au Canada.

### **Pourquoi l'INRE a-t-il effectué cette étude?**

Malgré la popularité croissante des projets de réutilisation de l'eau dans le monde, au Canada, les données à cet effet n'ont pas été compilées ni examinées. Une revue de littérature a été faite lors de la préparation de l'atelier du CCME sur les liens entre les sciences de l'eau et les politiques de réutilisation et de recyclage de l'eau; le présent article est né de cette revue de littérature.

### **Quels sont les résultats?**

Différentes applications pour l'eau réutilisée ou recyclée sont examinées, dont l'irrigation agricole, les utilisations urbaines d'eau non potable, la réutilisation des eaux ménagères et industrielles, la collecte et l'utilisation des eaux de pluie, l'apport d'eau de surface et le réapprovisionnement des nappes souterraines de même que la réutilisation de l'eau potable. Les enjeux liés à la qualité de l'eau et à la santé publique de même que les problèmes techniques sont indiqués pour chaque application. L'expérience canadienne dans le domaine de la réutilisation de l'eau est décrite dans le contexte des pratiques employées à l'échelle mondiale.

### **Comment ces résultats seront-ils utilisés?**

Le présent aperçu vise à informer les professionnels canadiens de l'environnement des possibilités et des pratiques actuelles en matière de réutilisation de l'eau; ces renseignements peuvent servir de point de départ à la planification et à la mise en œuvre de nouveaux projets de réutilisation de l'eau, ou à l'élaboration de lignes directrices.

### **Quels étaient nos principaux partenaires dans cette étude?**

Sans objet, bien que le présent travail provienne de la préparation de l'atelier du CCME sur les liens entre les sciences de l'eau et les politiques de réutilisation et de recyclage de l'eau.

## REVIEW ARTICLE

# A Review of Water Reuse and Recycling, with Reference to Canadian Practice and Potential: 2. Applications

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Common water reuse applications include agricultural and landscape irrigation with treated municipal wastewater, industrial recirculation of process waters, rainwater collection, and groundwater recharge for non-potable and indirect potable reuse. As compared to other countries worldwide, water reuse is currently practised infrequently in Canada, with the focus of most of the water reuse effort within Canada on agricultural irrigation applications. Landscape irrigation and other non-potable urban uses are practised to some extent, but provide an opportunity for expanded application of reclaimed water. Similarly, while water recycling is practised to various degrees within specific industrial sectors, further industrial water reuse and recycling affords an opportunity to conserve large volumes of water. The Canada Mortgage and Housing Corporation (CMHC) has supported a great deal of research into treatment and reuse of domestic greywater for non-potable uses within individual buildings, as well as some work on rainwater collection and use. Groundwater recharge and potable reuse are practised to some extent in extremely dry regions of the world, but public health concerns with respect to emerging trace contaminants may limit the spread of these reuse applications. The main issues associated with each of the above applications are reviewed, and the state of Canadian water reuse and recycling is described.

**Key words:** water reuse, water recycling, wastewater, greywater, groundwater recharge

## Introduction

Water reuse is gaining popularity throughout the world as an option for supplying a reliable alternative supply of water for applications that do not require high-quality water, freeing up limited potable water resources, while reducing effluent discharges into receiving waters. At present, water reuse is practised in Canada on a relatively small scale, and mostly in isolated cases. Typical examples of such reuse include agricultural cropland irrigation in British Columbia and the Prairie Provinces (BC MAFF 2001; Alberta Environment 2000; Hogg et al. 1997), golf course and landscape irrigation, and isolated facilities and experimental housing (Marsalek et al. 2002; Waller et al. 1998). As water demands increase and the readily available supplies dwindle, the interest in water reuse in Canada will likely increase. The companion paper to this one (Exall et al. 2004) examined incentives for water reuse in Canada, and reviewed a number of issues involved in the implementation of water reuse applications. The goal of this paper is to review Canadian applications of water reuse in the context of global practices. Worldwide, water reuse applications include

agricultural irrigation, non-potable urban and recreational reuse, on-site greywater reuse, industrial reuse, rainwater or stormwater collection and reuse, surface water augmentation and groundwater recharge, and even potable reuse.

## Agricultural Irrigation

One of the most common applications for reclaimed water is as irrigation water for agricultural purposes. Agricultural irrigation with treated wastewater (also known as effluent irrigation) is particularly widely applied in water-starved regions in the Middle East and Mediterranean, but is increasing in practice in other countries, as well. In 1999, California used 48% of its reclaimed water for agricultural irrigation purposes (State of California 2000).

Water reuse for agricultural irrigation is typically separated into restricted and unrestricted uses. The former application involves the use of lower quality water under specific agricultural conditions, and includes the irrigation of such crops or operations as fodder, fibre, seed crops, pastures, commercial nurseries, sod farms, turfgrass and commercial aquaculture. In the latter approach, high-quality reclaimed water is applied for

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irrigation of such crops as foods grown for human consumption and potentially consumed uncooked. However, this form of reuse typically involves other restrictions, such as processing of food crops before sale or use of a specified irrigation method (e.g., reclaimed irrigation water often cannot be applied in such a way that it creates drift of aerosols or comes into contact with the edible portion of the plant; U.S. EPA 1992).

Feigin et al. (1991) reviewed the principles and practices of effluent irrigation in the book "Irrigation with Treated Sewage Effluent." Sources, contaminants, treatment processes, and uses of sewage effluent were discussed, and the effect of irrigation with treated sewage effluent on soil, plants and the environment was reviewed. Examples of practical uses of effluent irrigation were included, with case studies from around the world (including Alberta). Irrigation and fertilization management, and irrigation systems for sewage effluent were also discussed. The main water quality concerns in effluent irrigation pertain to efficient use of irrigation water, salinity, nutrients including nitrogen, phosphorus and trace elements, and microbiological aspects, although more recent contaminants of concern were not covered.

Effective use of irrigation water to meet the water needs of a given crop is a critical aspect of planning for irrigation projects with reclaimed water. The British Columbia Ministry of Agriculture, Food and Fisheries produced the fact sheet "Guide to Irrigation System Design with Reclaimed Water" (BC MAFF 2001), in order to provide a reference for the design of irrigation systems in British Columbia using reclaimed water in accordance with the Municipal Sewage Regulation (MSR). Reclaimed water can be applied with irrigation systems to landscape and agricultural crops in regions with a moisture deficit during the growing season, for frost protection in the spring and fall, and crop cooling purposes during the hot part of the summer. Irrigation systems must be designed and operated in such a way as to make beneficial use of reclaimed water and avoid excessive irrigation. Seasonal irrigation requirements are determined by the crop type and rooting depth, infiltration capability and water storage capacity of the soil, and climatic conditions. Good agronomic practices take these factors into account. Other considerations for the design of effluent irrigation projects include irrigation system selection (e.g., sprinkler or drip), irrigation system application efficiency (which relates to water losses due to spray drift and evaporation from crop and soil surface), and reclaimed water storage systems for daily, seasonal and emergency storage (BC MAFF 2001). Runoff of effluent irrigation water should be avoided, as pharmaceutically active compounds and personal care products have been identified in surface runoff from fields irrigated with tertiary treated wastewater effluent (Pedersen et al. 2002).

