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Managing Municipal Water Supply and Use in Water-Starved Regions: Looking Ahead

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In this editorial, the author shares 30 years of experience with water management in a semiarid region (specifically California). The focus of this writing is on municipal water supply; that is, water supplied by public water systems that support residential, commercial, industrial, and governmental users in populated areas. The editorial examines ways to improve the reliability of municipal water supply in water-scarce, fast-growing regions such as southern California. The challenges and the possibilities that arise concerning municipal water supply in southern California are not unique. They are similar in many parts of the world, whether it is northern China, the Middle East, or other drought-stricken regions. The author argues for unconventional approaches to help meet municipal water use in drought-vulnerable regions. A greater reliance on sustainable water sources, local in origin, is envisioned to diminish the dependence on imports and on the vagaries of the climate. Specifically, this editorial makes the case for reliance on "toilet-to-tap" sewage recycling and seawater desalination, both of which are herein shown to be unconventional sources of municipal water in California at this time. These two sources of water have excellent potential for stabilizing municipal water supply in drought-vulnerable regions.

Droughts Are Inevitable, But the Unessential Use of Municipal Water Is Not

Reports about California's current water plights are common nowadays. Below-average rainfall statewide in the last three years has exacerbated the scarcity of water available to supply a burgeoning population of close to 39 million people. Fig. 1 shows the annual rainfall in the city of Santa Barbara from 1868 through 2013. Long-term patterns of precipitation are critical to water-supply management. After all, rivers, lakes, and aquifers are replenished by natural precipitation, and they are the main sources of conventional municipal water supply

The rainfall graph of Fig. 1 provides an excellent insight into how a highly variable source of natural fresh water looks. Although the data graphed in Fig. 1 are from a specific locality, they represent the natural variability of precipitation and drought incidence in most of California and, in fact, of larger regions that encompass multiple states, such as the Colorado River basin. This is because protracted droughts tend to be of regional character in the semiarid western United States (Loáiciga et al. 1993). The author defines a drought as a period of three or more consecutive years with below-average precipitation. Fig. 1 demonstrates that there have been 11 droughts in the Santa Barbara region (and in most of California) since 1868. The longest such period was from 1894 through 1902, lasting 9 years. The average annual rainfall during that drought was 32.1 cm, compared with the 46.1 cm long-term average annual rainfall. The driest drought lasted three years (1959–1961) and had an average annual rainfall of 25.37 cm. Fig. 1 depicts all the droughts since 1868 and their durations, showing the average annual rainfall during each dry period. The average time between the ending of a drought and the beginning of the next one is 10 years, according to Fig. 1. The current drought is nearing its third year.

If drought is a common condition in California, as Fig. 1 indicates, why does its frequent occurrence cause so much disruption of municipal water supplies? The answer to this question is multifaceted. This author posits that a key reason is cultural—that is, motivated by patterns of water use that are unsustainable in drought-ridden climates. Specifically, water use devoted to irrigating lawns, ornamental plants, parks, and golf courses; hosing down driveways; and frequent washing of motor vehicles may constitute

