A Feasibility Analysis Methodology for Decentralized Wastewater Systems – Energy-Efficiency and Cost

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ABSTRACT: Centralized wastewater treatment, widely practiced in developed areas, involves transporting wastewater from large urban areas to a large capacity plant using a single network of sewers, whereas decentralization is the concept of wastewater collection, treatment and reuse at or near its point of generation. Smaller decentralized plants can achieve extensive reclamation and wastewater management with energy-efficient reclaimed water pumping, modularized expansion and lower capital investment. We devised a methodology to preliminarily assess these alternatives using local constraints and conducted a feasibility analysis for each option. It addressed various scenarios using the pump-back energy consumption, sewer and treatment plant construction and capacity expansion cost. We demonstrated this methodology by applying it to the Hollywood vicinity (California). In this study, the decentralized configuration was more economical and energy-efficient than the centralized system. The pump-back energy consumption was about 50% of the aeration energy consumption for the centralized option. *Water Environ. Res.*, **88,** 201 (2016).

KEYWORDS: decentralization, reclamation, reuse, wastewater, energy, pumping, collection, satellite treatment, feasibility, cost.

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Introduction

Centralized wastewater treatment consists of a large treatment plant connected to an elaborate wastewater collection system. Wastewater collection, treatment and reuse at or near its point of generation is called decentralized wastewater treatment (Tchobanoglous and Crites, 1998). Decentralized configurations generally use shorter collection networks of relatively smaller size. Such systems are sometimes used to relieve sewers leading to larger central treatment plants. For example, in the City of Los Angeles, the D.C. Tillman and Glendale wastewater treatment plants, located upstream of the Hyperion treatment plant avoided overloading trunk sewers and provided reclaimed water near potential users (City of Los Angeles, 2013).

With increasing need for reclamation, it is necessary to have a simple system not only to reclaim the wastewater but also to convey it to the respective area for reuse. Since reclaimed pipelines generally flow in the opposite direction of sewers, they usually need to gain some elevation in their course. Reducing the length of the pipeline is the principle solution to minimize pumping energy consumption. Centralized plants generally cannot be located close to all the potential reclaimed water users. It is especially difficult to establish such a large treatment facility in any residential neighborhood. Thus, for centralized plants, returning recycled water can require tremendous energy due to pumping. Adapting the design of large centralized treatment plants to local reclamation needs to reduce pumping cost can be difficult. Decentralized treatment systems have a smaller scale, thus simplifying modification required to meet local needs. With smaller collection-reclamation loops, decentralized wastewater treatment systems can reduce pump-back energy consumption.

Decentralization is also an alternative to the expensive construction of larger trunk sewers to convey the added flow of newly developed or growing areas. With smaller sewers and treatment plants, these systems can also provide wastewater treatment and collection access to remote communities. Many developing regions do not have access to wastewater collection and treatment rendering them susceptible to disease outbreaks. Satellite or decentralized treatment systems can be an excellent solution to reduce public health risk.

Both treatment concepts have pros and cons; for instance, large treatment plants have more economy of scale. Satellite treatment plants are usually assumed to be limited to primitive treatment systems such as septic tanks, in turn difficult to optimize for energy and cost. (Massoud et al., 2008) But to take advantage of improved public health, energy-efficient reclamation and conveyance, and modular expansion, it is necessary to devise an optimization algorithm to obtain a customizable, cost-effective, energy-efficient wastewater collection and treatment configuration for such regions.

This study involves optimizing sewer networks and decentralized treatment plant locations in an urban area to minimize pump-back energy consumption for recycled water. We computed pump-back energy consumption as a fraction of treatment and aeration energy for a hypothetical but realistic example (Hollywood). We optimized the decentralized wastewater collection and treatment configuration for Hollywood for minimum energy consumption and cost.

