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ABEL WOLMAN'S "THE METABOLISM OF CITIES" REVISITED: A CASE FOR WATER RECYCLING AND REUSE

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ABSTRACT

Factors affecting the feasibility of water reclamation and reuse in an urban environment are discussed with special focus on reclaimed water quality and reuse applications. Water supplied to a city undergoes only small changes in quality and thus becomes a valuable resource ready for reuse and under local control. Successful development of water reuse must take into consideration technical, financial and social aspects. The quality of the reclaimed water must be matched to its intended use and alternative means of its distribution should be considered. Regional population growth patterns and their influence on economic feasibility of water reuse are examined. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Water reuse; water reclamation; water recycling; water quality; water supply economics.

URBAN METABOLISM OF WATER

"*The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play,*" so wrote Abel Wolman in his sentinel article in the Scientific American in September 1965. Wolman stated clearly that the metabolic cycle of the city must be sustainable. This concept, previously only implicitly recognized is especially applicable to the hydrologic cycle which includes water supply, wastewater discharge and also water reuse. Using a looming water shortage for New York City as a background, Wolman examined the availability of water resources in the US and compared them with anticipated consumption. By his estimates, the economically available surface water resources were approximately $7 \cdot 10^{11}$ gal/day ($1.8 \cdot 10^{8}$ m^3/d). In 1965, they could easily meet water demand (withdrawal from surface sources) of $3.2 \cdot 10^{11}$ gal/day ($8.5 \cdot 10^{7}$ m^3/d). However, Wolman predicted, the rising demand will exceed the available $7 \cdot 10^{11}$ gal/day sometime between 1980 and 2000. He further wrote,

> *"In the U.S. today attention is focused on shortages of water and the pollution of water and air. There is plenty of water, but supplying it requires foresight. While New Yorkers were watching empty reservoirs, Californians were building aqueducts. Thanks to foresight people in California were watering lawns and filling their swimming pools, while in New York lawns were dying and pools stood empty."*

Wolman's time was a heyday of water resources development, when plans for a 800 mile (1300 km) aqueduct from the Columbia River to Colorado were seriously considered. These types of projects are no longer feasible for political, environmental and economic reasons. Although, the water withdrawals in the U.S. peaked in 1980 at $3.7 \cdot 10^{11}$ gal/day and stabilized somewhat below this value, the available water resources also were likely to decline. Thus, water shortages are becoming a reality in some parts of the country and solutions other then constructing dams and reservoirs must be found to meet the water demands. Water reclamation and reuse can be a reliable part of such a solution.

Table 1. Inputs and outputs of a city with 1 million population

Input		**Output**	
Item	Mass per day (Mg/d)	Item	Mass per day (Mg/d)
Water	700,000	Wastewater	560,000
Food	1,800	Solid Waste	1,800
Fuel	8,200	Air Pollutants	520

1 Mg = 2,205 lb
updated from Wolman (1965)

Water in an urban environment has distinct characteristics which make it very different from other commodities supplied to a city. First, as noted by Wolman (1965), the amount of water consumed and wastewater generated by an urban population dwarfs all other supplies and products. Table 1 shows the daily inputs and outputs from a hypothetical U.S. city of one million people. Thus, the large quantity of water poses not only a challenge in terms of its availability but also limits the modes of transportations and delivery. It seems that for such huge quantities, delivery through a pipe network is the only feasible option. However, unlike other commodities (e.g., fuel), supplied water undergoes only small, though important, modifications before it is discharged as wastewater. The quantity of undesirable components in wastewater (pollutants) is only a few hundred parts per million, thus making wastewater "more then 99.9% pure". It is because the large majority of water supplied to the urban population is captured and returned as a wastewater stream that water recycling and reuse ***within*** an urban environment is a feasible opportunity. Reclaimed wastewater is, after all, a water resource developed right at the doorstep of the urban environment where water resources are needed the most and priced the highest. Furthermore, reclaimed wastewater provides a reliable source of water even in drought years because the generation of urban wastewater is affected little by drought. To make full use of this resource, several challenges must be met. They include institutional and social obstacles such as public acceptance or regulatory developments. Technical and economic challenges are also critical. For a success in water reuse, reclaimed water of required quality must be reliably delivered to the users at an economically attractive price. Thus, the technical aspects of assuring water quality and the economics of reclaimed water production, transportation and distribution must be carefully considered.

