Indirect potable reuse and reverse osmosis: challenging the course to 'new water'

● In many parts of the world, wastewater reuse is an important element in the water resource cycle. **JUAN ANTONIO LÓPEZ RAMÍREZ, JOSE MARÍA QUIROGA ALONSO, DIEGO SALES MÁRQUEZ** and **TAKASHI ASANO** review the promise and challenges that lie ahead for indirect potable reuse of wastewater.

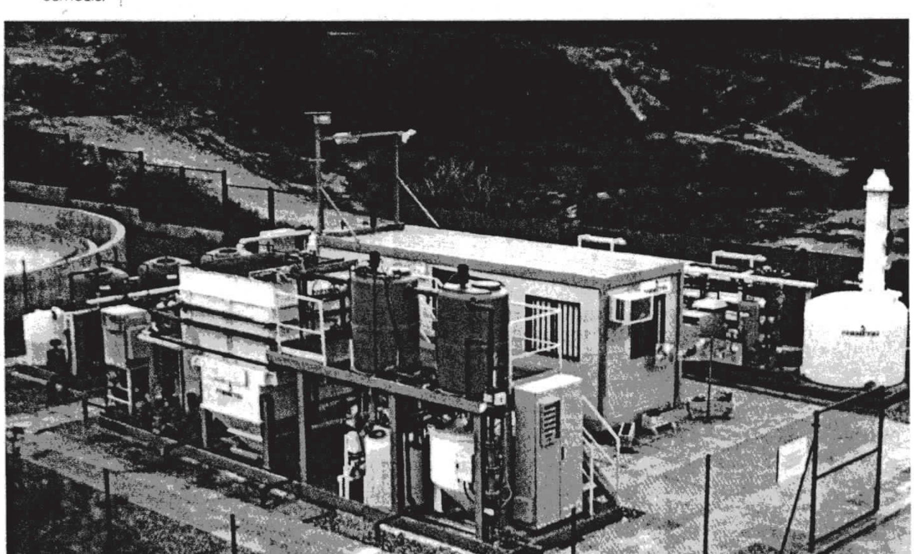
Wastewater reclamation and reuse is an intrinsic component of the water cycle, and has become an integral part of water resources management in the arid and semi-arid regions of the world. Several factors have contributed to this trend:

- a lack of adequate water in many regions of the world
- the increasing demand for water from modern societies
- the high costs and the environmental impact of locating new dams and reservoirs
- the need to meet water quality protection and pollution abatement requirements

As a consequence of these factors, wastewater reclamation and reuse is often the only dependable water resource to counteract hydraulic deficits in many regions of the world.

This paper discusses some of the issues related to technological challenges, public health protection and regulatory requirements that must be addressed if indirect potable reuse is to become fully implemented as an integral component in water resources management in the future.

View of the RO experimental plant for wastewater reclamation using reverse osmosis in Chiclana de la Frontera, Cadiz, Spain. This facility has been designed to carry out wastewater reclamation studies using reverse osmosis.



Indirect potable reuse

What exactly is meant by planned, indirect potable reuse? Planned, indirect potable reuse is the purposeful augmentation of surface or groundwater resources with highly treated reclaimed water, which will ultimately serve as a source of drinking water. Thus, planned indirect potable reuse requires treatment and operational reliability, and dilution with natural waters. Public policy and public acceptance are the most challenging aspects of indirect potable reuse.

In regions where droughts are frequent and have a significant impact in both socio-economic and environmental arenas, new strategies for water resources management must be developed to encompass indirect potable reuse. This approach should also alleviate effluent disposal problems, given the high treatment level required for reclaimed waters and the diversion of flows for beneficial uses. In addition, it represents a more practical and viable means of implementing water conservation policies, and is evidently a more rational solution than the construction of large water-related facilities which, whilst useful, are unable to solve the short-term problem of increasing water demand in many different regions.