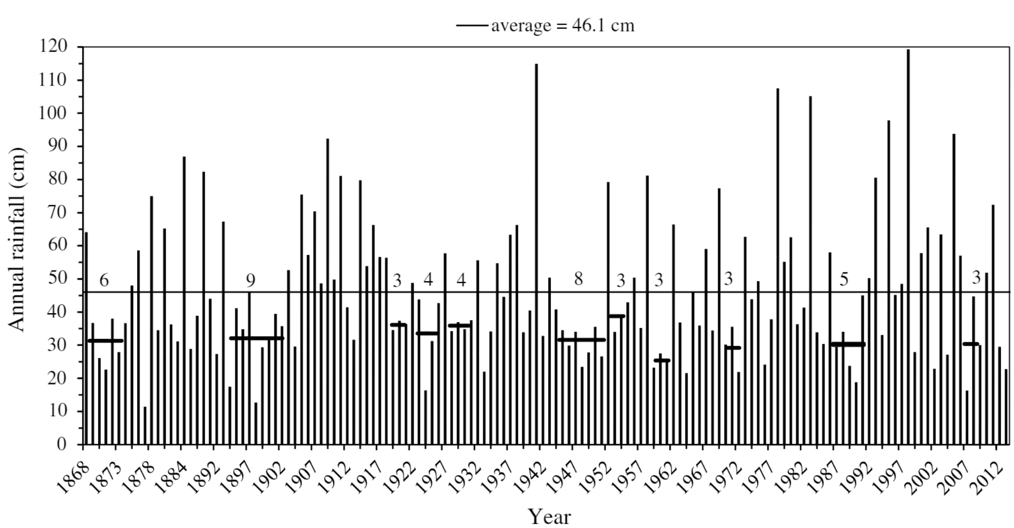

Fig. 1. Annual rainfall, average annual rainfall, and drought occurrence in the city of Santa Barbara, California, 1868–2013

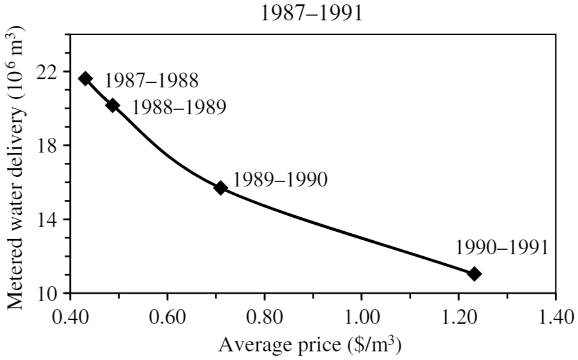

Fig. 2. Metered water delivery and average price of water in the city of Santa Barbara during the 1987–1991 drought

40–70% of potable water consumption in some municipalities, the percentage increasing with increasing degree of affluence of a community. The cited water uses are unessential (that is, not destined to satisfy basic use of potable water for drinking, cooking, bathing, and house cleaning), as illustrated by Fig. 2. This graph shows the reduction in metered water deliveries to users in the city of Santa Barbara during the 1987–1991 California drought. It establishes that water use in Santa Barbara declined from 21.6 million m^3 in 1987–1988 to 11.0 million m^3 in 1990–1991, or close to a 50% reduction in water use. Interestingly, the average price of water rose during the drought from $\$0.43/m^3$ to $\$1.23/m^3$, an increase of 186%. The water use and price data shown in Fig. 2 were normalized to a base population and dollar value corresponding to the year 1995. They were gathered by this author while serving as a member of the Board of Water Commissioners of the City of Santa Barbara in the 1990s. Other water-use and pricing data presented in this editorial were acquired by the author from water managers working with municipal water purveyors throughout California, as well as from water managers active in other countries. They represent average values. Moreover, because public municipal water purveyors in California practice average-cost pricing (that is, they sell water at prices that recover all the costs incurred in producing, delivering, and maintaining an adequate water supply), the average unit price of water equal to, say, $\$1.23/m^3$ (shown in Fig. 2 for 1990–1991), is equal to the unit cost of water supply. Average-cost pricing, therefore, is implied in the remainder of this editorial.

It would be erroneous to conclude from the data in Fig. 2 that the reduction of water use was caused exclusively by its increasing average price. Although the increase in the price of water was undeniably a factor that reduced water use, there were other simultaneous causes: a public education and awareness campaign that induced public cooperation to cut unessential use, and installation of water-efficient devices contributed to reducing water use. The 1987–1991 drought was followed by several wet years, culminating in 1998 with the wettest year on record (119.3 cm, nearly three times the long-term average). By the end of the 1990s, some of the reduction in unessential water use had waned, even though post-drought water rates remained substantially higher than predrought ones. This confirmed once more the price inelasticity of municipal water demand. The rise of water use in Santa Barbara following the 1987–1991 drought also shows how deeply ingrained the unessential use of municipal water use is in the example region, which is replicated in many other water-scarce regions.