Figure 1 describes water metabolism in a city showing its sources, users and discharges linked with various pathways. It also shows the links with a larger hydrologic cycle which may be affected by implementation of water reuse projects. Because of large volume of water, its transportation and distribution pose a serious challenge for water recycle. As seen in Figure 1, water withdrawn from a source is transported to users and collected from them as wastewater. If then the treated wastewater is used as a source for water reclamation, the reclaimed water must be transported back to the users. Closing the loop at the smallest possible scale will minimize the costs of transportation and distribution. Distribution of reclaimed water requires a special distribution system. Developing such a system poses an economic challenge for a successful water reuse project. At the same time, the quality of the water changes during municipal use (Figure 2). Through water treatment, drinking water of high quality is produced. Municipal and industrial uses degrade water quality which must be upgraded before it can be released to the environment or reused. Thus, the challenge of water recycling and reuse lies also in matching the quality produced during treatment with the requirements of various users.

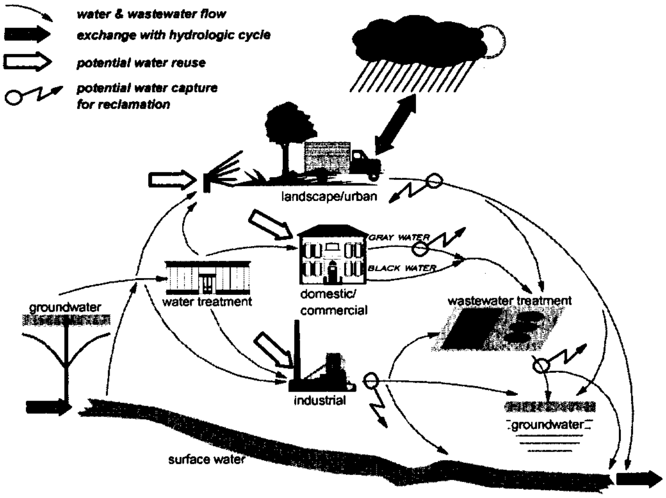


Figure 1. Water metabolism in a city.

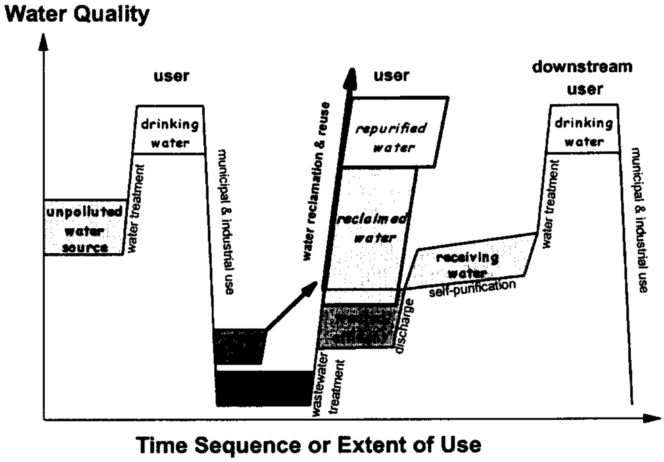


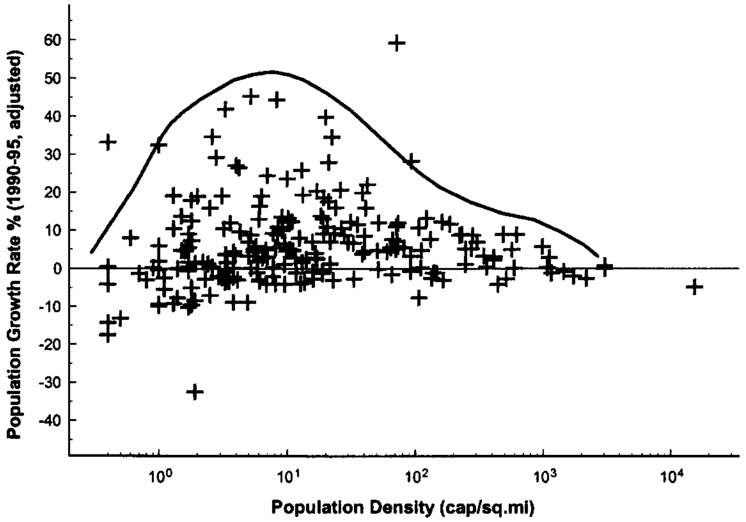
Figure 2. Water quality changes during municipal use and reuse.

