RECHARGE OF AQUIFERS WITH RECLAIMED WASTEWATER: A CASE FOR SAUDI ARABIA

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الخلاصـة :

لوحظ خلال السنوات القليلة الماضية أنّ هناك استنزافاً لمخزون الموارد المائية في المملكة العربية السعودية نتيجة لازدياد الطلب للأغراض الزراعية، والاستهلاك المنزلي. وقد بُذلت الجهود لزيادة الاستفادة من المياة العادمة المعالَجة. وتتوقع الخطة السادسة للتنمية الاستفادة من (٣١٠) مليون متر مكعب من مياه الصرف الصحي المعالج للعام ١٩٩٨ – ١٩٩٩ م. وتُعتبر تغذية المياه الجوفية من أفضل الطرق للاستفادة من مياه الصرف الصحي المعالَجة.

وحيث إنّ التحسن المتوقع لنوعية الماء والعوامل الاقتصادية تؤيِّد القيام بعمل مشروع حقلي تجريبي لتغذية المياه الجوفية المتناقصة في المملكة. تعتبر المكامن الرسوبية المنقولة ومنكشفات المكامن المائية أماكن ملائمة للتغذية. ومن الممكن استخدام المياه المغذّاة لأغراض الزراعة، واحتمال إستعمالها للشرب. وهذا الاستخدام لا يتعارض مع ماتسمح به الشريعة الإسلامية.

ABSTRACT

In recent years there has been an alarming depletion of groundwater resources in the aquifers of the Kingdom of Saudi Arabia due to increasing agricultural and urban water requirements. Efforts are being made to increase the use of reclaimed wastewater. The sixth development plan envisages the use of 310 million cubic meters of reclaimed treated wastewater in the year 1998–1999. Wastewater recharge is one of the most promising techniques available for reclaiming treated wastewater. Expected water quality improvements and economic considerations strongly favor the undertaking of large scale recharge projects to replenish the depleting water tables in the Kingdom. Alluvial aquifers and the outcrops of aquifers would be suitable sites for recharge. The recharged water can be withdrawn to be used for irrigation and possibly for potable use. Such use would be lawful from the Islamic viewpoint.

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INTRODUCTION

That the Kingdom of Saudi Arabia faces a water shortage is well known. In the past 25 years or so, the Kingdom has undergone massive urbanization and agricultural development, both of which require large volumes of water. The domestic demand for water, according to the Ministry of Agriculture and Water [1], is expected to increase from the present 12 000 million cubic meters (MCM) to 17 000 MCM by the year 2000. A net annual deficit (difference between demand and supply) of 16 000 MCM is projected for the year 2010. This shall be met by exploiting non-renewable groundwater resources [2]. Currently, the major part of this demand, around 80%, is met by mining non-renewable fossil groundwater resources.

According to the Ministry of Agriculture and Water [1], the age of groundwater in the Kingdom ranges from the very recent to 40 000 yrs old. The water in the principal aquifers is relatively old, indicating that the addition of new water through recharge is very small.

The mining of fossil water has lead to the water tables falling drastically at many places. The continued mining of these aquifers can lead to disastrous consequences in the future. The aquifers are recharged to a very limited extent by the meager rains and through the use of a few recharge dams. In the Kingdom, the majority of the modern dams (about 58) have been constructed with the main objective of storing floodwater derived from rainfall and releasing it gradually to recharge the aquifers downstream from the dam for subsequent utilization both for agriculture and domestic use [1]. Desalinated sea water is expensive and thus is not a very economical source of water.

While there is an acute water shortage, treated wastewater is being wasted. Currently, other than 150 MCM of treated wastewater, all of the reclaimed wastewater is discharged into the oceans or wasted. According to Al-Degaither [3], the city of Riyadh alone generates approximately 100 MCM of municipal wastewater annually. It is estimated that the present 1000 MCM of wastewater generated in the Kingdom will increase to a volume of 1500 MCM by the year 2000. In an arid country like the Kingdom, this could be put to better use. There is a need for effective water resources management. This has been realized by the national planners and efforts are being made to increase the use of reclaimed wastewater. The sixth development plan 1994–1999 envisages that, of the water demand of 17 500 MCM, 310 MCM will be met by reclaimed treated wastewater in the year 1998–1999. Taken against the 150 MCM of treated wastewater used during the year 1993–1994, this means a 15.6 % average annual growth in the use of treated wastewater [4]. The greater portion of this reclaimed water is to be used for landscape irrigation and agriculture. It could possibly also be used for potable purposes in the near future. A promising technique for reclaiming treated wastewater is wastewater recharge.

Wastewater recharge offers several advantages. It is more economical to recharge and use recharged water than to use water from other sources such as seawater treated by desalination or sewage effluent treated by other traditional tertiary treatment techniques. Other than that, the aquifers into which the wastewater is recharged can serve as reservoirs. Due to the desert climate, evaporation rates are about 2 m/yr and even higher, so an underground reservoir with no evaporation losses is ideal. The use of reclaimed wastewater for agriculture may lead to a reduced need for applied commercial fertilizers, due to the presence of nitrogen and phosphorus compounds in the reclaimed water [5]. It is a supply source that is secure even during times of drought [6]. When reclaimed wastewater is to be used for potable use, wastewater recharge introduces “nature” into the recycling chain, making the reclaimed water more acceptable to people.

RECHARGE METHOD AND RECHARGE SITE

Treated wastewater can be recharged either through injection wells or through spreading basins. Spreading basins are frequently used and it involves the surface spreading of water in spreading basins or recharge basins. For spreading basins highly permeable soils are needed. The amount of water entering the aquifer depends on three factors: (*a*) the infiltration rate; (*b*) the percolation rate; and (*c*) the capacity for horizontal water movement [7]. Recharge wells or injection wells are used to directly recharge water into deep water-bearing zones and for confined aquifers, injection/ recharge wells are the only alternative [8]. Where land is scarce and large areas for spreading cannot be made available, recharge wells are advantageous. In recharge wells the infiltration rate into the aquifer is higher than that in spreading basins so that the quality of the recharge water has to be better than that used for surface spreading else frequent clogging would take place. Though there are numerous cases of recharge wells being used for secondary wastewater recharge, spreading basins present fewer problems from the clogging point of view, and maintenance is cheaper.

Desert soils in the kingdom have high infiltration and percolation rates making them quite suitable for spreading basins. Surface spreading is most effective where there are no impeding layers between the land surface and the aquifer, thus alluvial aquifers and the outcrops of principal aquifers would be ideal sites for spreading operations.

Figure 1 [9] shows the alluvial aquifers in the Kingdom. The alluvial deposits fill many drainage areas on the western coastal plains of the Kingdom. The aquifers are generally unconfined but may be semi-confined or confined at some places. The transmissivity generally varies from 10^2 to 10^4 m^2/day [1].