The calculated average seasonal irrigation requirement must include the amount of leaching water necessary to

prevent salt accumulation in the soil. Concentration of salts in soil leads to an increase in osmotic potential of the soil solution, which interferes with proper water extraction by the plants. Crops vary in their salt tolerance, which can be defined in terms of threshold (highest salinity not causing yield reduction) and in rate of yield reduction with increasing salinity. The leaching requirement is a function of the salt concentration (or the electrical conductivity) of the applied irrigation water (Feigin et al. 1991). Bouwer (1996) cautioned that synthetic organic compounds from the effluent could be passed to underlying groundwater via the deep percolation water used to leach salts out of the root zone of the plants. This deep percolation water contains increased levels of all chemicals, including refractory organics, and these may be carried to the groundwater in the absence of removal processes in the soil.

Soils traditionally irrigated with raw sewage or treated with sewage sludge tend to contain high levels of heavy metals, which may be concentrated by vegetables grown on the soils (Feigin et al. 1991). A 1996 American National Research Council report (NRC 1996) on the use of treated municipal wastewater and sludge in the production of crops for human consumption, determined that harmful trace elements are a low risk to consumers of crops irrigated with treated effluent, as treatment processes, combined with industrial pre-treatment programs, chemical production and use bans, are successful in reducing concentrations of most toxic chemicals to acceptable levels. It was also stated that the immediate or long-term threat from organic chemicals to humans consuming food crops irrigated with reclaimed water is negligible, since many toxic organics are removed during wastewater treatment, volatilize or degrade when the water is added to the soil, or may persist in the soil, and are therefore not taken up by the crops. Due to the potential for surface runoff or percolation to groundwater, however, continuing studies of the behaviour of the various classes of trace organics that may be found in reclaimed water are necessary.

Nutrient removal from reclaimed water through irrigation has been extensively researched and the fertilizing value of reclaimed water has been recognized as one of its main benefits (e.g., Fasciolo et al. 2002; Sala and Mujeriego 2001; Alberta Environment 2000). Excessive nitrogen levels, however, may lead to groundwater contamination and be harmful to crops. This harm may not be visible, as vigorous plant growth may occur, but fruit maturation may be delayed or fruit quality may be affected. As well, variations in water quality can translate into variations in crop mineral composition (Marecos do Monte et al. 1996). Most nutrients in reclaimed water are present at levels that are within the range that could be assimilated by plants under normal water loading rates (Alberta Environment 2000), but fertilizer addition practices should be adjusted to avoid undesirable vegetative growth or potential contamination of groundwater.

Alberta Environment (2000) produced guidelines for irrigation with treated municipal wastewater, requiring evaluation of effluent quality, but also of land suitability for irrigation by characterization of chemical and physical soil parameters, and topography of the area. As well, it is advised that a buffer zone should be provided between irrigated land and adjacent properties, occupied dwellings, watercourses, surface water bodies, public roads, railway lines or water wells. Restrictions on timing of irrigation with regard to growing season, crop harvesting, dairy cattle grazing, or other livestock pasturing are also given.

A 1975 British Columbia Department of Land, Forests and Water Resources report on health aspects of effluent irrigation (Parsons et al. 1975) concluded that treated sewage effluents represent a valuable source of water and nutrients which may be reused to advantage in irrigation systems, but highlighted the need for pathogen reduction for public health protection. Microbiological safety and the efficiency of microorganism removal by land application of treated wastewater effluent continue to be investigated in more recent studies (Fasciolo et al. 2002; Armon et al. 2001; El Hamouri et al. 1996). Epidemiological studies indicate that infectious disease transmission has occurred through such practices as use of raw or minimally treated wastewater for food crop irrigation and regular contact with poorly treated wastewater used for irrigation (Crook 1998; Shuval 1993). As reclaimed water moves through soil, pathogens may be removed by filtration, adsorption and die-off processes, as well as by desiccation and exposure to sunlight on the soil surface. On fruits and vegetables, pathogenic bacteria may survive from a few days to weeks, depending on local conditions, weather and the degree of contamination. Viruses may survive for days on plants and there exists limited data regarding virus penetration into the interior of plants. The virus type, temperature and moisture content may impact the persistence of viruses in the soil, as can pH, soil texture, other microorganisms, cations and organics (Blanc and Nasser 1996). Additionally, the type of irrigation system used (i.e., spray, drip or subsurface) may influence the level of contamination of the crops (Oron et al. 2001; Marecos do Monte et al. 1996). Risks must therefore be considered and minimized for both consumers of the crop (taking into account crop processing, or whether the crop is consumed raw or cooked), as well as farm workers dealing with the irrigation equipment, the crop and soils after harvesting.

Although there are relatively few published reports of Canadian examples of reclaimed water irrigation, the practice is quite well established in the Prairies, and experimental effluent irrigation projects have been conducted in Canada for over thirty years (Coote and Gregorich 2000). Hogg et al. (1997) referred to approximately 65 established irrigation projects, covering a total of 5700 ha in the provinces of Alberta (3050 ha),

Saskatchewan (2620 ha) and Manitoba (53 ha). It was noted that this accounted for less than 5% of the total prairie effluent discharge, with the potential for a great deal of expansion of water reuse applications. At least three major centres (Swift Current, Moose Jaw and Northminster) and 28 smaller communities were conducting effluent irrigation in Saskatchewan alone. Monitoring data from the three large projects were analyzed. Although it was noted that alterations in the soil biosystems were occurring, the authors concluded that effluent irrigation is sustainable, as long as proper management practices are followed.

Multi-year studies have been described for evaluation of effluent irrigation of forage crops in Alberta (Bole and Bell 1978), alfalfa crops in Saskatchewan (Jame et al. 1984), and sweet cherry trees in British Columbia (Neilson et al. 1991). Typical crop yields were near or above average, although Neilson et al. (1991) observed increased growth in sweet cherry trees irrigated with chlorinated secondary effluent after two years, but not five years. Effluent irrigation altered both leaf and soil nutrient levels to some degree, and some salinity increase in the soil was commonly observed.

In order to achieve zero effluent discharge through evapotranspiration, effluent from a small wastewater treatment plant at a college in Ontario was applied to a multi-clonal poplar forest. Disinfected secondary effluent was applied seasonally through an automated sprinkler system. Effluent irrigation was seen to have a positive, but not necessarily significant, influence on poplar growth. The various poplar clones were also evaluated in terms of ability to utilize and remove water by evapotranspiration; the authors suggested that evapotranspiration from such a poplar plantation could be 3 to 4 times higher than would be achieved with grass, due to the increased foliage, larger direct evaporation and advection (Laughton et al. 1990).

Effluent irrigation projects require a balanced approach, and water quality of the effluent must be carefully characterized and monitored. Although nitrogen and phosphorus in the reclaimed water may be of benefit to plant growth processes, excess nutrients may cause leaching concerns for groundwater supplies. Similarly, the risk of salinity build-up in the soil requires adequate soil drainage, while avoiding nutrient or contaminant leaching to the groundwater. Irrigation site, soils, crops, and irrigation methods must all be carefully selected, taking into consideration such issues as salt tolerance, nutrient requirements and leachability, and trace metal uptake, as well as the risk of pathogen exposure to consumers and farm workers.

### **Non-potable Urban and Recreational Reuse**

Urban and recreational applications may also occur in a restricted or unrestricted manner. Restricted uses are those in which either access to the affected areas is restricted, or



activities themselves are restricted. These restrictions imply limited exposure of urban populations in the case of restricted activities and/or exposure of limited populations to reclaimed water. Unrestricted urban and recreational uses therefore require a relatively high water quality.