TRANSPORTATION AND DISTRIBUTION CHALLENGES

Water supply and sanitation system are the primary infrastructure needs of any communities, playing a key role in providing amenities to the people, protecting the environment, and eliminating water-borne diseases. The demands for water in an urban environment and consequently the strain on the distribution systems will grow as the urban population increases. However, the growth of population may evolve following many demographic patterns. We believe that these patterns should be examined as they will have a significant impact on water reuse feasibility. It is generally assumed that the growth of urban population will result in ever larger metropolitan areas similar to those already existing in several countries. However, we can also expect different patterns to emerge in various regions. As projected by the World Resources Institute

(1996), a very large fraction of people live (and will continue to live) either in rural habitats or in smaller cities with the population less than one million.

The Western United States is one of the regions where water recycling and reuse are most advanced. It is instructive to examine population growth patterns in this region and consider their implications on water reuse. Figure 3 (data from U.S. Census Bureau) describes population growth rates of individual counties from 1990 to 1995. As shown in the graph, the counties with the highest growth rates, up to 60% above the average, were characterized by low-to-medium population density (around 10 people/square mile or 4 people/km^2). In contrast, the counties with high population densities (large cities and densely populated suburbs) and those with very low population densities grew at a much lower rate, sometimes even losing people. Such high growth rates at relatively modest population densities result in significant challenges for water supply, wastewater disposal and water reuse. At these densities, individual solution such as wells for water supply, septic tanks and leach fields for wastewater treatment and disposal may no longer be feasible. Yet, traditional communal solutions in the form of pipeline and sewer networks become very expensive due to long distances between individual users. In general, providing the infrastructure is costly. For example, the total, 20-year capital cost to upgrade U.S. municipal sewerage systems is estimated to be $110 billion (for the design year of 2010 in 1990 dollars) according to the 1990 Needs Survey Report to the Congress. The cost for construction of conventional secondary ($37.3 billion) and advanced ($11.7 billion) wastewater treatment systems totals $49 billion (National Research Council, 1993). These costs will be unevenly distributed (in the absence of subsidies) with less densely populated communities liable for much higher *per capita* expenses. We analyzed the costs of building new water distribution systems based on the data from several water utilities with service areas in a very wide range (from 0.28 to 500 square miles or 0.11 to 195 km^2). The unit costs for pipeline construction used in this analysis were reported by Hertzler and Davies (1997). The results of this analysis are shown in Figure 4. As expected the *per capita* costs of the distribution system increase dramatically for lower population densities but also for larger absolute population numbers. A direct comparisons of population densities in Figure 4 with those in Figure 3 is not possible since Figure 4 refers to population densities based on service areas and Figure 3 to county-wide densities. However, higher costs for larger, less densely populated communities combined with the demographic trend towards modest population densities will create significant financial strain on future water projects.



Population growth rate adjusted by subtracting average growth rate (data: U.S. Census Bureau)

Figure 3. Population growth rates by counties inn the western U.S.

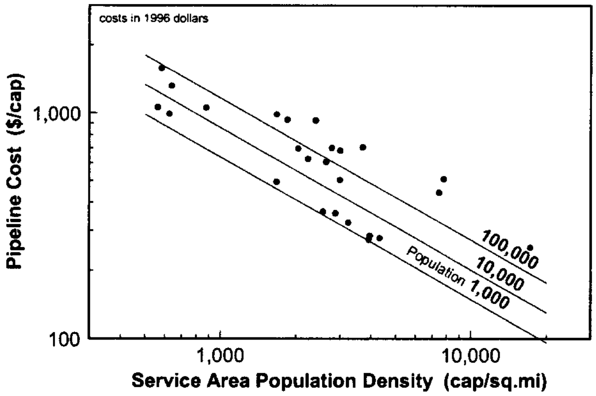


Figure 4. Per capita costs of pipeline construction.

ROLE OF WASTEWATER REUSE

Ultimately, after appropriate treatment, wastewater collected from cities must be returned to the land or water. The complex question of which contaminants in urban wastewater should be removed to protect the environment, to what extent, and where they should be placed must be answered in light of an analysis of local conditions, environmental risks, scientific knowledge, engineering judgment, and economic feasibility. Wastewater reclamation and reuse can serve several objectives. The most prominent can be summarized so as to provide: (1) a water supply to displace the need for other sources of water, (2) a cost-effective means of environmentally sound treatment and disposal of urban wastewater, and (3) an incidental secondary benefit to the disposal of wastewater; primarily crop production by irrigation.