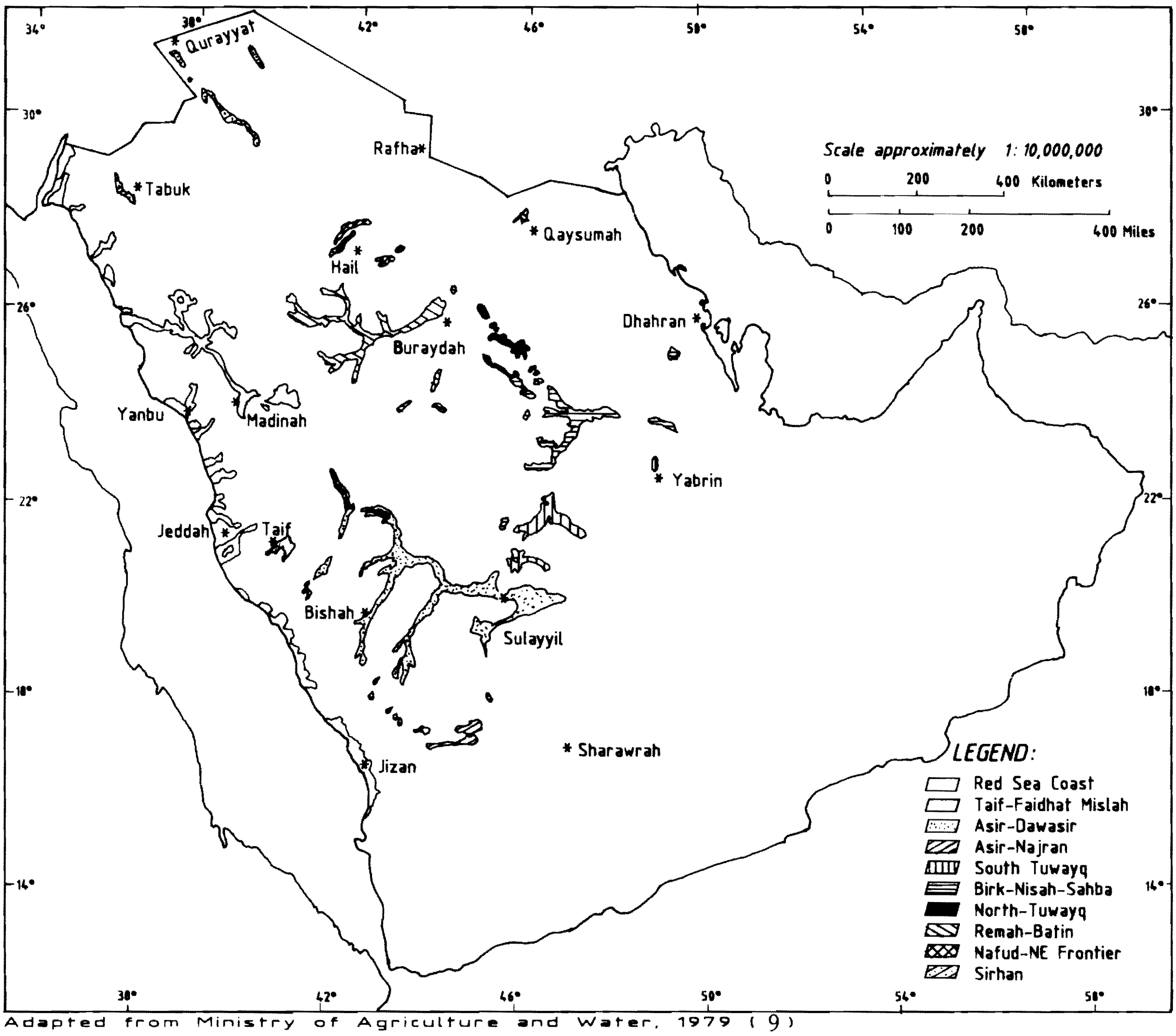


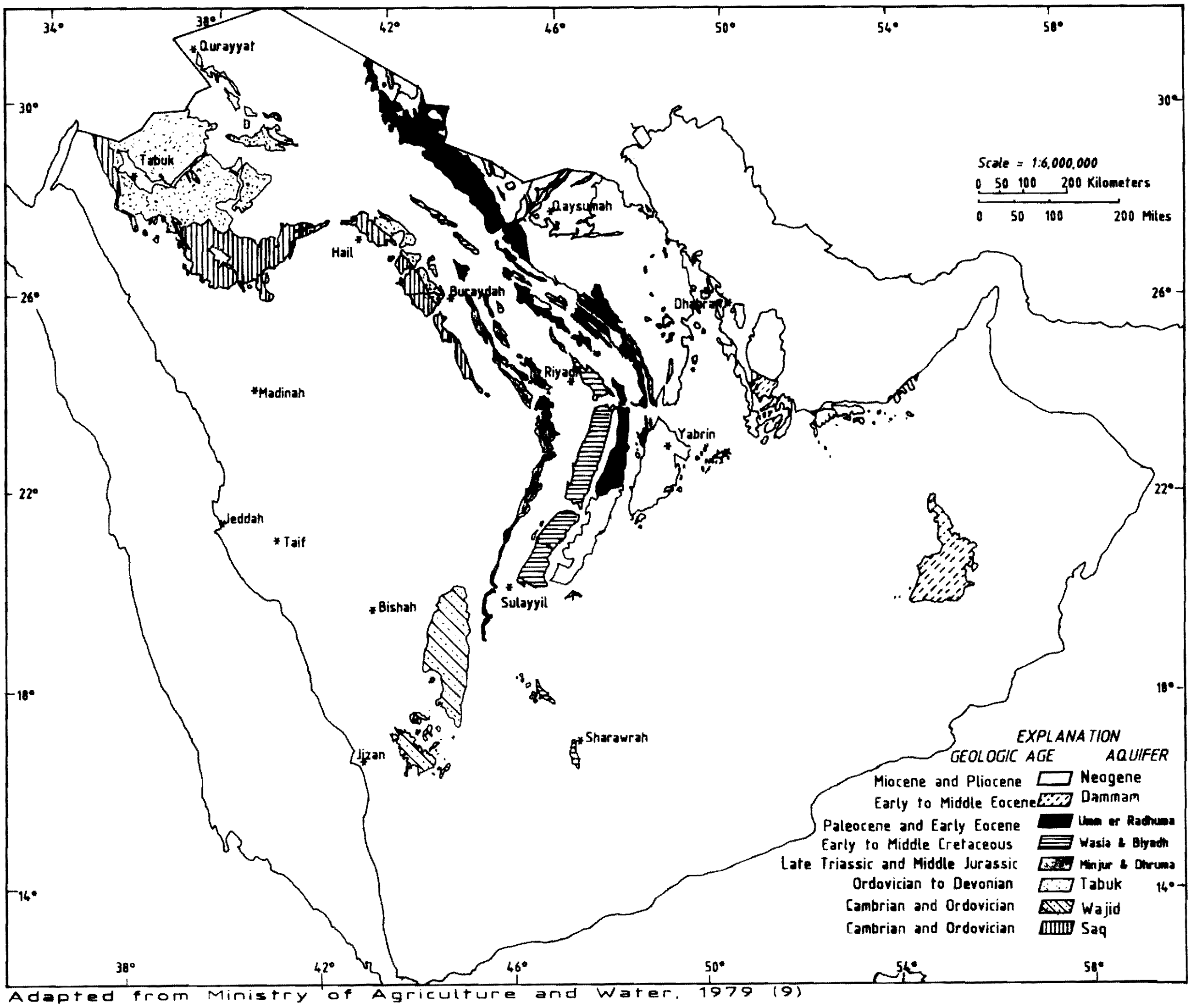
Figure 1. Location of Areas where Alluvial Deposits are Water-Bearing.