Typical examples of *unrestricted* urban and recreational use include:

- Urban use—landscape irrigation of parks, playgrounds, schoolyards; fire protection; ornamental fountains and impoundments; vehicle washing; in-building uses including air conditioning and toilet flushing.
- Unrestricted recreational use—no limitations on body contact, including feed water for lakes and ponds used for swimming; snowmaking.

Typical examples of *restricted-access* urban use and restricted recreational use include:

- Landscape irrigation—golf courses, cemeteries, greenbelts and highway medians.
- Restricted recreational use—augmentation of ponds or lakes for fishing, boating, and other non-contact recreational activities; wetland restoration or enhancement.

Use of reclaimed water for irrigation of public areas, such as golf courses, is rapidly increasing in application around the world. In Florida, 43% of the reclaimed water produced in 2001 was used in landscape and public access area irrigation, with almost half of that used to irrigate golf courses (Florida DEP 2002). The United States Golf Association published the 1994 book "Wastewater Reuse for Golf Course Irrigation" (USGA 1994) to help golf course superintendents and irrigation consultants with the technical and regulatory issues of implementing reclaimed water irrigation systems in the U.S. Landscape irrigation requires many of the same controls and considerations as agricultural irrigation. The nutrient value of the water may be beneficial to plants and grasses, and significant savings in fertilizer costs may be achieved, but issues of salinity build-up in soil and salinity tolerance of plant species, excess or insufficient nutrients, and heavy metals must be considered. Fungal infections can occur and are favoured by excessive nitrogen contributions. As well, the risk to public health must be considered and minimized through adequate disinfection (Mujeriego et al. 1996).

Use of reclaimed water for toilet flushing in commercial, industrial and even residential buildings (especially multi-storey facilities) leaves higher-quality water available for other purposes, although toilet and urinal flushing may still result in human contact due to the risk of splashing of flush water, or the formation of aerosols during flushing (Jeppesen 1996). In Japan, non-potable urban water applications are the primary uses of reclaimed water, in contrast to many countries, where agricultural

irrigation is the predominant application of water reuse. The major urban non-potable reuse applications include toilet flushing in large commercial buildings and apartment complexes, providing "environmental water" for urban water amenities, melting of snow removed from streets and roads, and irrigation of parklands. In the densely populated urban environment, where water is scarce and priced the highest, reclaimed water is seen as a dependable new source of water and dual distribution systems are mandated for newly constructed buildings with a certain floor space (often >3000–5000 m<sup>2</sup>). Both open-loop systems, in which the reclaimed water is supplied to off-site locations for use, and closed-loop systems, in which the reclaimed water is used at the site of its origin are in operation. The latter range from individual building or block-wide treatment and distribution systems, to large area water recycling systems fed by a centralized water reclamation plant (Ogoshi et al. 2001).

Reclaimed water may also be reused indirectly, as a heat source or sink. Funamizu et al. (2001) discussed the urban reuse of the heat energy in wastewater for heating and air conditioning, as well as for snow melting. By the time water was discharged to a receiving water body from the Sapporo wastewater treatment plant in February 1998, its temperature was estimated to have risen over 10°C from that of tap water. This results in the waste of about  $5.5 \times 10^{15}$  J of heat energy per year. Although this energy was determined to be of low quality in a thermodynamic sense (due to its low temperature), it was considered to be suitable for heating and snow melting applications. For snow melting, the snow can be thrown directly into the combined sewer pipe (although this practice may have implications in downstream treatment processes), or the warmed effluent can be diverted to a centralized basin for melting collected snow. The rate of snow melting depends on the flow rate of the effluent, as well as the temperatures, densities and specific heat capacities of the water and snow. Recently, two Canadian municipalities have received funding under the Federation of Canadian Municipalities Green Municipal Fund to study the feasibility of using wastewater as a heat source (FCM 2003).

Conversely, reclaimed water may be used to make snow. A ski resort in Victoria, Australia, has performed pilot plant trials of an ultrafiltration system combined with a storage tank and snow gun to demonstrate snow-making potential and assess the quality of the effluent and snow produced (Tonkovic and Jeffcoat 2002). Results from pilot trials (where wastewater treatment was performed at temperatures as low as 7°C) indicated that the treated water contained levels of pathogens and heavy metals that were within the Australian drinking water guidelines, encouraging the resort management board to state that the reclaimed water will be "safe to ski on."

In the Municipal Sewage Regulation, British Columbia has included guidance for the use of reclaimed munic-

ipal wastewater in both unrestricted and restricted public access urban uses, including irrigation of parks, playgrounds, cemeteries, golf courses, residential lawns, and building landscaping, street cleaning and vehicle or driveway washing, toilet flushing, landscape water features, fire protection, and snow-making (not for skiing or snowboarding) (BC MELP 2001). Effluent irrigation projects for golf courses and municipal lands exist or are proposed in many regions of Canada, although few are reported in the literature. The wastewater reclamation plant in the City of Vernon, B.C., reclaims approximately 13,000 m<sup>3</sup> of wastewater daily with secondary treatment and chlorination. When necessary, tertiary treatment to remove phosphorus is also applied. Since 1978, all of the reclaimed water has been pumped to a reservoir from which irrigation water is withdrawn to irrigate approximately 970 ha of land from late April to early October, including golf courses, a seed orchard, a forestry centre, and a nursery, as well as large areas of agricultural land used for grazing and hay production (City of Vernon 2003; Coote and Gregorich 2000). Ip et al. (2002) describe a remote monitoring system used for wastewater treatment systems on four Ontario golf courses utilizing effluent irrigation, and Fausto and Black (1999) describe the development of a water reuse and biomonitoring project for another golf course in Ontario. At the time of the latter report, background data were being collected and effluent irrigation had not yet commenced.

The application of reclaimed water for non-potable urban and recreational reuse is gaining in popularity throughout the world, allowing dwindling water resources of higher quality to be reserved for potable supply. The practice also appears to be growing in Canada, although little information on efficiency, monitoring programs, or long-term sustainability has been reported in the literature. A wide variety of applications exist, from use of reclaimed water for irrigation of golf courses and public lands, toilet flushing in commercial buildings, and production of snow for ski resorts, to indirect use of effluent as a heat source or sink. For landscape irrigation, the risks to public health are similar to those described for agricultural irrigation, but all reuse projects must

include adequate barriers to pathogen transmission, as well as considering environmental sustainability.

### On-site Residential/Greywater Reuse

Domestic wastewater can be separated at the source into two separate flows: blackwater, or toilet waste, and greywater, or all remaining household wastewater. Greywater has been suggested as an alternative source of water for such non-potable applications as toilet flushing and irrigation (Townshend 1993).

By definition, blackwater has gross fecal contamination, and greywater should not. However, studies (Ottoson and Stenström 2003; Casanova et al. 2001; Rose et al. 1991) have shown that household greywater contains significant concentrations of total and fecal coliform bacteria. The composition of greywater depends on the make-up of the family, with fecal and total coliform levels significantly higher in greywater from families with young children. The source of the greywater within the household may also affect the microbial quality as higher concentrations of fecal coliform bacteria have been observed in shower (Rose et al. 1991) and kitchen sink (Casanova et al. 2001) greywater (Table 1). The California Water Code (State of California 2001) defines greywater (for reuse purposes) as including wastewater from bathtubs, showers, bathroom washbasins, clothes washing machines, and laundry tubs, but not water from toilets, kitchen sinks or dishwashers.