Reverse osmosis and indirect potable reuse

Because indirect potable reuse will serve ultimately as a source of drinking water, reclaimed water quality must be of the highest level, at least meeting the applicable drinking water standards. A few technological choices exist. Among them membrane technologies - reverse osmosis in particular - are of utmost importance. Several advantages are listed below:

- high efficiency of the membranes in selective mineral rejection
- high permeability to water
- decrease in production costs
- fulfilment of the most stringent regulations for public health and environmental protection
- the separation process takes place at room temperature without phase change.
- there is no product accumulation inside the membranes, unlike processes such as ionic exchange.
- the separation does not require the addition of chemicals, as may be the case in water clarification by means of coagulation-flocculation processes.
- development of highly effective and more resistant polymers.

As a result, the use of membrane technologies is experiencing significant growth throughout the world. In 1987, the world membrane market totalled $363 million, compared to 1997, when the one billion dollar figure was reached (Wiessner and Chellam, 1999). Approximately 40% of this was subsequently employed in applications directly related to water and wastewater treatment.

Nevertheless, there are some issues that need to be addressed if reverse osmosis is to prove efficient and reliable in rendering reclaimed wastewater adequate for indirect potable reuse. The main problem is still inherent to the operational process itself: membrane fouling. This has a significant impact on unit efficiency, and leads to an increase in operating costs. Colloidal and biological fouling are, consequently, major obstacles to membrane system productivity, and despite much research in this area, the underlying physico-chemical processes have still not been adequately explained. Once these are fully understood, it will be a simple matter to determine the best conditions for correct membrane operation, to extend membrane life and to improve the cost-effectiveness of the process. Consequently, it is of paramount importance to achieve a better understanding of these mechanisms and to obtain reliable models that may help to eliminate, or at least to reduce pilot plant testing, commonly employed for large-scale water reclamation projects using membrane technology.

Fouling and biofouling

Fouling and biofouling are two processes that restrict membrane efficiency. Fouling is defined as undesirable deposit adhesion on the membrane surface. It happens when the rejected solids are not transported back from the membrane surface to the bulk solution. As a result, other processes occur: precipitation of the most sparingly soluble salts, organic molecule adsorption, colloidal material deposition and adhesion and growth of microorganisms. All of these have the effect of markedly diminishing membrane operational performance. Biofouling, on the other hand, is understood to mean the deposition and microbial adhesion by means of extracellular polymers on the membrane surface, which increases the fouling process. If the system is not properly controlled, both problems usually appear together.

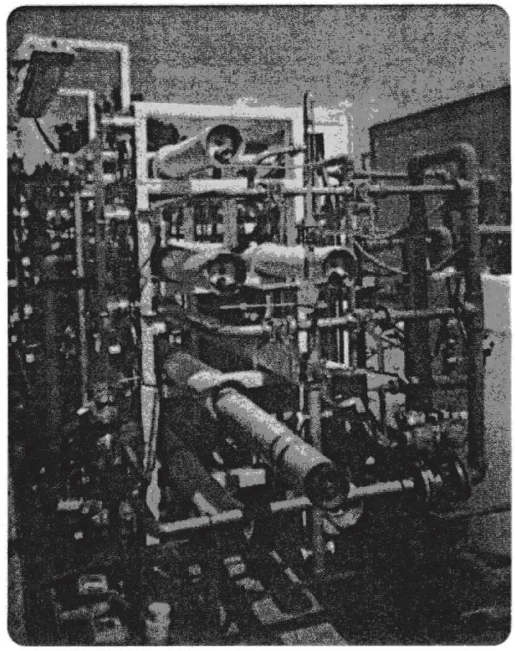
Effect of the operating conditions

The performance of the reverse osmosis unit is markedly affected by operating conditions, as well as by colloidal electrical charge, organic matter and membrane hydrophobicity/hydrophilicity characteristics, membrane surface roughness, and permeation rate. See boxed text for more detail on the effects of these parameters.