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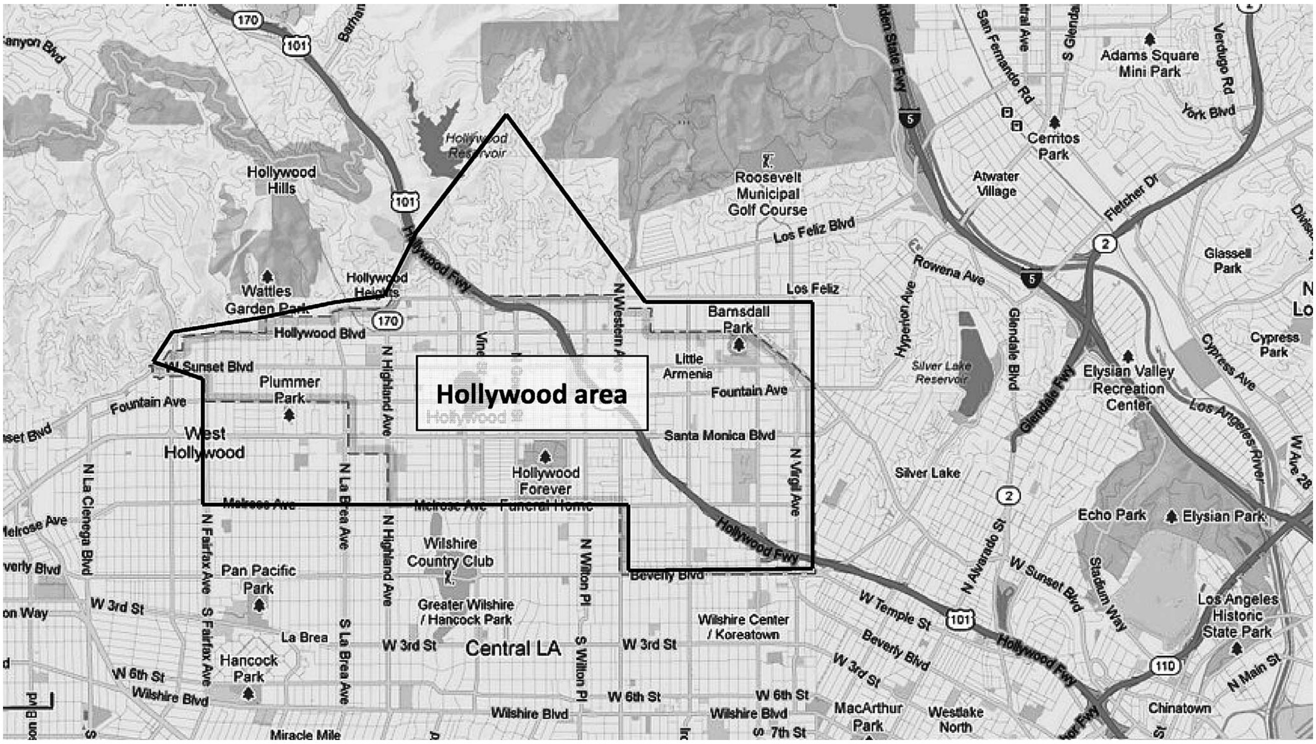

Figure 1—Geographical location and extent of the Hollywood area of the City of Los Angeles

Methods

Local and Treatment Process Characteristics. We applied this analysis to the locality of Hollywood in the City of Los Angeles, California. Figure 1 shows the geographical location and extent of this area. To assess the preliminary feasibility of a decentralized system, we quantified its benefits and compared them with those of a centralized system. The trunks of the sewer and reclaimed water lines that we designed for this study bifurcated based on topography. Figure 2 shows the reclamation pipeline direction and the bifurcation. It also shows the pipe lengths and the elevations at different points.

Table 1 describes the relevant demographics and flow characteristics. The distance from the central treatment plant is equivalent to the maximum distance of Hollywood's furthermost extremities from the plant. We assumed a uniform population distribution.

Figure 3 shows the typical treatment train for which the treatment energy was calculated. We selected this treatment plant configuration to avoid skewing of the relation between the pump-back and treatment energy consumption because of expensive treatment. We sized each process according to required standards and calculated the cumulative energy consumption. We also compared it with the expected capital cost of a decentralized treatment plant. Aeration energy is usually 45 to 75% of the entire treatment energy consumption (Hwang and Stenstrom, 1985; Rosso et al., 2008). Hence we analyzed the pump-back energy consumption, and compared it to the aeration and treatment energy consumption.

Collection System Design. To design the trunk sewer, we computed the flow generated at every mile along the sewer direction. We estimated the wastewater generation per mile by calculating the flow on a per capita per unit length (miles) basis and designed each unit length for that flow. Sewers are commonly designed using empirical curves relating the depth of flow ratio (partial to full flow) to other ratios such as discharge, velocity, wetted area, wetted perimeter and hydraulic radius (ASCE, 2007). Such curves are tedious to use in a sewer design model without a large amount of interpolation and the assumption of linearity. Hence, we designed the trunk sewer pipe using two methods: iteration and theoretical design (Ott and Jones, 1988). For the iteration method, we used a suitable depth of flow and velocity of flow ratios (for partial to full flow) to iterate between different solutions. This takes several manual trials and an approximate estimate of the sewer size for the initial guess. The theoretical design involves calculating the sewer size and depth of flow from theoretical equations relating the sewer diameter and depth of flow.

For the iteration method, we used sewer design curves to determine the velocity of flow ratio from the maximum diameter ratio. We iterated the sewer size to meet the constraints for velocity of flow and depth of flow ratios. After obtaining the desired pipe size and depth of flow ratio, we sized the pipe for that section. We applied this iteration technique to sections of entire sewer trunk at every mile.