Storage may also influence the microbiological safety of greywater. Rose et al. (1991) found that total and fecal coliform concentrations increased by an order of magnitude on storage up to 48 hours, but that after this time, the bacterial levels remained stable. *Salmonella* and *Shigella* bacteria and poliovirus introduced into the greywater were seen to persist for several days. Conversely, Dixon et al. (1999b) suggested that while storage of untreated greywater up to 24 hours may prove beneficial (leading to settling of solids), storage beyond 48 hours resulted in unacceptable reductions in dissolved oxygen levels and degradation of aesthetic quality.

Based on the contents of common Danish household chemical products ranging from shower creams to laun-

TABLE 1. Average coliform levels measured in greywater from various household sources

Source	Total coliforms (CFU/100 mL) <sup>a</sup>	Fecal coliforms (CFU/100 mL)	<i>E. coli</i> (MPN/100 mL) <sup>b</sup>	Reference <sup>c</sup>
Shower water	10 <sup>5</sup>	6 x 10 <sup>3</sup>	—	a
Laundry wash water	199	126	—	a
Laundry rinse water	56	25	—	a
Including kitchen sink water	—	8.84 x 10 <sup>4</sup>	94.8	b
Excluding kitchen sink water	—	822	8.33	b

<sup>a</sup>CFU; colony forming units.

<sup>b</sup>MPN; most probable number.

<sup>c</sup>References: a—Rose et al. (1991); b—Casanova et al. (2001).

dry detergents, Eriksson et al. (2002) identified 900 xenobiotic organic compounds (XOCs) potentially present in household greywater. The XOCs were classified according to toxicity, bioaccumulation and biodegradation, and 66 priority pollutants were identified. However, only 211 of the approximately 900 substances could be evaluated based on available information on toxicity, bioaccumulation and degradation. The need for a thorough characterization of greywater with an evaluation of pollutant sources and risk assessment was suggested before potential reuse applications can be evaluated, and treatment of the greywater before reuse was emphasized.

As in agricultural reuse, application of greywater to the soil may alter its microbiological quality. Casanova et al. (2001) analyzed greywater and greywater-irrigated soil and found that levels of fecal coliform bacteria were higher in soils irrigated with greywater than with potable water. As well, they noted that the time of year was important; this was suggested to be due to weather patterns affecting bacterial survival or greywater collection and irrigation practices. Ottoson and Stenström (2003) simulated exposure risk by greywater reuse in direct contact, irrigation of sports fields and groundwater recharge. They found that the poor reduction of somatic coliphages (used as a virus model) suggested an unacceptable viral risk, despite a low fecal load. Adequate pre-treatment of greywater in any reuse system is therefore essential to ensure the safety of users.

The Canada Mortgage and Housing Corporation (CMHC) has been involved in numerous research projects regarding residential water reuse applications (Canadian Water and Wastewater Association 1997, 2002; Stidwill and Dunn 2000; Waller 2000; Waller and Salah 1999; Waller et al. 1998; Totten Sims Hubicki Associates 1997; Townshend 1993). Waller et al. (1998) suggested that for a typical dwelling, water reuse for toilet flushing and irrigation (combined with water conservation measures) can reduce water supply needs and wastewater flows by >50% compared to a conventional system. Case studies of residential recycling and reuse in Canada include the Toronto Healthy House system, the CMHC Conservation Co-op in Ottawa, and a Sooke, B.C., office building in which reclaimed water is recycled for toilet flushing. Greywater reuse systems have also been considered for areas in northern Canada to reduce dependence on trucked water supply and sewage disposal services (Waller et al. 1998).

The Toronto Healthy House, a four storey duplex built in 1996, was an award winner in a design competition held to promote environmentally responsible housing. All potable water for the house was supplied by rain and snowmelt, which was treated and used for drinking water, food preparation and dish washing. The wastewater in the house (collected in a separate plumbing system) was treated and reused for toilet flushing, bathing and clothes washing. The residents of the Toronto Healthy House had to become involved in checking and

monitoring water quality in order to ensure good treatment performance, and a number of problems were observed after start-up. Insufficient nitrification led to an ammonia odour, and build-up of soluble recalcitrant organics resulted in a yellow colour in the recycled effluent. The showers and baths were therefore disconnected from the reclaimed water treatment system after two months of use, and were reconnected to the potable water system. The biological treatment systems (septic tank, biofilters) and sand filter all took time to become biologically mature, and after three months, the disinfection method was changed from UV to ozone disinfection, which reduced the colour and odour problems. The Conservation Co-op in Ottawa, which utilized treatment of light greywater (bath and shower wastewater) for reuse within an eight-unit apartment complex for toilet flushing, encountered similar treatment system design and equipment reliability problems. A dual plumbing system separated the wastewater lines for the baths and showers from those for the toilets and wash basins, while dual supply lines separated the reclaimed toilet flush water from all other water sources in the building. Preliminary treatment results showed that all reclaimed water quality objectives were being met, except for bacteriological quality (Waller et al. 1998).

Waller et al. (1998) and Townshend (1993) describe a number of greywater reuse applications in the U.S., including the Casa del Agua and Desert House prototypes in Arizona. Greywater reuse systems have also been gaining in popularity in European countries. Thames Water implemented the first major in-building water recycling scheme in England with a reclaimed water system for toilet flushing at the Millennium Dome in Greenwich (Hills et al. 2002). The reclaimed water system provided 55% of the 131,000 m<sup>3</sup> of water used at the site, in the form of greywater from washroom sinks in the building (10%), rainwater collected from the Dome roof (19%), and groundwater (71%), all treated on site. The volume of greywater produced was less than predicted, limiting its contribution, and the amount of rainwater that could be collected was limited by storage constraints on site, highlighting the importance of back-up water supply (supplied here by abstraction of on-site groundwater).

Nolde (1999) described studies of two greywater treatment systems in Berlin, where guidelines for service water reuse have been in place since 1995. One system was a rotary biological contactor built in 1989 for 70 persons, while the second system described was a fluidized-bed reactor for a one-family household built in 1995. Over the years, both systems have been optimized in terms of energy and maintenance demand. The quality of the greywater, biodegradability of household soaps and chemicals, and treatment efficiencies of the two systems have been evaluated. Due to the presence of fecal and chemical contamination of the greywater, biological

treatment was seen as indispensable in order to guarantee risk-free service water for reuse applications.

In discussing the possibility of domestic greywater reuse in Australia, Jeppesen (1996) noted that surveys in the U.S. and Australia have found that 60 to 80% of on-site domestic wastewater treatment operations are not maintained adequately, and consistently produce effluents of unacceptable quality. The author therefore concluded that the safest method of greywater reuse is to prevent human contact with greywater, such as by subsurface irrigation for lawn or garden watering, or surface irrigation confined to non-habitable areas. Model guidelines for domestic greywater reuse in Australia developed by the Brisbane City Council would only cover the use of hand basin toilets (which incorporate a basin in the top of the cistern with a tap for hand washing), and primary and secondary greywater systems, where the greywater would be treated and used for subsurface irrigation. Toilet flushing and surface watering with greywater were not included due to the high risk of human contact through splashing or aerosol formation and unreliability of household treatment (Jeppesen 1996).