Figure 2 [9] shows the outcrops of the principal aquifers. The Kingdom's 9 principal aquifers provide a dependable supply of water for most parts of central and eastern Saudi Arabia. They range in geologic age from Cambrian to Tertiary [1].

ECONOMICS OF RECHARGE

According to the Department of Economics and Social Affairs of the U.N. [10], the total cost of a project varies greatly with the purpose of the project, method of recharging, quantity and quality of water available for recharge, regimen of flow, surface and subsurface conditions, location of the artificial recharge project, and standards and requirements of the agencies involved in the recharging operations.

Wastewater recharge is cheaper than other traditional tertiary or advanced treatment techniques. In St. Croix, U.S. Virgin Islands, secondary effluent was used to recharge aquifers by use of spreading basins. The cost for the wastewater treatment, recharge operations, and recovery of groundwater was estimated to be about US$568 per 1000 cubic meters at 1890 cubic meters/day, with a reduction in estimated costs to US$433 per 1000 cubic meters if the operation is expanded to 3780 cubic meters/day [11]. As reported by Smith [12], an economic analysis showed the cost of recharge/recovery operations to be significantly less than the cost of desalination of sea water, which supplies the major portion of the water to the island.



Adapted from Ministry of Agriculture and Water, 1979 (9)

Figure 2. Outcrop Areas of Principal Aquifers.

If it is desired that the water reclaimed through wastewater recharge be used for potable purposes, wastewater recharge would prove more economical than other treatment schemes which would produce water of comparable quality. At the wastewater recharge Salt River bed site, west of Phoenix, Arizona, it has been shown that, to use the effluent from this for potable use, further treatment is required. Carbon adsorption is required to remove small concentrations (often on the micro mg/l level) of a wide spectrum of synthetic organic carbon compounds. The effluent would have to be disinfected, possibly by UV irradiation, and, to further reduce organic carbon and possibly reduce the salt content, about half the effluent would have to be sent through a reverse osmosis plant. For a 0.4 million cubic meters per day plant, the estimated cost is about $230 per 1000 cubic meters. This is less than 40% of the cost of the complete in plant treatment to produce potable water from secondary effluent in the Denver Potable Water Reuse Demonstration Project, which was $600 per 1000 cubic meters. Thus, groundwater recharge is worth more than $370 per 1000 cubic meters. The cost often consists mostly of that for pumping the renovated water from the aquifer and is about $2.5 to $25 per 1000 cubic meters depending on the depth of the groundwater (3 to 30 m). Thus, wastewater recharge gives about $370 worth of treatment for about $2.5 to $25 pumping costs [13].

WATER QUALITY TRANSFORMATIONS

As wastewater percolates through the porous matrix of the soil, its quality undergoes transformations. Transformations in the recharge water quality are the result of one or more of the following [14]:

1. Biodegradation by and growth of microorganisms, including nitrification and denitrification
2. Chemical oxidation reduction
3. Sorption and ion exchange
4. Filtration
5. Chemical precipitation or dilution
6. Volatilization or photochemical reactions (in spreading basins).

The transformations are site specific and to obtain optimum contaminant removal, land treatment systems must be carefully designed. The change in the water quality has been monitored in many waste water recharge projects and have been widely reported.

In the case of waste water recharge, Gerba *et al.* [15] indicated that land application of domestic wastewater can serve as an economical method for removing a wide range of contaminants so that the water can be safely reused.

The monitoring of the performance of a groundwater recharge basin at the Kwinana groundwater recharge site in Western Australia from 1983 to 1986 showed phosphorus removal at a high level (over 80%), and excellent fecal coliform removal with most bored samples containing no fecal coliforms/100 ml. Nitrogen removal of approximately 45% was obtained with primary effluent using a cycle of flooding and drying. No nitrogen removal was obtained with a mixture of two thirds secondary effluent and one third primary effluent. With one exception the groundwater met water quality criteria for irrigation [16].

The removal of organics too has been reported to be very good. The results of studies in Arizona showed that soil–aquifer treatment is effective in reducing concentrations of a number of synthetic organic compounds in the sewage water [13]. In wastewater treatment by infiltration basins in the sewage plant in Creances, France, the resulting infiltration leads to a total removal of suspended solids, and of 80 to 85% of COD initially present in the effluent [17].

Of late much attention has been paid to the fate of microbial pathogens. In studies in August and September, 1990 at a recharge site near Tucson, Arizona, the bacteriophage MS-2 and PRD-1 were used because of their poor adsorption to soil and long survival time. The results suggest that different viruses will experience different degrees of removal by the same soil. How much virus reaches the groundwater will also depend on the survival of the virus. It would appear that virus reductions of at least 99% or more after passage through 15 feet of the soil (sandy gravel and coarse sand with some clay lenses) used in the study are possible. Greater removal was observed at a slower infiltration rate (3 feet/day) [18]. Greater removals of enteroviruses and other human enteric viruses can probably be expected since they are adsorbed to a greater degree to soils than the bacteriophage used in the previous study [19]. Thus, soil aquifer treatment by wastewater recharge has much potential for reducing/removing microbial pathogens.

That there are changes in the water quality is thus clear, but the exact amount of change is a variable depending on the recharge water quality, the recharge method, seasons, and other factors. The potential for contaminant removal by wastewater recharge operations have been aptly summarized by Culp *et al.* [20] as shown in Table 1. Most reclaimed water contaminants are substantially removed during vertical percolation through soil and during horizontal movement in the aquifers. Notable exceptions are total dissolved solids, hardness, nitrates (if organic carbon for denitrification is lacking), and a few heavy metals (where pH of the soil and water is low). Though equally good removal can be expected in the Kingdom the exact removal for various sites in the Kingdom would have to be determined through laboratory and field studies.