For the theoretical design, we used explicit equations derived by Ott and Jones (1988). We created a routine in Matlab® to assume a sewer size, running in a loop to iterate the size as the flow depth ratio and velocity ratio requirement changes. Figure 4 describes the algorithm for designing an entire trunk sewer. Figure 4a denotes how we divided the trunk sewer, and designed each section sequentially. Figure 4b shows the detailed design procedure.

To design each link we used the theoretical equations derived by Ott and Jones. This is one of the few published techniques

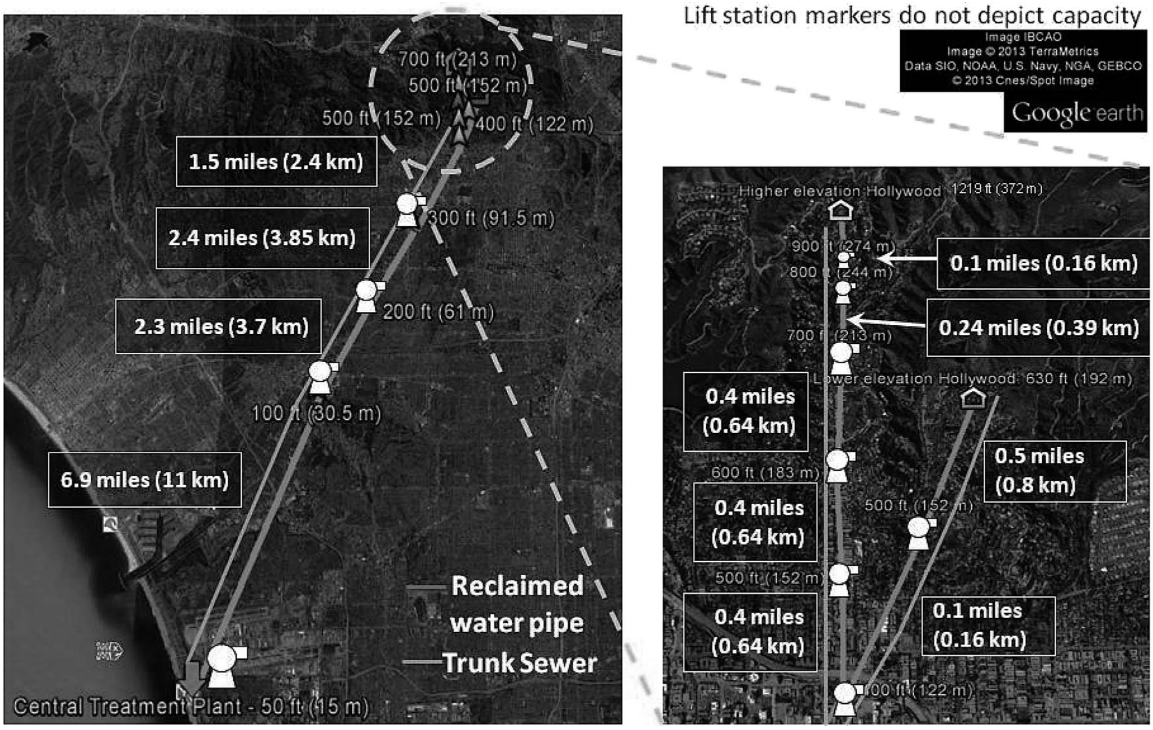

Figure 2—Locations of lift stations and reclaimed water pipeline direction (Google Earth© 7.0.2 2013)

that uses explicit theoretical equations to relate hydraulic parameters and ratios. The theoretical model considers two cases of flow: (1) Depth of flow $\leq$ Radius of pipe (2) Depth of flow $>$ Radius of pipe. Figures 5a and 5b consider both these cases and show corresponding schematics of the sewer pipe.

Table 2 describes the theoretical equations and the corresponding variables for the two cases of flow. The equations for the higher depth of flow have been simplified by changing the use of the subtended angle. These equations were used in the iteration part of the model after choosing a potentially suitable pipe size using the hydraulic parameter constraints.

Pump-Back Energy Consumption. We calculated the pump-back energy based on the topography of the region. As shown in Table 1, the distance from the Hollywood area to the central treatment plant is 16 miles (25.6 km). The Hollywood area at its lowest elevation is about 360 meters higher and at its highest elevation about 850 meters higher than the location of the central plant. We designed each section of the reclaimed water pipe for full flow. We divided the reclaimed water pipeline into sections based on the placement of the lift stations. We computed the pump-back energy consumption for each section. Figure 3 shows the placement of pumping stations and trunk pipeline for reclaimed water supply.