Diaper et al. (2001) used a simulation model of a single-household greywater recycling system to provide performance indicators in terms of water quality and water savings, and a risk model to assess microbial risks associated with the system, both during normal operation and during specific abnormal operating conditions. Based on the risk and simulation models, they recommended a number of operational and installation requirements to be included in manuals of single-house greywater recycling systems in order to ensure the proper operation of the system and the health and safety of the users. Dixon et al. (1999a) also performed a basic risk assessment in order to develop a framework to modify proposed U.K. greywater reuse guidelines, defining risk levels for various sectors and applications, based on populations involved, level of exposure, dose-response, and delay before reuse. Those applications deemed to involve a relatively high risk were suggested to require stricter water quality criteria.

Although less contaminated than blackwater, greywater may still contain significant concentrations of pathogenic organisms and xenobiotic organic substances. The risk of illness due to reuse of domestic greywater can be reduced by adequate treatment prior to reuse, requiring careful operation and maintenance of small-scale treat-

ment systems by the user. Proper operation of such systems can lead to significant reductions in potable water use, providing an alternative source of water for non-potable household uses, such as subsurface landscape irrigation. However, rigorous maintenance, monitoring and cross-connection controls must be implemented.

### Industrial Reuse

To satisfy the needs of industry, the reuse of treated municipal wastewater for industrial water supply started as early as in the 1940s with the reuse of Baltimore, Maryland water by Bethlehem Steel. Reclaimed water has been used industrially at crude oil refineries and electric utility plants in the greater Los Angeles area for over 30 years. Reclaimed municipal wastewater has also been used in such industrial process applications as pulp and paper, chemicals, steel manufacture, textiles, and petroleum and coal products, in construction projects for concrete production, dust control and cleansing, as well as in cooling towers, boiler feedwater, and for irrigation of plant grounds (Asano 2002; Okun 1997). In the Code of Practice for the Municipal Sewage Regulation (BC MELP 2001), British Columbia has included guidance for the use of reclaimed water in construction and industrial uses, including aggregate washing, concrete making, equipment washing, cooling towers (excluding evaporative cooling), stack scrubbing, boiler feed, and process water (excluding food processing).

Many industries also employ recirculation of their own process waters for use in such areas as cooling tower make-up water. Canadian industry accounts for over 80% of the total water intake, and of this total intake, approximately 40% is typically recycled (Statistics Canada 2002). Table 2 illustrates the total water intake, discharge, consumption rate and recycling rate statistics for 1996 (Scharf et al. 2002). The extent of recycling or recirculation can be expressed as the recirculation rate, defined as the volume of water recirculated as a percentage of total water intake; this value varied greatly by industry. Note that wastewater discharge in the mineral extraction sector included mine water (groundwater drained from the mines), so that discharge volumes were higher than intake volumes and consumption cannot be calculated. Even within each sector, the extent of recycling varied considerably. Within the man-

TABLE 2. Water use and recycling in Canadian industry, 1996 (after Scharf et al. 2002)

Industry sector	Total water intake (MCM/year) <sup>a</sup>	Discharge (MCM/year)	Consumption rate (as a % of intake)	Recirculation rate (as a % of intake)
Manufacturing	6037.4	5486.7	9	115
Mineral extraction	518.2	671.9	—	231
Thermal power generation	28,749.7	28,241.8	2	41

<sup>a</sup>MCM; million cubic metres.

ufacturing sector, recirculation rates ranged from a low of 22% in the wood products group, to a high of 292% in plastic products (Scharf et al. 2002).

Many industrial operations incorporate water recycling measures into plant design. Millar Western's bleached chemi-thermomechanical pulp mill in Meadow Lake, Saskatchewan, was built as a zero liquid effluent system, with rotary screening, flotation clarifiers, settling ponds and three mechanical vapour recompression evaporators treating the water before recirculation of the distillate. Some water is lost in process steam and evaporation from storage ponds, but demand for make-up water is 2 to 10% of that required for a typical mill. Initial problems with high polymer demand, foaming and fouling were overcome by process modifications in the first years of operation (Meadows 1996).

Alternatively, a plant may be retrofit to include water recycling. A wastewater treatment plant in the Greater Vancouver Regional District is currently planning a pilot wastewater reclamation project to provide 91% of the plant's water demand (FCM 2003). Bédard et al. (2000) describe an application of the process integration methodologies of water pinch analysis and mathematical optimization for the systematic design of a water reuse network for a Quebec paperboard mill. An optimized configuration showed reductions of 80% in fresh water consumption and 50% in process water volume to be treated. Petrides et al. (2001) describe a process simulation program used to help engineers at a semiconductor fabrication facility evaluate process water recycling options. The case study concluded that the reduced dependency on city water supply and an improved public image would be the main benefits of a water-recycling program, but that with a modest increase in the price of city water and wastewater disposal, water recycling would become economically advantageous, as well.

Specific water quality needs for industrial processes must be considered when planning a municipal wastewater reclamation facility for industrial customers. Selby et al. (1996) identified the water quality parameters of primary concern for cooling system makeup, including hardness, alkalinity, silica, and total suspended solids. When using reclaimed water, a plant must also consider ammonia, phosphate, total dissolved solids, and chlorides. Ammonia can be extremely corrosive to copper alloys causing metal loss and stress corrosion cracking, and nitrification processes are often required to remove ammonia prior to industrial use of reclaimed water. A planned  $1 \times 10^5$  m<sup>3</sup>/day water reclamation project in California in the 1970s failed when the low ammonia concentrations required by the proposed industrial customers (to avoid brass corrosion) could not be achieved (Hermanowicz et al. 2001). High phosphate, calcium, pH and temperature increases the potential for calcium phosphate scaling, although phosphate can be an effective carbon steel corrosion inhibitor at controlled levels.

Dissolved solids increase electrical conductivity of the water, also affecting corrosion reactions. Dissolved chloride, in particular, increases corrosion of most metals, leading to stress corrosion cracking or pitting corrosion of some stainless steels (Selby et al. 1996).

Another major concern for industrial users of reclaimed water is the biological stability of water, which can be affected by the choice of treatment process. Biological problems encountered during industrial reuse and recycling include re-growth of waterborne microbes, biofouling (which can reduce heat transfer performance in cooling towers) and microbial-induced corrosion. Re-growth of microorganisms and contamination of treated water during storage and distribution can be minimized by reducing the concentration of easily biodegradable (assimilable) organic carbon that can be used as a source of energy, using techniques such as biofiltration (Meesters et al. 2003; Ng et al. 2001).

Dalan (2000) discussed points to consider when evaluating, purchasing and optimizing zero liquid discharge systems. Estimates of flow rate and composition must be realistic in order to adequately plan a system, and suggestions were given on methods for accurately characterizing a waste stream. Reverse osmosis and electrodialysis techniques were described, and pre-treatment needs, methods for optimizing treatment and determining costs were discussed. Roeleveld and Maaskant (1999) evaluated the feasibility of the application of ultrafiltration for effluent reuse from various industrial treatment plants (representing the chemical, paper and food industries) in the Netherlands. The technical feasibility of industrial effluent reuse was found to depend on the type of industry, characteristics of the wastewater, the applied treatment system, and the requirements for water quality. The economic feasibility of effluent reuse will be determined by the price of potable water supply and disposal, as compared to treatment costs. In the paper industry, ultrafiltration resulted in water that met the requirements for reuse, with operational costs that were comparable to or lower than the costs of drinking water/groundwater. In the food industry application, on the other hand, ultrafiltration would need to be followed by reverse osmosis to reduce salts to levels acceptable for cooling, increasing the cost of the reclaimed water to higher than drinking water.