Table 1. Potential for Chemical Contaminant Removal by Wastewater Recharge Operation (after [21]).

Constituent	Removal potential (Percentage of influent concentration)
BOD	>50
COD	>50
NH_3-N	>50
NO_3-N	
Phosphorus	>50
Alkalinity	25 – 50
Oil & grease	>50
Total coliform	>50
TDS	
Arsenic	
Barium	
Cadmium	25
Chromium	
Copper	>50
Fluoride	25 – 50
Iron	
Lead	25 – 50
Manganese	
Mercury	
Selenium	
Silver	
Zinc	>50
Color	>50
Foaming	>50
Turbidity	>50
TOC	>50

The blank spaces denote no data, inconclusive results or an increase.

RELEVANCE TO THE KINGDOM OF SAUDI ARABIA

The relevance of wastewater recharge to the Kingdom can be highlighted by drawing parallels between the Kingdom and other places where wastewater recharge was used with success. Parallels can be drawn between the Kingdom and St. Croix, U.S. Virgin Island. St. Croix, which like the Kingdom gets its water supply from desalination plants, used effluent from the advanced wastewater treatment plant to recharge aquifers by use of spreading basins. Wells in the area were monitored to determine changes in static levels and in quality. The results indicated an increase in the quantity of water in the aquifer, an improvement in the quality of the recharged effluent and as stated earlier the cost of recharge/recovery operations was significantly less than the cost of desalination of sea water which supplies the major portion of the water to the island [12].

Parallels can also be drawn between the Kingdom and Atlantis in South Africa. Atlantis, an industrial town on the somewhat bleak and undeveloped west coast of South Africa, is entirely dependent on groundwater resources for its water supply. With a population of more than 67 000 people and about 140 factories, Atlantis requires a reliable supply of potable water of about 1.5 MCM/annum. The demand is met through artificial recharge of a local, shallow, sandy aquifer that supplies the town's water. All urban stormwater runoff and treated domestic sewage effluent is recharged. No water is wasted, even the water that is unacceptable for recharge in the main aquifer is recharged in strategic localities to counter saline intrusion [21].

A good example of reusing secondary effluents for unrestricted irrigation after underground storage is found in the Dan region project. The wastewater undergoes mechanical–biological treatment by activated sludge process with the option of a nitrification–denitrification stage. This then is spread over three sand dune leaching basins (420 000 m^2 area) and recharged to the regional groundwater aquifer which serves as a reservoir. The recharge cycle consists of one day flooding and two days drying at each spreading basin. The water is then pumped out of the aquifer by means of 52 pumps, conveyed through a pipeline and before exit to the first customer it undergoes chlorination. In its first year of operation it has supplied 75 MCM of water for unrestricted irrigation and is designed to supply up to 135 MCM per year to the arid and semi-arid regions of the country [22]. Such a project in the Kingdom would make good use of the secondary effluents presently going to waste. Apart from being a boost to the irrigation sector the excess water can be stored for the future.

In cities such as Riyadh the aquifer could be used as a treatment medium. The recharged water can be recovered at a later stage and, if of suitable quality, it can be treated further and used to augment the potable water supply. As has been reported earlier of the Salt Bed river recharge experimental project near Phoenix, Arizona, to use the effluent from the recharge project for potable use further treatment may be required [13]. The exact treatment required and the cost will vary, but if the economics are favorable, it is a proposal worth implementing. As pointed out by Bouwer [13], an advantage of using the aquifer as an intermediate step in the treatment chain is that it breaks the pipe-to-pipe connection of the direct recycling of sewage effluent with in-plant treatment only. This enhances the aesthetic aspects and public acceptance of potable reuse of municipal wastewater, because the water is pumped from wells and has lost its identity as sewage water. In many countries, cities upstream of a river draw water from the river, use it and discharge it back to the river. This water is again drawn upon by cities down stream and used for potable use. This is accepted by the public because here too the water loses its identity as sewage.

Treated sewage has also been used to prevent sea water intrusion into fresh ground water [23]. Similarly, in Saudi Arabia too, the use of wastewater recharge to mitigate salt water intrusion can find much application.

ISLAMIC PERSPECTIVE

If the water that has been reclaimed using wastewater recharge is to be ever used for purposes other than irrigation in Saudi Arabia, it is important that it be lawful from an Islamic standpoint.

As reported by Farooq and Ansari [24], the Organization of Eminent Scholars of Saudi Arabia considered the question of reuse of sewage after it has been purified by the water treatment methods available today. The organization expressed their confidence in the effectiveness of the modern techniques of purifying water and restoring it to its original cleanness (see the text of this *fatwā* in the daily newspaper, *Al-Madina*, Jeddah, April 17, 1979). They concluded that water which had been thus treated might be used for ritual washing or for washing, and that unless such water was found to have harmful health effects, it might even be used for drinking. The organization, however, expressed its preference for avoiding the use of such water for drinking if it was possible to do so, as a health precaution or because of the instinctive revulsion that men feel for such water.

In the case of wastewater recharge, secondary treated wastewater is further purified by soil–aquifer treatment and also diluted to a certain extent by mixing in the aquifer. As stated earlier, in order to use this reclaimed water for purposes such as drinking, it probably would have to be further treated, using reverse osmosis if dilution with native groundwater is inadequate. Such advanced treatment would remove all extraneous impurities and restore water to a very high degree of purity. Thus, the overall treatment would go beyond the minimum requirement of the law as laid down by Islam.

CONCLUSIONS

Thus far, an overview of wastewater recharge has been presented. It can be concluded without doubt that artificial recharge, especially wastewater recharge, is among the most promising water reuse/reclamation processes currently available to us. The benefits associated with wastewater recharge for the variety of purposes for which it can be used are many and have been validated by the many pilot and full scale projects that have been implemented to date.

Expected water quality improvements and economic considerations strongly favor the undertaking of large scale recharge projects to replenish the depleting water tables in the Kingdom. Alluvial aquifers and the outcrops of the principal aquifers would be suitable sites for recharge. The recharged water can be withdrawn to be used for irrigation and possibly for potable use. Such use would be lawful from the Islamic viewpoint.