Reflecting primary motivations and the experience in wastewater reclamation and reuse in the USA, the emphasis of this paper is on the first and second objectives listed above, that is, wastewater reuse planned as a water supply to offset alternative water development and as a cost-effective means of municipal wastewater pollution control. Today, technically proven wastewater treatment or water purification processes exist to provide water of almost any quality desired. However, the effective integration of water and reclaimed wastewater still requires close examination of public health issues, infrastructure and facilities planning, wastewater treatment plant siting, treatment process reliability, economic and financial analyses, and water utility management. Whether wastewater reuse can be implemented will depend upon careful economic considerations, potential uses for the reclaimed water, stringency of waste discharge requirements, public health considerations, and public policy emphasizing water conservation rather than constructing new water resources facilities.

As the link between wastewater, reclaimed water, and water reuse has become better understood, increasingly smaller recycle loops can be developed. Traditionally, the hydrologic cycle has been used to represent the continuous transport of water in the environment. The water cycle consists of fresh and saline surface water resources, subsurface groundwater, water associated with various land use functions, and atmospheric water vapor. Many sub-cycles to the large-scale hydrologic cycle exist, including the engineered transport of water such as aqueducts. Traditionally, a city was a once-through element of the hydrologic cycle with water withdrawn from a suitable source, used and discharged. However, in an urban environment (as seen in Figure 1), water serves many purposes with various quantity and quality requirements. After use, wastewater streams are generated, again in various quantities and of various qualities. Thus, the challenge of urban water reuse consists in closing the open links between wastewater sources and water demands while maintaining appropriate quality and flow.

Water reuse may involve a completely controlled "pipe-to-pipe" system with an intermittent storage step, or it may include blending of reclaimed water with natural water either directly in an engineered system or indirectly through surface water supplies or groundwater recharge. The major opportunities for water reuse are depicted in Figure 1 and include groundwater recharge, irrigation, industrial use, and surface water replenishment. Surface water replenishment and groundwater recharge also occur through natural drainage and through infiltration of irrigation and stormwater runoff. The potential use of reclaimed wastewater for potable water treatment is also shown. The rate and quantity of water transferred via each pathway depends on the watershed characteristics, climatic and geohydrological factors, the degree of water utilization for various purposes, and the degree of direct or indirect water reuse (Asano and Levine, 1995, Asano et al., 1996). The water used or reused for agricultural and landscape irrigation includes agricultural, residential, commercial, and municipal applications. Industrial reuse is a general category encompassing water use for a diversity of industries that include power plants, food processing, and other industries with high rates of water utilization. In some cases, closed-loop recycle systems have been developed that treat water from a single process stream and recycle the water back to the same process with some additional make-up water. In other cases, reclaimed municipal wastewater is used for industrial purposes such as in cooling towers. Closed-loop systems are also under evaluation for reclamation and reuse of water during long-duration space missions by the National Aeronautics and Space Administration (NASA).

WASTEWATER REUSE APPLICATIONS

To provide a framework for evaluating wastewater reuse, it is important to correlate major water use patterns with potential water reuse applications. On the basis of water quantity, irrigation use, consisting of both agriculture and landscape applications, is projected to account for 54% of total freshwater withdrawals in the U.S. by the year 2000. The second major user of reclaimed water is industry, primarily for cooling and process needs. However, industrial uses vary greatly and additional wastewater treatment beyond secondary treatment is usually required. Thus, the effective integration of wastewater reuse into water resource management is based on the quantity of water required for a specific application and the associated water quality requirements.

Significant regional and seasonal variations in water use patterns also exist. For example, in urban areas, industrial, commercial, and non-potable urban water requirements account for the major water demand. For agricultural applications in arid and semi-arid regions, irrigation is the dominant component of water demand. Water requirements for irrigation applications tend to vary seasonally whereas industrial water needs are more consistent. The feasibility of water reuse for a given watershed is limited by the degree to which reclaimed wastewater could augment existing water supplies through substitution of water in commercial, industrial, and agricultural applications.

An overview of the major categories of wastewater reuse is given in Table 2. These categories are arranged according to current and projected volumes of reclaimed wastewater. Treatment goals are based on effluent quality and the application of specific technologies. For most applications, effective secondary treatment is a prerequisite to production of high-quality reclaimed water. The primary incentives for implementation of water reuse are related to the need for augmentation of water supplies or control of water pollution in receiving waters. By reducing the quantity of treated wastewater discharged to surface waters, effluent requirements tend to be more favorable, particularly with respect to nutrient removal. Thus, water reuse is becoming an economic alternative for treatment facilities discharging into ecologically sensitive streams and estuaries.