Visvanathan and Cippe (2001) have discussed the potential for water reuse and strategies for its promotion within the industrial sector in Thailand. They estimated that 60 to 80% of the industrial water demand in Bangkok was used for cooling purposes that do not require high-quality water, but a survey of industrial reuse practices in Thailand showed that only 10.5% of the industries surveyed reused their treated effluent. The main reason given for the lack of reuse was the investment cost for new technologies and the cost of treatment. Other reasons given included the inconvenience of reuse

when the water supply is very cheap, a lack of incentives for reuse and a lack of awareness of new technologies. A number of potential policy approaches to deal with institutional, management and financial aspects were suggested, including the development of an industrial water reuse permit structure and legislation, development of an institutional structure to develop water reuse, modification of the existing industrial water pricing structure, subsidies for adoption of reuse strategies, implementation of fines for industrial wastewater discharge, and other enforcement tools (Visvanathan and Cippe 2001). A survey of recycled water users and providers in Australia (Higgins et al. 2002) also indicated that a major barrier to the use of reclaimed water by industrial processes was the high cost of local Environmental Protection Agency licence compliance.

Recognizing the large industrial water intake and relatively low consumption, industrial water reuse and recycling is clearly important for conserving water resources for other uses, as well as for reducing discharge of industrial effluents and the associated pollution. The water quality requirements for industrial water reuse may be determined by process and product quality constraints, and advanced treatment technologies are often required to produce water of acceptable chemical and microbiological quality. General advantages of industrial water recycling are broadly recognized and it is practised where deemed economically feasible, although recycling rates vary widely between industries.

### Rainwater and Stormwater Collection and Reuse

Collection of rainwater and stormwater for mostly subpotable water supply has been practised for thousands of years. With respect to terminology, the term rainwater is used for liquid precipitation usually collected directly in storage vessels (cisterns), or running off roof surfaces. The rainwater running off catchment surfaces is referred to as stormwater runoff, or just stormwater. While direct collection of rainwater provides source water of better quality, small collection areas, compared to stormwater runoff from large areas, limit its quantity. In the following discussion, both rainwater and stormwater sources are included and both terms are used interchangeably.

The island of Bermuda has relied on rainwater collection systems as the primary source of residential water supply for 300 years (Waller et al. 1998). Rainwater/stormwater reuse is currently practised in many countries, with examples reported from Australia, Canada, China, France, Germany, Japan, Singapore, U.K., and the U.S.A. (Dallmer 2002; Thomas et al. 2002; Li et al. 2000; Appan 1999; Chilton et al. 1999; Coombes et al. 1999; Herrmann and Schmida 1999; Zaizen et al. 1999; Waller et al. 1998). This increase in subpotable reuse follows from the widespread use of stormwater management, which serves to mitigate impacts of urban runoff on

receiving waters and their ecosystems. Many stormwater management practices represent various forms of rainwater/stormwater reuse and thus provide double benefits—mitigation of runoff and provision of secondary water supplies. Examples of such measures include collection and storage of roof runoff for reuse (e.g., irrigation, toilet flushing; Li et al. 2000; Chilton 1999; Waller et al. 1998), rainwater/stormwater infiltration and recharge of groundwater aquifers (e.g., direct rainwater infiltration via pervious surfaces, or stormwater infiltration in special infiltration facilities; NRC 1994), and collection, storage, treatment, and reuse of stormwater to create recreational and/or ecological amenities (OMOE 2003). In Singapore, Tay and Chan (1984) reported the reuse of stormwater from an unprotected urban catchment for water supply. No details on treatment or treated water quality were provided.

In stormwater reuse, the most feasible appears to be the reuse of roof runoff, which represents the source with the best water quality; other sources of stormwater, particularly runoff from streets and highways, may be too polluted and require expensive treatment, which renders them infeasible. Even in the case of roof runoff, there are some concerns about its quality (Simmons et al. 2001; Förster 1999; Yaziz et al. 1993), largely due heavy metals (from roofing materials, depending on pH of rainwater), chemicals in dry atmospheric deposition (depending on local sources and transport), and fecal bacteria (bird droppings). The first few litres of runoff during a rainfall event (the "first flush") appear to be the most heavily polluted.

Roof runoff reuse devices vary in their sophistication, ranging from simple storage barrels placed under the roof downspout (e.g., rain barrel programs in Canada; OMOE 2003) to special devices controlling storage and overflow into sewers. The latter devices may be designed for partial interception of roof runoff, or total flow interception with overflows when storage capacity is exceeded, or full interception with continuous drainage to sewers or an infiltration facility (Herrmann and Schmida 1999). Typically, some treatment is provided, by filtration or screening in the feed pipe and settling in the storage tank. Additional water quality benefits are obtained by judicious selection of roofing materials. In operation of these devices, the requirements of runoff control and water supply may be in conflict; water supply requires storage of a sufficient volume of water all the time, while for runoff control, storage should be empty before large events. A water balance equation for these devices can be expressed as:

$$\text{Precipitation} = \text{rainwater consumption (supply)} + \text{losses} + \text{overflow} \quad (1)$$

where losses include leakage and evaporation, and overflow occurs when maximum storage in the device is exceeded.

For a simple rainwater collection device, the available water supply can be expressed as (Appan 1999):

$$Q_i = A r_i - ((E_i + b_i)A + D_i) \quad (2)$$

where during an arbitrary time interval  $i$  (say 15 min);  $Q_i$  is the available rainwater volume ( $\text{m}^3$ );  $A$  is the roof (catchment) area ( $\text{m}^2$ );  $r_i$  is the rainfall depth (m) over the interval  $i$ ;  $E_i$  is the evaporation abstraction (m);  $b_i$  is the initial loss (wetting, surface storage, in m); and  $D_i$  is the consumed volume ( $\text{m}^3$ ). This model can be implemented as a spreadsheet program, using a long series of rainfall data as an input, estimating hydrological abstractions, and finding an optimal combination of  $D$  and  $Q$ . Typically, for rainfall-dependent reuse schemes, the shortage of rainwater for consumption is covered from conventional potable water sources (at higher costs).

A feasibility study of reusing roof runoff from an area of  $38,700 \text{ m}^2$ , for subpotable purposes, was carried out at the Nanyang Technological University in Singapore (Appan 1999). A rainwater storage tank with an optimal storage volume was designed. Whenever tank storage falls below the required minimum, additional water is supplied from the (separate) potable water supply system. The quality of rainwater at this site was investigated and the results are shown in Table 3. Rainwater treatment was recommended, by raising pH and providing disinfection, because similar stored water was found to be breeding grounds for mosquitoes spreading dengue fever. The proposed scheme would save about 12% of the monthly expenditures for water used at this facility.