Presence of trace organic substances in the permeate

An issue that is causing some concern over the use of reverse osmosis membranes for indirect potable reuse is the presence, even at very low concentrations (usually parts per billion), of organic substances in the permeate. Limited studies have been carried out in this field, due to the inherent difficulty of identifying these substances, the very low concentrations in which they appear, and their heterogeneity.

The first investigation of the presence of dissolved organic matter in reclaimed effluent was carried out in the Whittier Narrows in Los Angeles in the 1970s. Later on, other projects followed, such as the San Diego Total Resource Recovery project, the Lake Arrowhead project, and the one that is currently operating in West Basin, all in California. In West Basin, some attempt has been made to analyse part of the organic fraction of the neutral compounds present in reclaimed waters. Although reverse osmosis is a technique characterised by the high rejection of dissolved substances, it has been shown that some of the basic



Membrane module replacement in the experimental plant. Membrane performance plays a basic role in reclamation processes.

The effect of operating conditions

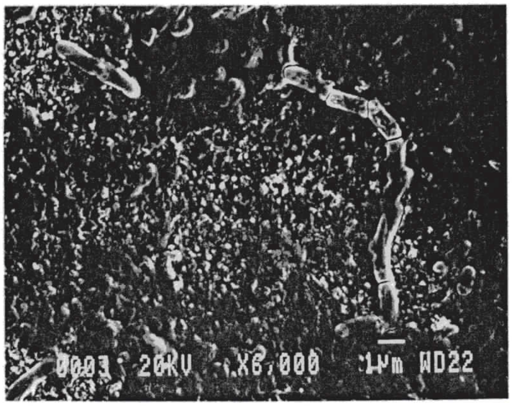
Although the reverse osmosis membrane fouling phenomenon has been the subject of numerous studies, some issues still remain that need to be clarified. Winfield (1979 A and B) carried out one of the first investigations in this area: the examination of cellulose acetate membrane fouling using a secondary effluent. One of the conclusions this research reached was that dissolved organic matter played a more important role in membrane fouling than suspended solids. Colloids present in wastewater normally possess a negative charge, although this tends to decrease when the ionic solution strength increases as a consequence of double layer compression. Polyamide and cellulose acetate membranes also show negative charges at normal pH operating values (pH equal to 6.5 and 5.5 respectively). A certain degree of electric repulsion is therefore expected between the double layers of colloidal particles and the membrane surface, which helps to avoid fouling. But this does not always occur. If the recovery rate applied to the membrane increases significantly, the magnitude of the repulsive force decreases, sometimes becoming negligible.

The permeate rate is of the utmost importance in membrane fouling because, as Song and Elimelech (1995) have demonstrated, the colloidal deposition rate on a permeable surface is controlled by an interaction between the repulsion force between the double electric layers (membrane-colloid) and a hydrodynamic force (permeation drag) resulting from the convective transport (the product of the recovery rate and the colloidal concentration) towards the membrane.

The permeation drag force is proportional to the permeate flow, and it acts perpendicularly to the membrane surface and in an opposing direction to the repulsion force of the double electric layers. Under typical operating conditions its value could be significant, overcoming the double layer repulsion, to result in particle deposition and consequently in membrane fouling. Zhu and Elimelech (1997) also demonstrated that membrane fouling increases with the recovery rate, because the convective transport towards the membrane also increases.

The surface structure of cellulose acetate and polyamide membranes also plays a significant role in their tendency to foul. The surface of the former is almost smooth, whilst the latter has a notably rough structure comprised of peaks and valleys, characteristic of the manufacturing process and which, together with a higher degree of permeability, leads to polyamide membranes having a more pronounced tendency to foul.

One way of reducing membrane fouling is to increase the repulsion force between the double electrical layers, adding for example, an anionic surfactant (Liton and Olson, 1994). The adsorption of the anionic surfactant molecules on the chemically heterogeneous surface leads to a uniform distribution charge across the surface layer and, as a consequence, an increase in the repulsion forces. Nevertheless, the fouling of the membranes does not disappear. Campbell et al (1999) observed this phenomenon when studying the reduction of Mycobacterium species' adhesion to cellulose acetate and polyamide membranes by using several types of surfactants.