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MUNICIPAL WASTEWATER TREATMENT AND REUSE IN SAUDI ARABIA

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الخلاصة :

تعتبر معالجة مياه الصرف الصحي وإعادة استخدامها في المملكة العربية السعودية في حاجة ماسّة إلى التطوير وتحسين الكفاءة من جميع النواحي. ونورد في هذا البحث عدة توصيات رئيسة مثل: سرعة توسيع شبكات الصرف، والطاقة الاستيعابية لمحطات المعالجة، والتوسع في برامج إعادة استخدام المياه المعالجة، ووضع أنظمة وإرشادات خاصة باختيار أنظمة المعالجة وتصميمها بحيث تتوائم مع ظروف المملكة، ووضع معايير نوعية منطقية ومطبقة للتخلص من المياه المعالجة ولإعادة استخدامها. والبَدْءُ لوضع برنامج لمراقبة محطات المعالجة مبنيٌّ على رفع تقارير دورية عن الوضع الفعلي لأداء المحطات بحيث تكون الجهات المشغّلة للمحطات مسئولة عن جميع المخالفات .

ABSTRACT

The practice of municipal wastewater treatment and reuse in the Kingdom of Saudi Arabia is in urgent need of improvement in all aspects. Major recommendations include the need to: immediately expand wastewater collection, treatment capacity, and reuse; establish process selection and design guidelines considering the Kingdom's local requirements; establish rational and enforceable quality criteria for effluent disposal and reuse; and start a system of plant inspection and reporting that holds plant operating entities liable for any violations.

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MUNICIPAL WASTEWATER TREATMENT AND REUSE IN SAUDI ARABIA

INTRODUCTION

Treatment of municipal wastewater in urban areas is considered an important element in the development of a country and for preserving the health and welfare of its people. The consequence of not treating wastewater is the spread of disease in the form of many types of endemic and epidemic illnesses.

Water is the most basic need of mankind. Global water needs surpass national, economic, and political bounds. Increasing demands for this exhaustible resource have resulted in a critical evaluation of water reuse as a means of supplementing municipal and industrial water supplies [1]. Reuse of reclaimed or recycled wastewaters for nonpotable applications is currently the rule rather than the exception in many parts of the world. Such uses include crop and landscape irrigation, industrial and recreational uses, and groundwater recharge [2]. Although direct potable reuse of wastewater is still not accepted, it is obvious that the obstacles are rapidly being overcome by current research. An example worth noting here is the Denver Direct Potable Water Reuse Demonstration Project [3, 4]. This 3800 m^3/day reuse demonstration plant was operated from 1984 through 1990 with extensive studies aimed at determining product water safety, demonstrating process dependabilities, generating public acceptance, and providing data for a large scale implementation.

There are many ways and means for treating wastewaters, ranging from very simple, cheap, and less efficient processes to very advanced, highly efficient, and costly operations. The selection from among these processes should be based carefully on thorough evaluation of local conditions such as: weather, social characteristics, economy, availability of enforceable standards, availability of land and power, required operation skills and its availability, monitoring activities, effluent disposal options, effluent reuse practices and/or requirements.

In the Kingdom of Saudi Arabia, only 30% of the total generated urban wastewater flow is treated in central facilities. The remainder is treated mostly through septic tanks and/or cesspools. Although the treatment plants process only a small fraction of generated wastewater, these plants are considered as an important asset that should be maintained and expanded as they should provide a great reduction in environmental pollution. The ultimate goal, of course, is to have all urban areas sewered and have appropriate treatment plants. Only a limited amount of treated municipal wastewater in Saudi Arabia is reused. Applications of reclaimed wastewater are generally devoted to landscape, agriculture, and industry.

This paper discusses municipal wastewater treatment and reuse in Saudi Arabia. It examines the diversity of treatment operations, treatment capacity, performance of treatment plants, suitability to the Kingdom's requirements, and reuse practices. Information and discussions presented are based on the author's many years of experience in wastewater treatment within the Kingdom and on his most recent participation as a co-investigator in a funded research project aimed at evaluating wastewater treatment plants throughout Saudi Arabia [5].

WATER SOURCES AND CONSUMPTION

The sixth development plan of the Kingdom of Saudi Arabia stressed that the increased demand on water in recent years has changed the water balance in the Kingdom. The agricultural sector is the largest water consumer, amounting to 90% of total water consumption in 1415 H (1995 G). There is also a significant increase in water consumption for municipal, recreational, and industrial purposes, due to increased population, development, and improved standard of living [6]. The estimated contributions from the different available resources in 1995–1996 were surface water and renewable ground water (13.8%); nonrenewable groundwater (81.5%); desalinated sea water (3.8%); and reclaimed municipal wastewater (0.8%). The sixth development plan calls for immediate and effective measures to reduce water consumption in agriculture and more polices aimed at water preservation, including conservation efforts and increased use of reclaimed municipal wastewater.

MUNICIPAL WASTEWATER TREATMENT

The total amount of drinking water supplied by the Water and Sewage Authorities (WSA) to all cities of the Kingdom was estimated at 3.4×10^6 m^3/day (1995–1996). The total flow of municipal wastewater which is collected in sewer networks and passes through wastewater treatment plants is 1.44×10^6 m^3/day. This implies that the amount of treated municipal wastewater is equivalent to 41% of the total amount of municipal water delivered by WSA. It should be emphasized, however, that not all urban water requirements are provided by WSA. In many urban and rural areas, water may be provided from private sources other than those operated by WSA. Another factor to be considered is the fact that part of the wastewater collected from urban areas result from extensive infiltration to the sewer systems due to rising water table (perched water), which is itself a result of the absence of sewer systems in many urban areas. Hence, it is safe to say that existing sewer systems and municipal wastewater treatment operations are adequate for approximately 25–35% of generated wastewaters throughout the Kingdom.

An examination of wastewater treatment plants reveals that almost all types of unit processes and operations are being used. We find the simple and low cost treatment plants utilizing stabilization ponds and aerated lagoons, the more efficient, moderate cost, secondary treatment (activated sludge, trickling filters), and the high cost advanced treatment plants (nitrification, denitrification, gravity media filtration, chemical clarification, activated carbon adsorption, reverse osmosis, *etc.*). In an attempt to summarize the details of plants, they are grouped here into four categories for ease of general comparison. For each category several examples of plants are given and summarized.

Stabilization Ponds and Aerated Lagoons

Stabilization ponds use simple processes that treat wastewater based on natural low-rate biological activity. They are relatively shallow man-made basins in which organic matter is oxidized or reduced, and pathogenic organisms destroyed, by the action of natural biodegradation phenomena [7]. Ponds can be classified as anaerobic, facultative, or maturation ponds. Each has its characteristics and works for a specific purpose in a specific mode. Aerated lagoons are ponds in which all or part of the oxygen required is supplied by mechanical aeration.