Figtree Place is an Australian redevelopment project with 27 housing units, which was designed according to the water-sensitive urban development principles (Coombes et al. 1999). The design objective was to reuse stormwater to provide 50% of in-house needs for hot water and toilet flushing, 100% of domestic irrigation needs, and 100% of the bus washing demand (providing water to a project partner—a bus depot). In the proposed scheme, roof water passes through a first flush pit into a rainwater tank, from there it is pumped to houses for hot water supply and toilet flushing, and the rest overflows to an infiltration trench. The infiltration trench outflow and runoff from the site are directed to a grassed infiltration basin serving to recharge a groundwater aquifer, from which water is pumped back and used for bus washing and irrigation. To assess the collected roof water quality, it was compared against the drinking water quality guidelines (DWQG). Only infrequent exceedances of DWQGs were noted for such constituents as ammonia, pH and lead. However, frequent and significant bacterial contamination was noted (caused by soil falling into tanks). Storage of roof water in an enclosed tank contributed to water treatment, coagulation and settling. In hot water reuse, the bacteriological quality of water was improved significantly with heating. If the systems maintain temperature  $>50^\circ\text{C}$ ,

drinking water quality can be attained. The reuse of roof water produced about 60% of the on-site demand (45% of internal demand and 15% for irrigation), and produced costs savings of \$26,000 on the development costs (about 1%) and annual savings of about \$4000. However, the developer felt that these savings were not large enough to outweigh any potential risks and decided against implementing the scheme.

The Renault MCA plant in Maubeuge (France) was required by authorities to treat stormwater by settling, prior to discharge into receiving waters (Thomas et al. 2002). Considerations of associated costs led to the proposal of reusing such treated stormwater, rather than simply disposing of it. At the plant site, about  $300,000 \text{ m}^3$  of stormwater could be collected, treated by the ACTIFLO™ process, and reused in plant operations. The payback period was calculated as almost 8 years; on receipt of a subsidy, it was shortened to 2.33 years. The designer developed software for evaluation of technical and economic feasibility of stormwater reuse at industrial sites (SIRRUS).

Rainwater harvesting agriculture (RHA) systems have shown promise for agricultural irrigation in semiarid areas of China with mountainous or hilly topography, where increasing food needs resulting from population growth have led to increased cultivation of steep, erodible slopes (Li et al. 2000). Rainwater harvesting systems consist of a waterproofed collection surface, a runoff channel, sediment tank, and a storage container. Combined with water-saving irrigation systems and highly effective crop production techniques, small-scale RHA systems can provide farmers in water-limited areas an affordable method of access to water needed to meet domestic and agricultural needs, while reducing soil erosion by reducing runoff.

Other studies describe rainwater collection from a supermarket roof in the U.K. for WC and urinal flushing (Chilton et al. 1999), roof water collection from three dome sports stadiums in Japan for toilet flushing and landscape irrigation (Zaizen et al. 1999), and a stormwater landscape irrigation project in Sydney, Australia (Dallmer 2002). Herrmann and Schmida (1999) provide an overview of rainwater reuse in Germany, using runoff simulations for 10 years of precipitation

TABLE 3. Quality of rainwater from the roof of the Nanyang Technological University, Singapore (Appan 1999)

Parameter	Mean value in rainwater
pH	4.1
Colour (colour units)	8.7
Turbidity (NTU)	4.6
TSS (mg/L)	9.1
TDS (mg/L)	19.5
Hardness as $\text{CaCO}_3$ (mg/L)	0.1
$\text{PO}_4$ as P (mg/L)	0.1
Fecal coliform (MPN/100 mL)	6.7



data to estimate storage tank volumes, overflows, and drinking water savings, and Fewkes (1999) discusses models used for simulating the performance of rainwater collectors with respect to water demand.

Results from a recent survey by the Canadian Water and Wastewater Association (2002) indicate that rainwater harvesting is rarely practised and almost never encouraged in Canada. A similar situation was noted in the U.S., except in areas experiencing a critical water shortage, such as California and Florida. Waller et al. (1998) describe traditional rainwater cistern systems in Nova Scotia, used by isolated lighthouses on rocks or islands, or to replace wells contaminated by road salt. The Toronto Healthy House demonstration project also collected rainwater from three roof surfaces and two ground patio areas with a total area of 80 m<sup>2</sup>, for settling and storage in two concrete cisterns. The collected rainwater underwent treatment by multi-media filtration and UV disinfection before supplying potable water to the house (Waller et al. 1998).

Stormwater reuse in subpotable water supply is generally possible, and often fairly feasible, particularly when using roof runoff. As with all water sources (particularly in densely populated urban areas), however, the collected rainwater must be monitored and treatment measures taken to reduce health risks associated with its reuse. Several types of benefits are attained—savings on potable water supply, environmental benefits arising from reduced discharges of runoff and associated pollutants into receiving waters, and economic benefits.

### **Surface Water Augmentation and Groundwater Recharge**

Reclaimed water may be pumped from a treatment works to a stream or river to augment various in-stream flow needs and compensate for upstream water extractions (Ogoshi et al. 2001; Asano and Levine 1998). This water reuse scheme is equivalent to widely practised effluent disposal methods. Restoration or enhancement of wetland habitats may also be achieved by application of reclaimed water to affected areas. The town of Strathmore, Alberta, recently announced plans for a pilot project, entailing enhancement of a local wetland with tertiary treated effluent from the town. The three-year pilot study will evaluate the effects of adding a controlled volume and quantity of the treated effluent to the marsh in the spring and fall, when there is little natural runoff, in order to restore nesting and rest habitat for waterfowl (FCM 2003; Toneguzzi 2003).

Groundwater recharge occurs when water from the surface infiltrates the water table, replenishing groundwater levels in the aquifer. The rate of recharge depends on such variables as soil type, geology and hydrogeology, precipitation, prior soil moisture conditions, runoff, topography and evapotranspiration (Coote and Gre-

gorich 2000). Artificial recharge can be used to replenish groundwater supplies by assimilation and storage of reclaimed water in groundwater aquifers, or to establish hydraulic barriers against saltwater intrusion in coastal areas, reduce land subsidence caused by decreasing water levels, or maintain base flows in streams.

The American National Research Council's Committee on Ground Water Recharge (CGWR) was formed to study issues associated with groundwater recharge using source waters of impaired quality, including treated municipal wastewater, stormwater runoff and irrigation return flow, and the subsequent use of the recovered recharge water. Of the three impaired-quality water sources, the CGWR concluded that treated municipal wastewater is usually the most consistent in terms of both quality and availability, and artificial recharge with such waters was determined to be a viable way to augment regional water supplies. However, due to uncertainty regarding identification of potential toxins and pathogens, use for in-ground or non-potable applications was suggested as being preferable to potable uses, and rigorous monitoring of recharge water as it moves through the system was noted to be essential (NRC 1994).

Either surface spreading or direct injection to groundwater aquifers can be used to bring about groundwater recharge. While direct injection requires a high quality source water to avoid clogging problems, surface spreading can tolerate water of poorer quality as the soil-aquifer system can remove certain chemicals and pathogens under appropriate conditions. The ideal soil for soil-aquifer treatment (SAT) balances rapid recharge (requiring a coarse-textured soil) with efficient contaminant adsorption and removal (which is improved in fine-textured soils). The processes through which removal occurs are not entirely efficient, however, nor do they occur to the same extent for different constituents, so both pre-treatment and post-treatment processes (when extracting the water) must be combined with SAT to ensure the quality and safety of the water (NRC 1994).

Surface infiltration systems for SAT and groundwater recharge require deep, permeable soils. In cases where permeable surface soils are not available, vadose zones have restricting layers, or aquifers are confined, direct well injection may be necessary. Larger diameter dry wells, or vadose zone wells, may be used for recharge of unconfined aquifers. The main difficulty encountered in well recharge is clogging around the well. Various methods used to predict the clogging potential of the recharge water have been described, although full-scale studies on injection test wells are still necessary. Where permeable surface soils are not available, but permeable layers occur within trenchable depth (5 to 15 m), seepage trenches may be used instead of vadose zone wells (Bouwer 1996).