The previous discussion has highlighted several facts that influence the supply and use of municipal water in California and other semiarid regions with similar degrees of economic development. One is the inevitability of droughts; others involve cultural and societal practices: the purposes to which potable water is dedicated, how water is priced, water efficiency and other conservation practices, and proper maintenance of water conveyance infrastructure. Other conventional practices to mitigate droughts, such as interbasin water transfers, may not materialize in times of need. For example, droughts that affect water-scarce southern California can hardly be mitigated by regional transfers of water from other basins (say, from northern California or the Colorado River). This is because droughts tend to be regional in scope, and the reduction of fresh water may affect all its regional sources. The author and collaborators (Loáiciga et al. 1993) used tree-ring measurements from long-lived conifers to reconstruct drought occurrence in the Sacramento River and Colorado River basins for nearly 500 years in the preinstrumental period. They showed the occurrence of simultaneous droughts affecting the two basins that lasted in excess of 10 years. The unreliability of water-transfer schemes to southern California is illustrated currently by the fact that water transfers from northern California to southern California via the State Water Project are about 5% of normal contractual deliveries (A. Hutchinson, Recharge Planning Manager, Orange County Water District).

The next part of the editorial explores unconventional approaches to improving the resilience of municipal water supply and its sustainability in California and many other parts of the world with similar geographic settings and economic capacities.

Unconventional, Sustainable, Municipal Water Sources

This section proposes two unconventional means to help meet dwindling municipal water supplies in water-scarce regions. The first, sewage recycling, applies to any municipality with adequate technical and financial wherewithal. The second, seawater desalination, requires access to the coastal zone as well. Sewage recycling as proposed herein (that is, of the toilet-to-tap vintage) is currently unacceptable by regulatory fiat in California. It is unconventional in this sense: it consists of recycling municipal sewage to turn it into a permanent and reliable source of municipal drinking water. Currently, the largest operation of municipal sewage recycling in California takes place at the Orange County Water District (OCWD). The OCWD acquires municipal sewage from neighboring municipal water purveyors and processes it with advanced tertiary treatment. Thereafter, the treated sewage is recharged to aquifers underlying the Santa Ana River basin. The recharged treated sewage blends with groundwater and travels to downgradient extraction wells owned by municipal water purveyors, which then extract groundwater bought from the OCWD, treat it so that it meets potable standards, and sell it to their customers. Current California regulations governing the type of sewage recycling scheme practiced by the OCWD (and others) require that the residence time of treated sewage injected into an aquifer be not less than 2 months.

Seawater desalination is already used in many parts of the world, Saudi Arabia being almost entirely dependent on it. Interestingly, to the author's knowledge, California has only two municipal seawater desalination plants at this time, neither of which is currently operational. One is owned by the city of Santa Barbara, which is being rehabilitated to cope with the current drought. It will have an installed capacity of nearly 9 million m^3 annually. The other is being built by the San Diego County Water Authority. Its installed capacity will be close to 310 million cubic meters annually. Evidently, seawater desalination for municipal water supply is not a household name in California at this time, and it is in this sense that the author categorizes it as unconventional. This author believes seawater desalination could play a much larger role than it currently does in semiarid coastal regions such as California. Insofar as availability is concerned, seawater is the only truly inexhaustible water source.

Seasoned managers of municipal water systems in California frequently ask why current drinking-water regulations do not allow treating municipal sewage to tertiary level and feeding the treated sewage to water-treatment plants directly to be rendered potable and reused. Sewage recycling in this manner is not currently allowed by the state of California, or, for that matter, by other governments that regulate public water systems in the United States. This is the case in spite of the fact that available technologies for sewage treatment and its retreatment to make it potable are proven, safe, and widely available. Fig. 3 shows the approach proposed to improve the reliability of municipal water-supply systems.