Waste stabilization ponds are among the oldest treatment processes used for processing municipal wastewater. They are also used for treatment of many industrial wastes. Recently, these systems were stipulated as the most suitable wastewater treatment systems for effluent use in agriculture [8]. Stabilization ponds are the preferred wastewater treatment process in developing countries, where land is often available at reasonable cost and skilled labor is in short supply [9]. Such natural systems are lower in cost and less sophisticated in operation and maintenance than conventional wastewater treatment systems. Although ponds tend to be land intensive when compared with the conventional high-rate biological processes, such as activated sludge — biological filters — rotating biological contactors, they are often more effective in removing pathogens. They do so reliably and continuously if properly designed and operated. Table 1 illustrates examples of plants utilizing these simple systems. Although ponds and lagoons are simple to design and operate, they do require attention and have proved to be successful in many urban and rural areas.

Trickling Filters

Trickling filters, or biological filters, are a form of secondary treatment of wastewater. They consist of circular or rectangular basins filled with filter media (crushed stone, or plastic) on which biological mass can grow, also called an attached growth process. Wastewater is sprayed on top of the media and trickles down the filter through pores passing over the biological mass which oxidizes the organic matter and reduces wastewater biochemical oxygen demand (B.O.D.). Sloughed biological mass, together with suspended solids (S.S.), are separated in a secondary clarifier. Part of the clarified effluent is recirculated back ahead of the filter for improved process efficiency.

Table 2 illustrates examples of plants utilizing trickling filters in secondary treatment mode. These systems when operated properly can produce effluents with low B.O.D. ($\leq$20 mg/l) and S.S. ($\leq$20 mg/l) which is acceptable for discharge to land or surface water and for reuse in restricted agricultural and landscape irrigation. A form of effluent disinfection is required in most applications [2,10,11].

Activated Sludge and Its Modifications

Activated sludge, a suspended growth process, consists of relatively deep basins in which oxidizing bacteria are kept in suspension through mechanical mixing and aeration. The level of treatment is controlled through hydraulic and solids retention times provided a reasonable level of biological mass is maintained in the aeration basin. The flocculated biological mass oxidize organic matter coming in the influent and then itself separated in a secondary clarifier, leading to the reduction of both B.O.D. and S.S. Part of the settled biological mass is returned ahead of the aeration basin for process activation. These systems can provide effluents with low B.O.D. and S.S. suitable for many disposal and reuse applications.

Table 1. Examples of Plants Utilizing Stabilization Ponds and Aerated Lagoon Systems.

City	Plant Name	Treatment Scheme	Avg. Daily Flow (m^3/day)		Influent*		Effluent*		Effluent Chlorina-tion	Effluent Disposal and/or Reuse
			Design	Actual*	BOD	S.S.	BOD	S.S.		
Buraidah	Buraidah	Facultative + Maturation Ponds	11000	13000	230	200	70	100	Yes	To sand dunes
Unaizah	Unaizah	Aerated Lagoons	7080	9900	170	230	26	40	Yes	To Wadi
Al-Kharj	Al-Kharj	Aerated Lagoons + Partially Aerated Lagoons + Sand Filters	21000	21600	277	257	11	8	Yes	To Wadi
Qatif	Sanabis	2-Stage Facultative	8340	22195	101	237	46	255	Yes	Gulf
Qatif	Gesh	2-Stage Facultative	8990	15930	100	210	67	196	Yes	Gulf
Qatif	Awamia	2-Stage Facultative	9260	13430	70	200	43	157	Yes	Gulf
Al-Ahsaa	Oyoon	2-Stage Facultative	6310	17100	320	110	130	30	Yes	To Lagoon
Al-Ahsaa	Emran	2-Stage Facultative	13320	22100	305	110	125	30	Yes	To Lagoon
Al-Ahsaa	Hufuf-Mubarraz	2-Stage Facultative	29500	136780	170	130	150	50	Yes	To Lagoon
Khafji	Khafji	2-Stage Facultative	25000	5190	–	–	–	–	Yes	Gulf

* Actual in 1995 BOD = Biochemical Oxygen Demand S.S. = Suspended Solids.

Table 2. Examples of Plants Utilizing Trickling Filters.

City	Plant Name	Treatment Scheme	Avg. Daily Flow (m^3/day)		Influent*		Effluent*		Effluent Chlorina - tion	Effluent Disposal and/or Reuse
			Design	Actual*	BOD	S.S.	BOD	S.S.		
Jeddah	Al-Khomra	Trickling Filters (Stone media)	36000	66000	–	–	–	–	Not used	Red Sea
Makkah	Old Plant	Trickling Filters (Stone media)	24000	65000	200	300	–	–	Not used	Wadi + A.I.
Riyadh	Al-Hayer Old Plant	Trickling Filters (Plastic media) + Polishing Lagoons	200000	200000	270	340	20	20	Yes	Wadi + A.I. + Refinery

* Actual in 1995 A.I. = Agricultural Irrigation.

There are several modifications of the activated sludge process designed to: improve process reliability, reduce operation skill requirements, optimize oxygen supply and demand, and induce nitrogen and phosphorus reduction. Table 3 provides summaries of treatment plants utilizing the activated sludge process or its modifications.

Advanced Wastewater Treatment

Advanced treatment, or tertiary treatment, is defined as additional treatment needed to remove suspended and dissolved substances remaining after conventional secondary treatment. Strict discharge requirements, reuse of treated wastewater in food-crop irrigation, industry, and groundwater recharge all resulted in the need for effluent quality much better than can be accomplished by secondary treatment of wastewater. Substances that are removed by advanced treatment include B.O.D., chemical oxygen demand (C.O.D.), S.S., N, P, total dissolved solids (T.D.S.), and many synthetic compounds, depending on the treatment scheme utilized. The advanced waste treatment process may be used following or in conjunction with the conventional secondary process, or it may replace secondary treatment entirely. Examples of advanced treatment processes include disinfection, chemical clarification, filtration, chemical and biological nitrogen removal, carbon adsorption, and desalination [2, 12]. Table 4 illustrates examples of treatment plants utilizing advanced treatment.

EVALUATION OF TREATMENT, DISPOSAL AND REUSE

As seen in Tables 1 to 4, the treatment systems utilized in the Kingdom are diversified and represent almost all types of treatments one can imagine. This, however, reflects the lack of proper understanding of the objectives, and goals of wastewater treatment. There are no established guidelines identifying treatment objectives as related to effluent disposal and reuse. There is also no clear understanding regarding what type of treatment to be selected and on what basis. Plants are being designed based on consultants' preferences, which is mostly based on experiences in industrial nations with no regard to local needs, capabilities, quality control measures, and level of criteria enforcement. Wastewater treatment is still viewed in the traditional concept of aesthetic considerations. There is an urgent need to look at wastewater as being a direct threat to human health which requires a great deal of attention. Wastewaters contain ample quantities of pathogens and probably many toxic substances that can directly or indirectly cause disease and toxicity to humans and to the environment.