We used a maximum design head of 100 ft (30.5 m) for lift stations for the reclaimed water. From elevation data of the points in the direction of the reclaimed water pipeline from the central plant to Hollywood, we determined the positions of the pumping stations and the distances of the sections. To account from deviations from the assumed direction, we assumed that the actual length of each section of the pipe was 20% more than the straight line measurement.

$$P = \frac{\rho g Q h}{\eta}$$

P: Power (kW), ρ: Density of water (N/m^3); Q: Discharge in pipe (m^3/s);
h: Head (m); η: Pump efficiency

We calculated the aeration energy consumption for the secondary process theoretically. According to previous studies and energy benchmarking reports, a conservative estimate of the aeration energy consumption ranges from 45 to 75% of the total treatment energy consumption (Rosso et al., 2008; Reardon, 1995; WERF, 2011). We also calculated the total treatment energy consumption from previously reported specific energy consumption normalized by plant capacity (EPRI, 2002; Mizuta, 2010).

Table 1—Regional characteristics and assumptions for case study.[a]

Regional characteristics	Value
Population of Hollywood	123 000
Flow rate per capita	300 Liters/day (0.3 m^3/day)
Distance from central treatment plant	15.8 miles (25260 km)
Percent wastewater recycled	90%
Population density	7540 per sq. mile (2950 per sq. km)
Average elevation for Hollywood	1219 ft (372 m)
Average elevation for Central Treatment Plant	50 ft (15 m)
Flow treated	45 MGD (1.97 m^3/s)

[a] United States Census, 2011; Google Earth, 2013; Tchobanoglous et al., 2003.)

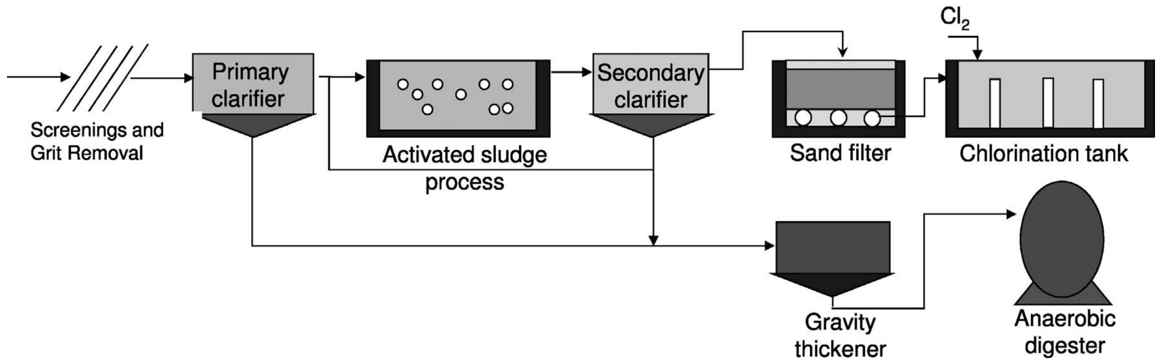

Figure 3—Hypothetical wastewater treatment configuration for analysis

Capital Investment. We assumed the same treatment configuration for both, the decentralized and centralized systems. The capital cost was calculated based on capacity of the plant, using literature cost relationships that incorporate economies of scale. This assumption simplified the determination of the capital cost of two plants of different capacities and identical treatment configuration. We conducted a literature review establishing and describing relations of cost with the capacity of the plant corresponding to various years. Table 3 summarizes these relations from different sources.

The entire set of equations was assessed for consistency by projecting the values from one year to the rest of the years. We used Producer Price Indices calculated by the Bureau of Labor Statistics (U.S.A) to project the values (U.S. Dept. of Labor,