Bouwer (1996) reviewed issues in artificial recharge, including infiltration basins, SAT of sewage effluent,



nitrogen removal, pre-treatment of effluent, well recharge (or direct injection), clogging parameters, vadose zone wells, and seepage trenches. Primary treatment of municipal wastewater prior to SAT may be sufficient and even advantageous to improve trace organic removal by co-metabolism of total organic carbon (TOC) compounds, and to provide an energy source for denitrifying bacteria (although primary effluent may produce more clogging of basin bottoms due to higher suspended solids content, or increase biological clogging due to high organic levels). Nitrogen removal in SAT systems is achieved by biological denitrification of nitrate, which occurs under anaerobic conditions. In order to achieve the anaerobic conditions required, flooding periods must be quite long, and soils such as sandy loams with some cationic exchange capacity are desirable. Fox (2001) described tools and methodologies used to evaluate the fate of dissolved organic carbon and nitrogen species at field sites throughout the southwestern U.S. The dissolved organic carbon concentration was found to be a function of the drinking water organic carbon concentration and the production of soluble microbial products. The majority of trace organic compounds were removed to below detection limits after residence times in the subsurface of greater than one year. Although effluent pre-treatment processes can remove nitrogen efficiently, it was found that properly operated SAT systems could also remove nitrogen by anaerobic ammonia oxidation.

The State of California's Department of Health Services has developed draft regulations regarding groundwater recharge reuse (State of California 2003). All water used for a groundwater recharge reuse project must be from a wastewater management agency that administers an industrial pre-treatment and pollutant source control program. In the regulations, requirements are given for control and monitoring of pathogenic microorganisms, nitrogen compounds, regulated contaminants, physical characteristics, and non-regulated contaminants such as TOC, endocrine disrupting chemicals and pharmaceuticals. Monitoring wells must be constructed between the recharge site and downgradient drinking water supply wells to allow monitoring and reporting of recharge water movement and contaminant levels.

In 1998, approximately 30 percent of the population of Canada relied on groundwater for their domestic water supply, ranging from 22% of the population in Alberta to 100% in P.E.I. Approximately 40% of municipal water systems were reliant on groundwater (Statistics Canada 2002). The use of artificial recharge using treated surface water has been discussed as a viable option for providing a valuable commodity to rural water users in Saskatchewan, where the groundwater is often highly mineralized and unpalatable due to odour and taste (Digney and Gillies 1995). However, a lack of information on existing projects and guidelines for operation of recharge projects were seen as hindrances to further

progress at that time. The use of reclaimed water for groundwater recharge was not discussed, and there are no reports of its practice in Canada.

### Potable Reuse

Direct potable reuse, or the introduction of reclaimed water directly to a potable water distribution system, has been in use for over 25 years in Windhoek, Namibia, and studies to date have not uncovered any adverse health effects of the practice (Haarhoff and van der Merwe 1996). This application of water reuse is rather rare, however, and is not applied in Canada or the U.S., although it has been studied in feasibility studies in Denver and San Diego (Olivieri et al. 1996; Rodgers and Lauer 1992).

Indirect potable reuse refers to the augmentation of potable water supply sources with highly treated reclaimed water, most commonly through artificial recharge of aquifers. The recharge water typically resides within the aquifer system for many years before removal for potable use; the long residence time and "buffering" of reclaimed water with groundwater may provide additional health safeguards in the form of blending and dilution, natural treatment processes, and time for water quality monitoring and potential corrective actions (McEwen 1998). Planned indirect potable reuse has been studied in demonstration and pilot projects in a number of locations in the U.S., including the Whittier Narrows Water Reclamation Plant in Los Angeles County, Water Factory 21 in Orange County, California, as well as locations in El Paso, Texas, and Scottsdale, Arizona (Asano 2002; Crook et al. 1999). Additionally, many communities use water sources that include a significant wastewater component from upstream users. Long river systems such as the Thames, Rhine, Mississippi, and St. Lawrence rivers serve many municipalities along their length which use the rivers as both sources of drinking water and receiving waters for treated effluent discharges. Downstream users consequently practise unplanned indirect potable reuse.

Largely due to uncertainty regarding health effects, the American National Research Council concluded that while indirect potable reuse is a viable application of reclaimed water, direct potable reuse is not (Crook et al. 1999; NRC 1998). Although no adverse health effects have been uncovered in health-related research to date, the health data are sparse and the methods for research are limited. The potential human health risk of indirect potable reuse applications necessitates a thorough, project-specific assessment (including contaminant monitoring, health and safety testing, and system reliability evaluation), and it was suggested that reuse requirements should exceed those applied for wastewater treatment or drinking water facilities. Additionally, the report suggested that even indirect potable reuse should only be considered as a last resort in communities in which all other water conservation and non-potable reuse efforts

have been examined, in accordance with the long-standing principle that the most protected source should be sought for drinking water supplies.

Unplanned indirect potable reuse occurs regularly in rivers and lakes that serve as both sources for drinking water supplies and receiving waters for municipal wastewater effluents around the world, and health studies to date have not shown any adverse health effects from either direct or indirect potable reuse. However, there remain serious concerns about this type of reuse from the public health point of view, public perception, and new knowledge about trace contaminants and emerging chemicals of concern, such as endocrine disruptors and pharmaceuticals, which may not be fully removed by traditional treatment processes (e.g., Drewes et al. 2002; Sedlak et al. 2000). In light of such concerns, it is certainly preferable to examine all available non-potable reuse options before any form of potable reuse is considered.

## Conclusions

While water reuse and recycling is currently in limited practice in Canada, experiences from other countries can be used to help identify potential future applications. Water reuse has primarily been applied for agricultural and landscape irrigation in Canada, as it is in most areas of the world. This practice is most commonly applied in British Columbia and the Prairie Provinces, although some cases of effluent irrigation of golf courses have been reported for Ontario, as well. Effluent irrigation projects must take into account water use, nutrient loading, salinity, and the presence and persistence of pathogens and trace contaminants. Potential exists for other non-potable urban reuse applications as well, such as use of effluent heat energy and snow-making.

Research in the area of domestic greywater reuse indicates that, while not as contaminated as blackwater, greywater still contains substantial levels of bacteria. Similarly, rainwater collected from roof surfaces may contain heavy metals, fecal bacteria and other chemicals. Such contaminants can be reduced by careful operation and maintenance of wastewater treatment systems, and substantial water savings can be associated with greywater and rainwater reuse. A number of pilot projects have been described.

Industrial recycling is practised to varying degrees in different industrial sectors in Canada. The water quality requirements for reuse are often specific to the industrial process and application of the water; advanced treatment systems are often required to produce water of acceptable chemical and microbiological quality. Industry represents the largest water user in Canada, and further application of industrial water reuse and recycling could result in the conservation of large volumes of water.

Surface water augmentation may be used to compensate for upstream withdrawals or to restore wetland

habitat. Despite the fairly large dependence on groundwater supplies in Canada, artificial recharge using reclaimed water is not applied at this time. Due to uncertainty regarding long-term health effects and the presence of emerging contaminants, potable reuse, while practised in some areas of the world, is less attractive than non-potable reuse applications.

Each of the above applications of water reuse provides an opportunity for water conservation and reduction of effluent discharges into receiving waters. Reclaimed water quality is a function of the treatment applied, however, and each form of reuse carries unique health and environmental risks. Environmental sustainability and protection of public health must be carefully considered for any water reuse application.

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