Although operating municipal treatment plants in the Kingdom handle only a fraction of generated urban and rural wastewaters, they should be viewed as a positive activity that need to be preserved, improved, and expanded. However, improperly selected, designed, and operated treatment plants can be dangerous to human health and the environment and probably should be viewed as a useless economical burden. One important aspect to be mentioned here is the selection of proper treatment. This requires knowledge of raw wastewater characteristics, effluent disposal and/or effluent reuse, availability of quality criteria and standards, availability of required technical skills, and proper enforcement and accountability.

Currently, there are several effluent disposal and reuse practices in Saudi Arabia. Coastal cities and towns on the Red Sea and the Arabian Gulf discharge effluent either to the sea or to wadis, or reuse effluent for agricultural and landscape irrigation. Inland cities and towns discharge effluent to wadis or reuse for agricultural and landscape irrigation. The total amount of reused municipal wastewater in the Kingdom is estimated at 335 800 m^3/day [13]. This is equal to 23% of treated municipal effluents and 7% of all generated municipal wastewaters. The rest, however, infiltrates to the ground, is discharged to the sea, or evaporates. It is important to note that each form of effluent disposal and/or reuse requires effluent that meets specific quality criteria. Such criteria should be based on protection of human health, soil, and water supplies. Evaluation of wastewater treatment plants in the Kingdom revealed many observations, the details of which were reported elsewhere [5]. Some important observations are reported and discussed below.

Quality Criteria for Effluent Disposal

There is no enforceable quality criteria for effluent disposal and reuse in Saudi Arabia. This is a serious problem that requires great attention. The tentative wastewater reuse criteria, published by the Ministry of Agriculture and Water (MAW), were never approved and never enforced. These criteria specify maximum contaminant levels for effluent reuse in agricultural irrigation. Some of these levels are not reasonable and cannot be accomplished by common reclamation practice. The water environmental standards specified by the Meteorology and Environmental Protection Administration (MEPA) is also not enforced. These standards, published as MEPA Document No. 1409-01, are full of contradictions and did not specify

Table 3. Examples of Plants Utilizing Activated Sludge or its Modifications.

City	Plant Name	Treatment Scheme	Avg. Daily Flow (m^3/day)		Influent*		Effluent*		Effluent Chlorination	Effluent Disposal and/or Reuse
			Design	Actual*	BOD	S.S.	BOD	S.S.		
Dammam	Dammam	Oxidation Ditch	208 000	140 000	105	205	5	23	Yes	Gulf + L.I.
Al-Khobar	Al-Khobar	Oxidation Ditch	133 000	100 000	134	153	4	8	Yes	Gulf
Qatif	Qatif	Oxidation Ditch	210 000	35 000	93	180	4	11	Yes	Gulf + L.I.
Safwa	Safwa	Completely Mixed	7570	8600	220	250	15	15	Yes	Gulf
Jeddah	Plant C	Package Contact Stabilization	40 000	63 000	260	300	80	170	Yes	L.I. + Lagoon
Jeddah	Plant A	Package Contact Stabilization	32 000	55 000	200	230	35	100	Yes	Red Sea + L.I.
Jeddah	Bani Malik	Package Contact Stabilization	8000	6500	180	220	25	50	Yes	L.I. mostly
Jeddah	Al-Jamia	Package Contact Stabilization	8000	7000	310	310	27	58	Yes	Red Sea + L.I.
Madinah	New	Conventional Activated Sludge	120 000	100 000	210	250	7	5	Yes	Wadi + L.I. + A.I.
Khamis-Mushait	Al-Dhoba	Oxidation Ditch	7500	10 000	600	400	5	7	Yes	Wadi + L.I. + A.I.
Abha	Abha	Extended Aeration	9000	11 500	500	350	7	10	Yes	Wadi

* Actual in 1995 L.I. = Landscape Irrigation A.I. = Agricultural Irrigation.

Table 4. Examples of Plants Utilizing Advanced Treatment.

City	Plant Name	Treatment Scheme	Avg. Daily Flow (m^3/day)		Influent*		Effluent*		Effluent Chlorination	Effluent Disposal and/or Reuse
			Design	Actual*	BOD	S.S.	BOD	S.S.		
Jeddah	Tertiary (Al-Khomra)	Trickling Filters + Ozonation + Clarification + Sand Filtration + Reverse Osmosis	30 000	20 000	80**	62**	13	19	Yes	Red Sea + L.I. (R.O. out of order)
Makkah	New	Plug Flow Activated Sludge with Nitrification Denitrification	50 000	–	200	300	–	–	Not used	Wadi + A.I.
Taif	Taif	Activated Sludge with Nitrification Denitrification + Clarification + Filtration (mixed) + Activated carbon filtration	67 000	34 000	330	360	–	–	Yes	L.I. + A.I.
Riyadh	Al-Hayer New	Activated Sludge + Nitrification – Denitrification + Filtration	200 000	200 000	270	340	6	5	Yes	Wadi + A.I. + Refinery
Riyadh	Refinery	Al-Hayer Effluent + Clarification + Filtration + Reverse Osmosis + Ion Exchange	20 000	10 000	34** COD = 48	29**	2*** COD = 5	0.0***	–	• Cooling, • Boiler feed, • Desalter make-up

* Actual in 1995. ** Before Clarification *** After Reverse Osmosis

L.I. = Landscape Irrigation A.I. = Agricultural Irrigation standards for effluent discharge to wadis [14]. They also failed to define sampling and testing procedures to obtain the numerical effluent levels. Both MAW and MEPA standards are often ignored by designers and operators of treatment plants.

Suitability of Treatment Schemes

It is important to link treatment requirements with effluent disposal and reuse practice. Disposal of effluent to sea, for example, requires proper biological treatment with partial disinfection. Plants discharging to the Arabian Gulf, [Dammam, Al-Khobar, and Qatif (oxidation ditch)] fulfil this criteria. Plants in Jeddah on the Red Sea, [plant A, Al-Jamia, and Al-Khomra (trickling filter)] do not satisfy the criteria. This is due to plant overloading, improper operation, and lack of effluent disinfection.

The other most common type of wastewater reuse in the Kingdom is unrestricted agricultural and landscape irrigation with discharge to wadis, which recharge nonpotable groundwater aquifers. This type of reuse, most common in the central and southern regions and in Madina, requires biological treatment with chemical coagulation, granular media filtration, and disinfection. Such systems can only be found in the tertiary treatment systems of Taif, Al-Hayer (New), and probably Al-Khomra (tertiary). Effluents from the rest of the mechanical treatment plants, if operated properly, can only be acceptable for restricted agricultural and landscape irrigation. Aquifers recharged from such plants should be declared as of nonpotable groundwater.