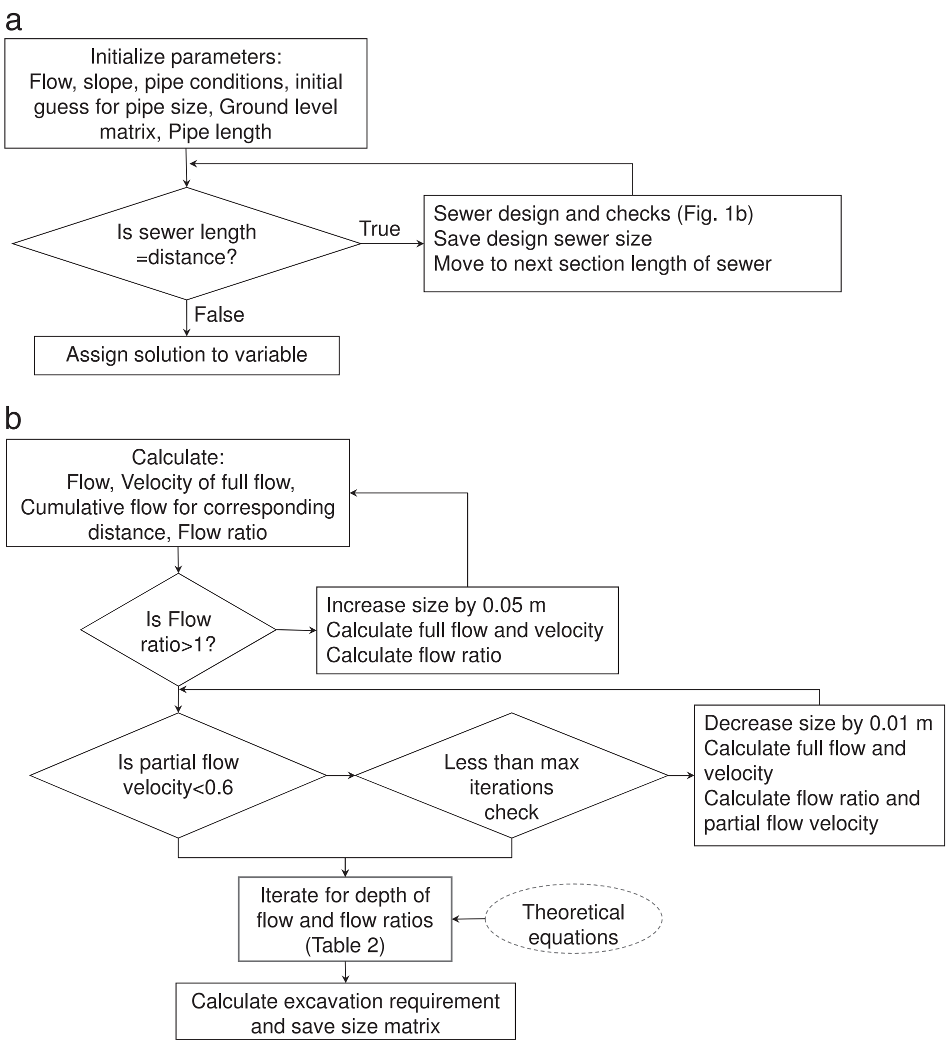

Figure 4a—Basic algorithm for collection system design. Figure 4b—Detailed algorithm for sewer design

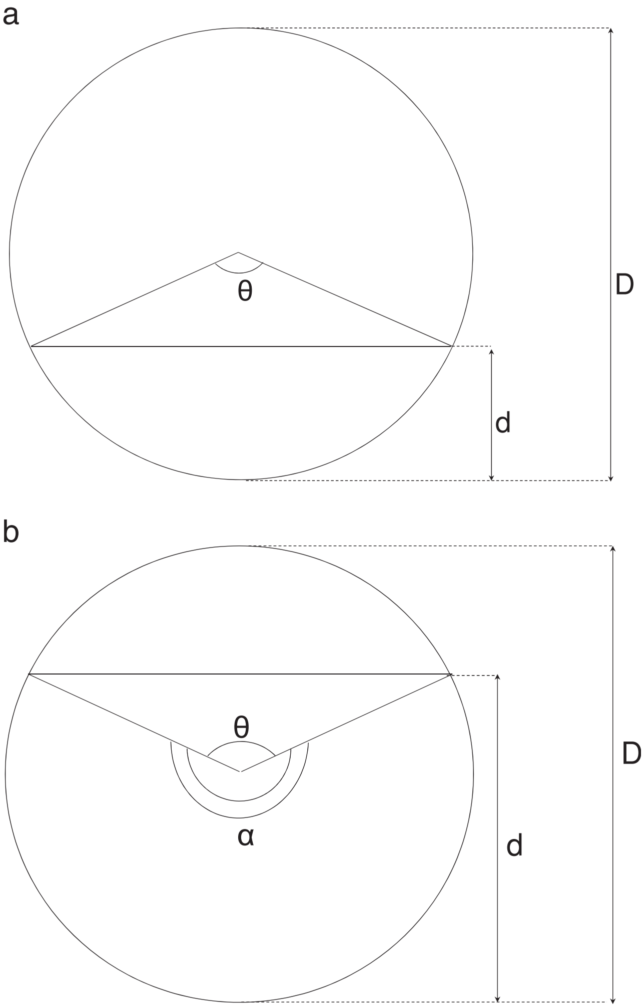

Figure 5a—Sewer with partial flow (d/D $\leq$ 0.5). Figure 5b—Sewer with partial flow (d/D $>$ 0.5).

2013). The costs calculated from the cost equations were projected to present values (2013). They were not consistent with the reported values over the time period of the references. Hence it was necessary to compute the construction costs from the correlations from all the years and project them to 2013 and report them as a range of values.

The collection system cost is computed based on the LADWP (1983) and the Producer Price Index developed by the Bureau of Labor Statistics, U.S.A. The reported construction cost per unit length of the collection system followed an exponential relation with the diameter (Figure 6). The Producer Price Index is a parameter that is used to project the production cost of a commodity to any desired year for which this index is available. (U.S. Dept. of Labor, 2013).