SEM photomicrograph depicting biological and non-biological foulants on a thin-film composite reverse osmosis membrane.

neutral organic matter is able to cross the membranes; especially those elements with lower molecular weights and higher volatile characteristics (Levine, 2000).

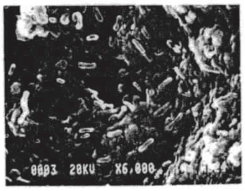
Presence of viruses in the permeate

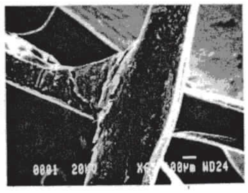
Reverse osmosis membranes have been shown to be able to remove several kinds of microorganism when treating secondary effluents: bacteria, viruses, parasites and fungi (Iranpour, 1998; Madireddi et al, 1997). Nevertheless, surprisingly, in some assays where the objective was to test membrane integrity using reverse osmosis as the only treatment, and with different concentrations of seeded virus in the influents, the results revealed the presence of viral units in the effluents (Gagliardo et al, 2000).

Quality of reclaimed wastewater in the experimental plant in Chiclana de la Frontera, Cadiz, Spain.

Parameter	Secondary effluent	Reclaimed water
pH	8.0	7.0
Conductivity (uS/cm)	1507	66
COD (mg O_2/l)	34	4
BOD (mg O_2/l)	16	-
SS (mg/l)	22	0
Turbidity (NTU)	1.7	0.35
Sulphates (mg/l)	127	5.1
Nitrates (mg NO_3/l)	13.5	1.8
Chlorides (mg/l)	226	9
Phosphates (mg PO_4^{3-}/l)	6	0.03
Nitrites (mg NO_2/l)	0.22	<0.02
Alkalinity (mg $Ca(HCO_3)_2$/l)	330	20
Calcium (mg/l)	109	4
Magnesium (mg/l)	39	1
Total coliforms (CFU/100ml)	$1x10^7$	Not detected
Faecal coliforms (CFU/100ml)	$1.5x10^6$	Not detected
Aerobes (22°C) (CFU/ml)	$3.0x10^5$	Not detected

SEM photomicrographs taken at increasing magnifications showing the attached fouling layer on a membrane feed-channel spacer. Note that most of the bacteria cells are partially buried into the layer.





This research examined the disinfection capacity of different types of microfiltration, ultrafiltration and reverse osmosis membranes. When seeded water containing MS2 viruses was treated with microfiltration membranes, a virus reduction of between 0.0 and 3.3 log was achieved, with ultrafiltration membranes achieving more than 6 logarithms of removal. Surprisingly, however, the three types of reverse osmosis membranes used (from three different manufacturers) only achieved between 2.1 and 5.5 logarithms of removal, depending on the type of membrane used. Because reverse osmosis uses non-porous homogeneous membranes, the existence of viral particles in the permeate is particularly surprising. Nevertheless, in neither case was the presence of faecal or total coliforms observed (Gagliardo, et al, 2000).

The explanation for this phenomenon is that the reduced size of the virus allows it to pass through the irregularities existing on the surface of some reverse osmosis membranes. Although these irregularities are too small to be perceptible from the point of view of the system controls (for example, the increase in permeate conductivity), they are, however, large enough to allow viruses to appear in the permeate. This demonstrates the need for the highest quality membrane manufacturing systems, capable of assuring the integrity of membrane elements, and the need for disinfection processes.

Indirect potable reuse and public health protection

In indirect potable reuse, apart from various multi-barrier treatment systems, there are processes that mix and dilute the permeate with natural waters, constituting an additional barrier to chemical and microbiological agents. These provide psychological reassurance for sensitive sectors of the population, and represent an additional treatment for the reclaimed waters before they enter into drinking water treatment systems, and constitute another multi-barrier system.