One can start reading Fig. 3 in a clockwise sense with the water sources (rivers, lakes, aquifers, seas) where raw water is sent to the water treatment plant (WTP). A daily volume Q is produced at the WTP, from which it is conveyed to municipal water users. A total of 10% of the initial volume disappears from the municipal system as conveyance losses. This fraction of water loss is considered average in well-managed municipal conveyance systems. [For comparison, the most recent annual report by the Comisión Nacional del Agua (CONAGUA) of Mexico states that conveyance losses amount to 40% of the total municipal water produced in that country.] Of the potable water that reaches the users, 20% leaves the municipal system as consumptive use (for example, water used for landscape irrigation, in construction, etc.). Some of this water may return to the local hydrologic cycle.

After municipal use, 70% of the initially produced potable water has been converted by the users to sewage, which is sent to a sewage treatment plant (STP). It has been assumed for the purposes of Fig. 3 that sewers may lose sewage but may gain groundwater

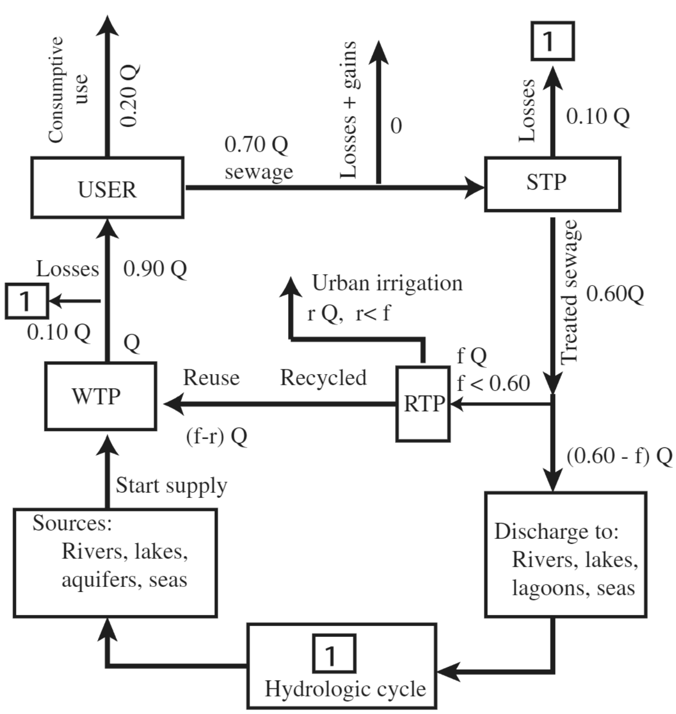

Fig. 3. Schematic of municipal water recycling

so that a volume of sewage equal to $0.7Q$ reaches the sewage treatment plant. Here, 10% of the initially produced volume of daily water is lost (primarily as evaporation) as it undergoes treatment at the STP. This leaves an effluent of treated sewage equal to $0.6Q$.

A fraction $f < 0.6$ of the treated sewage is diverted to a recycling treatment plant (RTP), where it undergoes tertiary treatment. A fraction r of the recycled water might be used for municipal irrigation. Many municipalities in California recycle some of their treated sewage for this purpose. Commonly, r does not exceed 10%. The remainder of this editorial assumes, for the sake of argument, that $r = 0.10$. At this point, a fraction $(f - r < 0.50)$ of the initially produced daily volume Q is available for reuse after it is treated at the water treatment plant. The volume $[(f - r)Q]$ enters an endless cycle of use and reuse.