We calculated the cost for small treatment plants based on the EPA Report on Biological Nutrient Removal Processes and Costs (2007) and the EPA cost-flowrate correlations from the years 1978, 1980 and 1992 (1996 dollar values) (USEPA,1978; USEPA, 1980; Qasim, 1992; UNESCWA, 2003; USEPA, 2007). We used this relationship to compute a construction cost and projected it to 2012. As the decentralized plant belonged to the category of small treatment plants similar to those reported, one value of construction cost was computed using this relationship. We assumed that the cost of lift stations is 10% of that of a treatment plant. We considered the cost of multiple lift stations is 30% higher than that of a single station (USEPA, 2000).

Results and Discussion

While analyzing the concept of decentralization, we used identical treatment process trains and the same set of cost and energy equations to compare centralized and decentralized configurations on an equal platform. Depending on ambient conditions, the desired product water quality and volume and reuse applications, water reclamation plants can have different configurations and thus different cost and energy equations. This study demonstrates how decentralization can facilitate integrated water management and provide alternative solutions for better reclamation.

We compared the centralized and decentralized configurations for three types of scenarios for the central plant:

- No capital investment required at treatment facility or collection network (Incurs reclaimed water pump-back energy consumption)
- No expansion required at treatment facility, collection network capacity expansion required (Incurs reclaimed water pump-back and trunk sewer expansion/reconstruction cost)
- Capacity expansion for the treatment facility and collection network expansion required (Incurs reclaimed water pump-back energy consumption, trunk sewer expansion/reconstruction and treatment plant capacity expansion cost)

Table 2—Theoretical equations for sewer design model.[a]

Equation (d/D) $\leq$ 0.5	Equation (d/D) $>$ 0.5	Variables
$\frac{d}{D}=\frac{[1+\cos(\frac{\theta}{2})]}{2}$	$\frac{d}{D}=\frac{[1-\cos(\frac{\theta}{2})]}{2}$	*d*: Depth of flow *D*:Pipe size θ:Angle subtended at center (refer to Fig. 2) α: (2π- θ) R_{PF}:Hydraulic radius of wetted area A_{PF}:Wetted area of pipe Q_{PF}: Partial flow rate Q_F:Flow for completely filled pipe V_{PF}:Velocity at partial flow
$\theta=2\arctan\{\frac{\sqrt{1-[2(\frac{d}{D})-1]^2}}{[2(\frac{d}{D})-1]}\}$	$\theta=2\arctan\{\frac{\sqrt{1-[1-2(\frac{d}{D})-1]^2}}{[1-2(\frac{d}{D})-1]}\}$	
$R_{PF}=\frac{D}{4}[\frac{2\pi-(\theta-\sin\theta)}{(2\pi-\theta)}]$	$R_{PF}=\frac{D}{4}[\frac{(\theta-\sin\theta)}{\theta}]$	
$A_{PF}=\frac{D^2}{8}[2\pi-(\theta-\sin\theta)]$	$A_{PF}=\frac{D^2}{8}(\theta-\sin\theta)$	
$\frac{Q_{PF}}{Q_F}=[\frac{(\theta-\sin\theta)^{5/3}}{2\pi(\theta)^{2/3}}]$	$\frac{Q_{PF}}{Q_F}=\left[\frac{(\alpha-\sin\alpha)}{2\pi(\alpha)^{2/3}}\right]$	
$V_{PF}=[\frac{8Q_{PF}}{D^2(\theta-\sin\theta)}]$	$V_{PF}=[\frac{8Q_{PF}}{D^2(\alpha-\sin\alpha)}]$	

[a] Ott and Jones, 1988

Table 3—Literature review of relations between construction cost and flowrate of wastewater treatment plants.

Reference	Region	Source of data	Type of cost	Unit process	Regression	Variables
USEPA, 1978	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Site work excluding excavation	$C = (1.12 \times 10^5)(3780Q)^{0.97}$	C = cost (dollars) Q = flow rate (m^3/day)
				Preliminary treatment	$C = (5.79 \times 10^4)(3780Q)^{1.17}$	
				Influent pumping	$C = (1.47 \times 10^5)(3780Q)^{1.03}$	
USEPA, 1980	U.S.A	Winning bids for Construction Grants Program for EPA	Construction cost, piping, excavation	Equalization	$C = (6.76 \times 10^4)(3780Q)^{0.60}$	C = cost (dollars) Q = flow rate (m^3/day)
				Oxidation ditch	$C = (4.68 \times 10^5)(3780Q)^{0.57}$	
				Rotating biological contactor	$C = (6.09 \times 10^5)(3780Q)^{0.77}$	
Tsagarakis et al., 2003	Greece	National survey of MWTPs	Construction	Conventional ASP (whole plant)	$C = 0.116X^{0.954}$	C = cost in 10^6 dollars per 1000 population equivalent X = plant size in 1000 population equivalent
UNESCWA, 2003; Qasim et al., 1992	U.S.A.	Manufacturers, conceptual design and published data from USEPA report	Construction (1996 dollar values)	Screening and grit removal with bar screens	$CC = 674Q^{0.611}$	CC: Capital cost in dollars Q: average design flow in m^3/day
				Conventional activated sludge with diffused air	$CC = 72Q + 368{,}043$	