The increased implementation of wastewater reuse projects in various regions has facilitated the evolution of new water reuse alternatives. As treatment systems and applications are tested and design parameters are developed, technical barriers to wastewater reuse are reduced. Geographic, climatic, and economic factors dictate the degree and form of wastewater reclamation and reuse in different regions. In agricultural regions, irrigation is, naturally, a dominant reuse application. In arid regions, such as California and Arizona, groundwater recharge is a major reuse objective either to replenish existing groundwater resources or to mitigate salt water intrusion in coastal areas. Industrial reuse of water varies with industries and locations. In contrast to the arid or semi-arid regions of the world where irrigation comprises a major beneficial use of reclaimed wastewater, wastewater reuse in Japan is dominated by non-potable urban uses such as toilet flushing, industrial use, and stream restoration and flow augmentation.

Table 2. Categories of municipal wastewater reuse[a]

Category of wastewater reuse	**Treatment goals**	**Example applications**
Urban use		
Unrestricted	Secondary, filtration, disinfection BOD_5: <10 mg/L; Turbidity: <2NTU Fecal coliform: ND(b)/100 mL Cl_2 residual: 1 mg/L; pH 6 to 9	Landscape irrigation: Parks, playgrounds, school yards; Fire protection; Construction; Ornamental fountains; Impoundments; In-building uses: Tilet flushing, Air conditioning
Restricted access irrigation	Secondary and disinfection BOD_5:: < 30 mg/L; TSS: < 30 mg/L; Fecal coliform: < 200/100 mL; Cl_2 residual: 1 mg/L; pH 6 to 9	Irrigation of areas where public access is infrequent and controlled; Golf courses; Cemeteries; Residential; Greenbelts
Agricultural irrigation		
Food crops	Secondary, filtration, disinfection: BOD_5:: < 10 mg/L; Turbidity:< 2NTU; Fecal coliform: ND/100 mL;Cl_2 residual: 1 mg/L; pH 6 to 9	Crops grown for human consumption and consumed uncooked
Non-food crops and food crops consumed after processing	Secondary, disinfection: BOD_5: < 30 mg/L; TSS: < 30 mg/L; Fecal coliform: < 200/100 mL;Cl_2 residual: 1 mg/L; pH 6 to 9	Fodder, fiber, seed crops, pastures, commercial nurseries, sod farms commercial aquaculture
Recreational use		
Unrestricted	Secondary, filtration, disinfection: BOD_5: < 10 mg/L; Turbidity:< 2NTU; Fecal coliform: ND/100 mL;Cl_2 residual: 1 mg/L; pH 6 to 9	No limitations on body-contact: lakes and ponds used for swimming, snowmaking
Restricted	Secondary, disinfection: BOD_5: < 30 mg/L; TSS: < 30 mg/L; Fecal coliform: < 200/100 mL Cl_2 residual: 1 mg/L; pH 6 to 9	Fishing, boating, and other non-contact recreational activities
Other uses		
Environmental enhancement	Site specific treatment levels comparable to unrestricted urban uses; Dissolved oxygen; pH Coliform organisms; Nutrients	Use of reclaimed wastewater to create artificial wetlands, enhance natural wetlands and sustain stream flows
Groundwater recharge	Site specific	Groundwater replenishment. Salt water intrusion control. Subsidence control
Industrial reuse	Secondary and disinfection: BOD_5: < 30 mg/L; TSS: < 30 mg/L; Fecal coliform: < 200/100 mL	Cooling-system make-up water, process waters, boiler feed water, construction activities and washdown waters
Potable reuse	Safe Drinking Water Requirements	Blending with municipal water supply. Pipe to pipe supply

[a] Adapted from U.S. Environmental Protection Agency, 1992

[b] ND - Not detected.

CONCLUSIONS

Successful implementation of a water reuse project must rely on consideration of multiple factors including public health, community acceptance, required water quality and quantity, reliability of supply and variability of demand and economic aspects. Reclaimed water should be treated as a commodity with quality and methods of treatment matching the required use. In an urban environment, several levels of water quality correspond to its different uses including drinking, washing and personal hygiene, landscape irrigation, urban cleaning and industrial. Transportation and distribution of reclaimed water has a significant influence on the economic viability, especially in communities with low-to-moderate population density. Complex factors of economics and public health risks will play a major role in the decision-making process.

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