Recycling Efficiency and Relative Costs of Sewage Recycling and Seawater Desalination

What volume of water is gained by recycling municipal sewage as depicted in Fig. 3? To answer this question, consider that, on average, reclaiming of treated sewage to tertiary-level treatment for reuse is about 1.5 times more expensive than producing the same amount of potable water from raw water at a WTP (the standard process). Furthermore, any volume of tertiary-treated sewage sent for reuse to the WTP incurs the standard cost of treatment there. Evidently, the recycling of water is costly. Yet, when conventional water sources dwindle to near-exhaustion, recycling is cheaper than other measures that would have to be taken to find water by other means—including desalination of seawater—as discussed next. It is useful at this juncture to introduce the recycling efficiency (E), which is defined as the ratio of the additional volume of potable water (ΔQ) produced by recycling (after a very large number of cycles) to the initial volume of water produced by the standard process (Q in Fig. 3). It is intuitive that the recycling efficiency depends on the recycling fraction $f(< 0.6)$, as confirmed next.

Any gains on water supply from recycling municipal sewage must come at a price, obviously, which, under the practice of average-cost pricing, is recovered through water sales. To measure the increased cost implied by sewage recycling and, at the same time, compare this cost with that incurred by augmenting the water supply by seawater desalination, one can resort to relative costs. Let ΔQ denote the additional volume of water produced by recycling municipal sewage (after a very large number of cycles). The relative cost of recycling (RCR) is the ratio of the cost of producing an additional volume of water by recycling (ΔQ) to the cost of producing the same volume of additional water by the standard process (that is, without recycling). The relative cost of desalination (RCD) is defined as the ratio of the cost of producing the additional volume of water (ΔQ) by desalination to the cost of producing the same volume of additional water by the standard process. The derivation needed to arrive at the RCR is presented in the Appendix. The RCD equals the unit cost of water desalination divided by the unit cost of standard water production at a WTP (or $3.75/1.5 = 2.5$), for any value of the recycling fraction f.

Fig. 4 graphs E, RCR, and RDC as functions of the recycling fraction. The calculations leading to these values relied on a (standard) cost of potable water production at a WTP equal to $\$1.50/\mathrm{m}^3$. The cost of reclaiming sewage at the RTP is 1.5 times the cost of water production at the WTP, or $\$2.25/\mathrm{m}^3$. The cost of seawater desalination was estimated to be 2.5 times the cost of water production at the WTP, or $\$3.75/\mathrm{m}^3$.

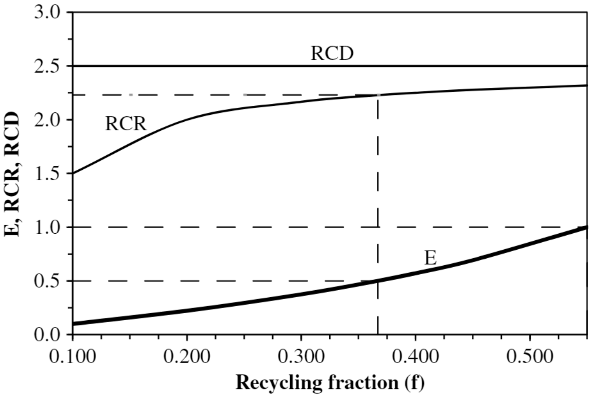

Fig. 4. Recycling efficiency (E), relative cost of recycling (RCR), and relative cost of desalination (RCD), graphed as functions of the recycling fraction

Fig. 4 demonstrates that $E = 0.50$ when $f = 0.367$. In other words, recycling 36.7% of the municipal sewage increases the water supply by 50% ($\Delta Q = 0.5Q$). Furthermore, recycling 55% of municipal sewage ($f = 0.55$) increases the water supply by 100% ($\Delta Q = Q$). Under this second scenario of sewage recycling, a municipal water system would double its water supply. Also, Fig. 4 demonstrates that the cost of recycling at the 36.7% level is 2.23 times the cost of producing the same amount of additional water ($\Delta Q = 0.5Q$) by the standard process. In other words, RCR = 2.23 when $f = 0.367$ and $\Delta Q = 0.5Q$. Moreover, RCR reaches 2.32 when $f = 0.55$. That is, doubling the production by recycling more than doubles the cost of additional production relative to what the cost would be if pursued by the standard process. One must remember, however, that during droughts, conventional sources of water supply may not be available, in which case the cost of finding alternative water supplies could exceed that of recycling. This is occurring nowadays in California, where many water-starved municipalities are buying water from willing sellers (if they can be found) at several times the normal cost of production. Seawater desalination is such an alternative water source in coastal regions with adequate degrees of development and energy sources. Fig. 4 shows that the relative cost of desalination RDC (= 2.5) exceeds the relative cost of recycling for all levels of sewage recycling. The larger cost must be recovered by higher water rates, as required by average-cost pricing.