Table 4 summarizes the above mentioned financial and energy implications of each configuration. Absent from our comparison is the case with decentralized water treatment with return of the biosolids to a central treatment plant. Such alternatives are practiced now in the Los Angeles City and County areas due to the fortunate topology and planning. In cases such as Los Angeles, this option of decentralized water treatment and central biosolids treatment will likely be more favorable that the proposed options, but suitable conditions are probably rare.

Reclaimed Water Pumping Energy Consumption (Central Plant). We computed the pumping energy consumption at every 100 feet of elevation. Figure 7 shows the pump-back energy consumption at every point. The total pump-back energy consumption was 0.1 MW/day. We calculated the aeration energy consumption as 0.25 MW/day based on average values of energy consumption for the oxygen required for BOD removal and the influent BOD. We computed the treatment energy consumption from the specific energy consumption normalized by plant capacity from previous studies and some USA state environmental authority benchmarking studies (Mazuta, 2010; EPRI, 2002). Since energy consumption is not linear with the plant capacity, these results were inconsistent. Thus, we assumed the total treatment energy to be twice the aeration energy (referring to references from the 'Methods' section), which is about 0.5 MW/day for the central plant for Hollywood.

Collection Network, Reclaimed Water Pipe Construction and Lift Stations Cost Without Capacity Expansion. To connect Hollywood to the central treatment plant, the collection pipe size has to be enlarged to accommodate the flow. Figure 8 shows the increase in pipe size with flow for the same case. Near the central plant, the design diameter approaches 2 meters. In the case of the decentralized treatment plant for Hollywood, the design trunk sewer diameter is 0.45 meters. We computed a total construction cost of all the lift stations as $7.25 million to $13.8 million.

Expansion of old sewers is more expensive than building a smaller new collection network. The cost for the entire network is computed to be $129 million (LADWP, 1983) and the Producer Price Index developed by the Bureau of Labor Statistics, U.S.A (U.S. Dept. of Labor, 2013). Figure 8 shows the relation of construction cost of a collection network pipeline with its size from the years 1983 to 2013. The construction cost for a main collection pipeline connecting the region to a decentralized plant at a radius of 5 miles is calculated to be $6 million, conservatively assuming a constant pipe size of 0.2 m sufficient for the decentralized flow.

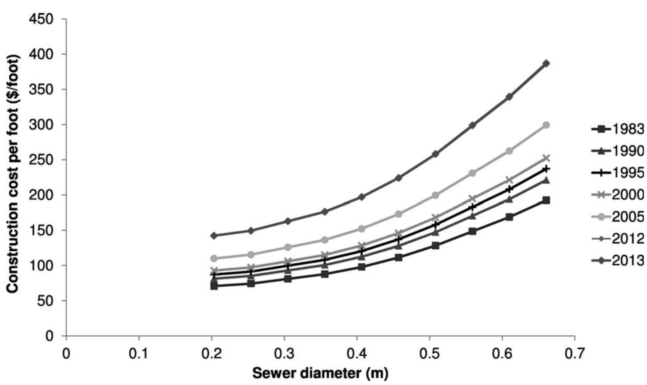

Figure 6—Variation of construction cost of sewer per length with sewer diameter and time (LADWP, 1983)

Table 4—Comparison between centralized and decentralized configurations.

Factor	Centralized Plant	Decentralized Plant
Pump-back energy consumption (reclamation)	32.7 MW/d	Negligible
Reclaimed water pipeline cost	$67.7 million	$2 million
Sewer re-construction cost (with excavation)	$866 million	$6 million
Construction cost for centralized WWTP	$55.8 −106.3 million	$6-22.5 million
Expansion cost (50% expansion)	$28-53 million	–
Lift stations cost	$7.25-13.8 million	–

(Table footnote: Naik and Stenstrom, 2012.)

The construction cost of the decentralized treatment plant of the required capacity of 2.5 MGD was calculated to be in the range of $6 million to $22.5 million (USEPA, 1978; USEPA, 1980; LADWP, 1983; Qasim, 1992; UNESCWA, 2003; USEPA, 2007). The upper limit of this range is a conservative estimate, since it estimates the construction cost of a BNR-based (Biological Nutrient Removal) system rather than a conventional ASP-based (Activated Sludge Process) system. Thus, construction cost for the collection system connecting to the central plant exceeds the combined cost of the decentralized treatment plant and the corresponding collection system.