Almost all stabilization pond plants are not functioning well, mostly due to over loading and neglect. The aerated lagoon-pond system at Unaizah serves as a good example of a simple treatment plant which is meeting its design objective and providing reclaimed water acceptable for discharge to wadis recharging nonpotable groundwater. Another excellent example is the tertiary treatment aerated lagoon system of Al-Kharj. This adequately designed and operated system utilizes aerated lagoons, partially aerated lagoons, sand filtration, and chlorination. Effluent from this system is suitable for uncontrolled discharge to wadis with possible recharge of potable groundwater. It is important to emphasize that stabilization pond systems are effective for removal of pathogens (bacteria, viruses, helminth eggs, and protozoa cysts). In warm climates, pond systems of 10 to 20 days retention time can remove pathogens at a much lower cost than any other treatment [15–17].

Selection of a suitable treatment scheme should be based on careful consideration of treatment level required, which is linked to a disposal or reuse practice. Simple and less costly systems should be investigated and selected, if adequate for the objectives. Enhancement of the treatment plants operating in the Kingdom requires complete evaluation of each system regarding loading, operation and maintenance, and system capabilities. In many cases, secondary system performance can be improved through adjustments of the above factors. In other cases, upgrading of an existing system through addition of a treatment step, such as filtration, polishing ponds, or chlorination may lead to the required performance.

Plants Design, Operation, and Maintenance

Although there are several design problems associated with certain treatment plants, the majority of problems relate to plant operation and maintenance. Deficiencies reported include incompetent operational staff, inadequate laboratories, improper sampling and testing, neglect of maintenance requirements, inadequate number of staff, improper reporting and documentation of plant performance data, and falsified reporting. It must be stressed here that such irregularities are quite expected in the absence of performance criteria and accountability. Wastewater treatment plant operations require continuous inspection from a regulating agency. There is no such entity in the meantime. Plants are operated either by contractors or by the Water and Sewage Authorities. Many contractors and some Authorities do not have qualified staff, and with the absence of inspection and accountability, such plants are operating haphazardly.

Effluent Disinfection

Disinfection of plant effluent is an important practice and is considered a must where effluent is discharged to the sea, wadis, or reused for landscape and agricultural irrigation. Disinfection, mostly attained by chlorination, is essential for prevention of enteric diseases. The Kingdom of Saudi Arabia is most vulnerable to disease transmission through wastewater contamination. Great numbers of pilgrims and expatriates come to the Kingdom from all over the world, mostly from the third world countries. All forms of pathogens can be found in wastewaters throughout the Kingdom. Disinfection practice should be given great attention, although disinfection alone may not be adequate to prevent all forms of enteric diseases.

The serious problems at Makkah plants is worth drawing attention to. Both new and old plants at Makkah suffer from operational problems, and effluent is discharged to the wadi totally unchlorinated. Furthermore, the new plant was built in a way that it shares several treatment units and operations of the old plant including grit chambers and sludge treatment processes. As a result, the new plant's performance is totally inadequate.

Control Over Influent Quality

Municipal wastewater treatment plants are normally designed to handle wastewaters from residences, institutions, and commercial establishments. Industrial wastewaters may be allowed to be discharged to municipal sewers after a specified degree of pretreatment. One of the apparent causes of plant failure or improper operation is admittance of industrial wastewaters to city sewers without any form of pretreatment. In some cases tankers carrying wastewater from industrial activities are allowed to empty their loads at the inlets of treatment plants. This situation need to be assessed carefully and proper measures should be established. Treatment of industrial wastes require special design and/or treatment schemes, depending on type of industry.

CONCLUSIONS AND RECOMMENDATIONS

This paper has provided a comprehensive look at municipal wastewater treatment, effluent disposal, and reuse in Saudi Arabia. Following are some conclusions, and recommendations, that the author sees as timely and very important.

- Approximately 30% of all generated municipal wastewaters are collected and treated. There is an immediate need to rapidly expand sewage systems and treatment capacity to include all generated wastewaters. Not only is this important from environmental and public health standpoints, it is also economical when considering the costs of damage caused by rising groundwater table (perched water) to foundations, structures, and roads.
- It is estimated that only 7% of all generated municipal wastewaters is accounted for in direct reuse applications. Reuse of treated wastewater in agricultural and landscape irrigation should be given a priority in the Kingdom. This is an important conservation measure. Reclaimed wastewater can supplement the already declining water supply that has to be satisfied through costly sea water desalination or depletion of nonrenewable groundwater.
- The absence of established guidelines for treatment plant selection, and of treatment objectives specific to Saudi Arabia's requirements, have led to construction of treatment plants with diversified technologies and objectives, many of which did not give attention to local needs, technical capabilities, quality control measures, level of plants inspection, and availability of enforcement and accountability. It is important at this stage to learn from experiences at existing plants and establish clear and enforceable guidelines to be followed for plant selection and design based on local needs and specified national goals.
- It is highly recommended to establish a governmental department, with the required expertise, to oversee the establishment of national criteria and standards for effluent disposal and reuse, taking into consideration actual reuse practice, protection of public health and the environment, and capabilities of common wastewater treatment operations. Such a department should have the authority to perform plant inspections and to hold plant operating entities accountable for any violations.
- Only a few of the currently operating treatment plants have effluents suitable for their actual disposal practice or reuse option. This is because the remaining plants either have great operation and maintenance problems or because the treatment scheme is not suitable for the application. Mismanagement of treatment plants has to be stopped and effluents have to be disposed of and/or reused in a way compatible with effluent quality.
- Improperly treated wastewater can be a serious public health disaster when reused. Pathogens have to be inactivated or reduced to the lowest possible risk. Disinfection of reclaimed wastewater for such uses as applied in Saudi Arabia is a significant factor in disease control. It is urgent to make sure that every treatment plant has the proper chlorination equipment and a well established chlorination practice, which is applied on continuous basis, with proper testing for microbiological quality of final effluent.
- Aerated lagoons — stabilization pond systems have to be considered seriously as excellent treatment systems that can satisfy most disposal and reuse options in the Kingdom. They can do so with less cost and with very much lower

operating skills than other mechanical systems. Such systems when upgraded by gravity media filtration and proper disinfection can produce reclaimed wastewaters acceptable for unrestricted landscape and agricultural irrigation with possible recharge of potable groundwater.

- There is a lack of extensive studies aimed at investigating the impacts of current wastewater reuse practices in the Kingdom on human health, soil characteristics, and groundwater resources. Such studies are extremely important for planning future reuse activities and establishing reuse criteria.

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