Closure

The recurrence of droughts in densely populated, water-starved regions poses serious challenges from the perspective of municipal water supplies. Droughts are inevitable, recurrent, and frequently severe. At the same time, population growth continues unabated. We must think outside the box to be able to match water use with water supplies in the future. On the demand side, cultural patterns of unessential water use must change and adapt to changing conditions. Municipal water use must become harmonious with the natural, semiarid nature of the climate of heavily populated regions like California. On the supply side, this editorial advocated and provided reasons for a transition to recycling municipal sewage for human use, as well as greater reliance on seawater desalination as circumstances demand.

Appendix. Recycling Efficiency, Relative Cost of Recycling, and Relative Cost of Desalination

This appendix presents the formulas used to calculate the recycling efficiency, the relative cost of recycling, and the relative cost of desalination graphed in Fig. 4. Let Q be the volume of potable water produced daily by standard (nonrecycling) methods, this is the daily base production; f = recycling fraction; r = fraction of reclaimed water used for municipal irrigation ($r \leq f$, $r = 0.10$); $p = f - r$, $r \leq f < 0.60$: ΔQ = volume of daily water produced by recycling; C_{st} = unit cost of treating water in the standard water treatment plant (= \$1.50/m^3); C_{rec} = unit cost of recycling water at recycling plant (= \$2.25/m^3); unit cost of desalination $C_{\text{desalt}} = \$3.75/\text{m}^3$. The daily water volume produced by recycling is (based on Fig. 3, after many cycles through the water system) as follows:

$$Q = pQ + p^2Q + p^3Q + \cdots + rQ + rpQ + rp^2Q + rp^3Q + \cdots = Q\frac{f}{1-(f-r)} \quad (1)$$

The recycling efficiency is the ratio of the volume of potable produced by recycling, ΔQ, to the initial volume of water produced by the standard process, Q:

$$E = \frac{Q\frac{f}{1-(f-r)}}{Q} = \frac{f}{1-(f-r)} \quad (2)$$

The cost of producing a volume of water ΔQ in a standard water treatment plant is

$$C = \frac{f}{f-(f-r)} Q \cdot C_{st} \quad (3)$$

The actual cost of producing a volume of water ΔQ of recycled water is

$$CR = fQC_{\text{rec}} + fpQC_{\text{rec}} + fp^2QC_{\text{rec}} + fp^3QC_{\text{rec}} \cdots + pQC_{st} + p^2QC_{st} + p^3QC_{st} + \cdots \quad (4)$$

Therefore

$$CR = f \cdot C_{\text{rec}} \cdot Q(1 + p + p^2 + p^3 + \cdots) + C_{st} \cdot Q \cdot (p + p^2 + p^3 + \cdots) = \frac{f \cdot c_{\text{req}} \cdot Q}{1-p} + \frac{p \cdot c_{st} \cdot Q}{1-p} \quad (5)$$

Based on Eqs. (3) and (5), the relative cost of recycling is

$$RCR = \frac{CR}{C} = Q \cdot \left(\frac{C_{\text{rec}}}{C_{st}} + \frac{f-r}{f}\right) \quad (6)$$

The cost of producing a volume of water ΔQ by desalination is

$$CD = \frac{f}{1-(f-r)} Q \cdot C_{\text{des}} \quad (7)$$

Finally, the relative cost of desalination is

$$RCD = \frac{CD}{C} = \frac{C_{\text{des}}}{C_{st}} \quad (8)$$

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