Finally, the sources of drinking waters are subjected to rigorous analyses and monitoring in order to guarantee their safe consumption. All these barriers have shown their effectiveness in several health effects studies for different demonstration projects. The final effluents were shown to be at least as safe for consumption as the distributed waters in the areas under analysis. Such was the case in the comprehensive projects carried out in Denver, Tampa and San Diego (Rogers and Lauers, 1992; McEwen, et al, 1997).

Indirect potable reuse and regulations

The development and wider implementation of indirect potable reuse projects will depend upon the adoption of appropriate regulatory requirements. Some regulations from different countries are presented below.

United States

There is no federal law regulating wastewater reclamation and reuse practices, so the responsibility for regulation rests with the different states. Some of them have their own regulations and others have adapted the recommendations in the 1992 EPA publication (USEPA, 1992). As a consequence, there is considerable variation in regulations among the states.

For example, California has been a pioneer in water reclamation and reuse and has its own proposed comprehensive regulations for indirect potable reuse via groundwater recharge. Due to the lack of specific health based requirements however, the most stringent requirements derived from four different regulations were combined: inland water quality requirements, anti-degradation policy, wastewater recycling criteria, and California drinking water criteria. By contrast, in the state of Florida, indirect potable reuse regulations are less restrictive than those currently in force in California. Nevertheless, they are to be revised and brought into line with Californian regulations.

European Union

In EU countries there is a certain degree of disquiet due to the lack of unified regulations for wastewater reuse. The only reference to water reuse in European legislation is in article 12 of European Directive 91/ 271/ EEC. Because there is no quality standard unifying the criteria, a new guideline is being developed. This will incorporate IPPC Guidelines (Integrated Pollution Prevention Control) and BAT principles (Best Available Techniques). Currently, the World Health Organization is planning to develop water reuse recommendations including groundwater recharge in cooperation with the EU.

Spain

There are no specific regulations for this type of activity. In fact, current legislation considers water reuse as a disposal to the common water domain, and not as a water reuse practice. In special cases, aquifer recharge is permitted if favourable reports are issued from the responsible hydrogeological, environmental and health authorities. Nevertheless, new regulations are due to appear. These will establish standards for each of the 14 different kinds of reuse, including groundwater recharge.

The challenges to be met

From a practical point of view, one of the more sensitive issues, due to its effects on public health, is the development of an appropriate chemical and microbiological risk assessment methodology that helps to establish the necessary criteria for reclaimed wastewater. It is therefore important to correctly interpret, on the basis of a sound scientific approach, what is held to be an 'acceptable risk' in water reclamation and reuse. In addition, real time monitoring of chemical and microbiological indicators and the evaluation of the appropriateness of potential risk to real public health protection should also be considered.

Several benefits will be obtained from this type of approach. The public - the ultimate user - will develop an understanding of need, and confidence and acceptance of water reuse. For their part, the legislative authorities will possess specific tools with which to establish an even balance between public health protection and the costs associated with the projects, and most importantly, solid scientific knowledge will form the basis of the rational approach.

Conclusions

Reverse osmosis has proved to be an essential element of treatment technologies in planned, indirect potable reuse in the United States and the Mediterranean countries, making 'new water' a reality.

Indirect potable reuse has been shown to be both practical and viable in terms of water resource management. A rational, technological approach and comprehensible health assessment should guarantee wider implementation in the future.

The level of technological expertise that currently exists will help to encourage the implementation of indirect potable reuse projects. Nevertheless, the presence and fate of trace substances in reclaimed waters requires further study.

Finally, the detailed assessment required for regulations governing public health protection will serve to provide a solid foundation for wastewater reuse. At the same time, it would help the public to gain a better and fairer understanding of planned indirect potable reuse activities such as groundwater recharge projects. ●

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