Comparison Using Capacity Expansion Cost for Central Treatment Plant. The capital cost for central plant was computed to be in the range $55.8 million to $106.3 million. The minimum expansion cost can be assumed to be 50% of the construction cost, i.e. $28 to $53 million. As compared to the combined cost of the decentralized plant ($6 million to $22.5 million) and the connected sewer ($6 million), the combined cost of expanding the sewer connecting to the central plant ($121.4 million) and expansion of the central plant facilities ($28 million) is much higher (USEPA, 1978; USEPA, 1980; LADWP, 1983; Qasim, 1992; UNESCWA, 2003; USEPA, 2007).

A decentralized treatment system can be optimized and controlled more efficiently by utilizing the central treatment facilities for biosolids treatment, similar to the Los Angeles City D.C. Tillman and Glendale wastewater treatment plants. At these plants and upstream plants operated by the Los Angeles County Sanitation Districts, primary sludge, waste activated sludge, screenings and grit are all returned to the trunk sewers. This simplifies the distributed plant design and construction, and does not overload the collection system, since these flows are typically less than 1% of the treated flow. In this case study, the decentralized plant was assumed to have biosolids treatment facilities.

For this study, we considered one decentralized treatment system for Hollywood. Decentralizing the entire central wastewater management system serving Los Angeles City will require multiple smaller wastewater systems. Multiple smaller wastewater systems might not achieve economy of scale similar to a large system. The decision of completely replacing a centralized system requires a feasibility analysis methodology

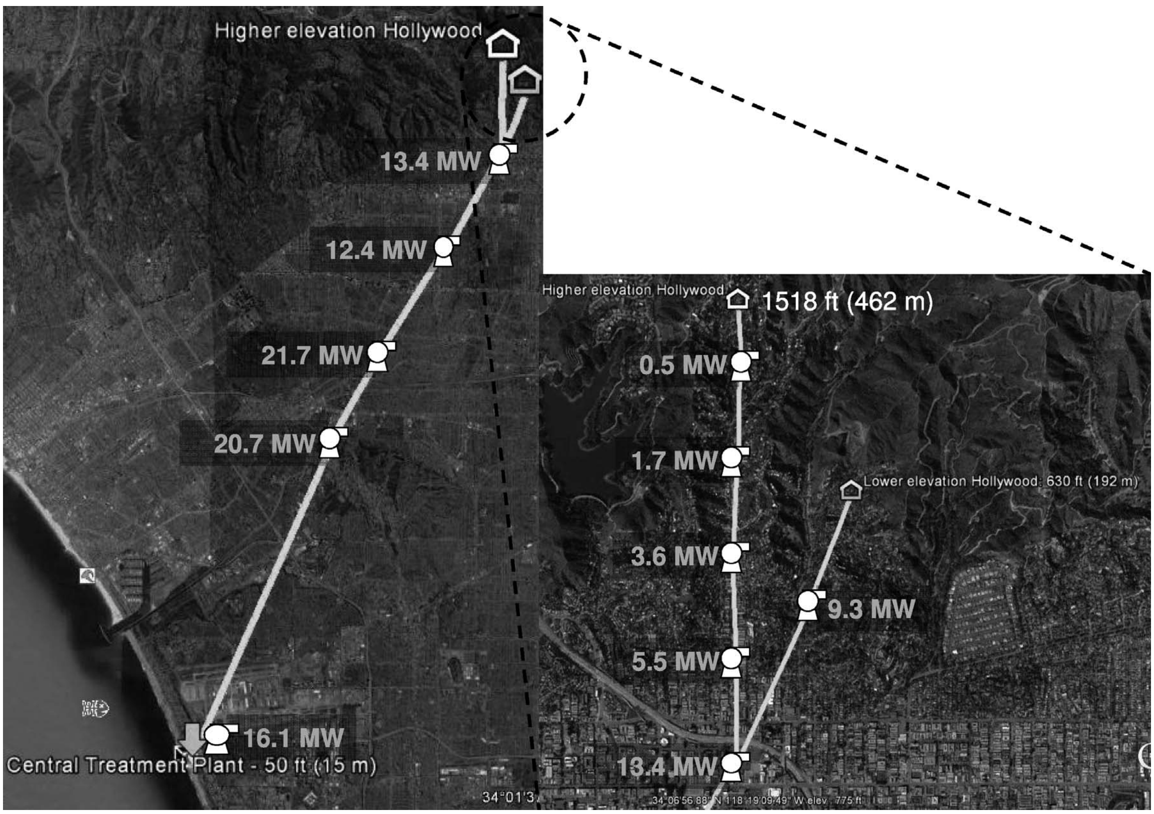

Figure 7—Pump-back energy consumption for Hollywood, CA (Google Earth© 7.0.2, 2013)

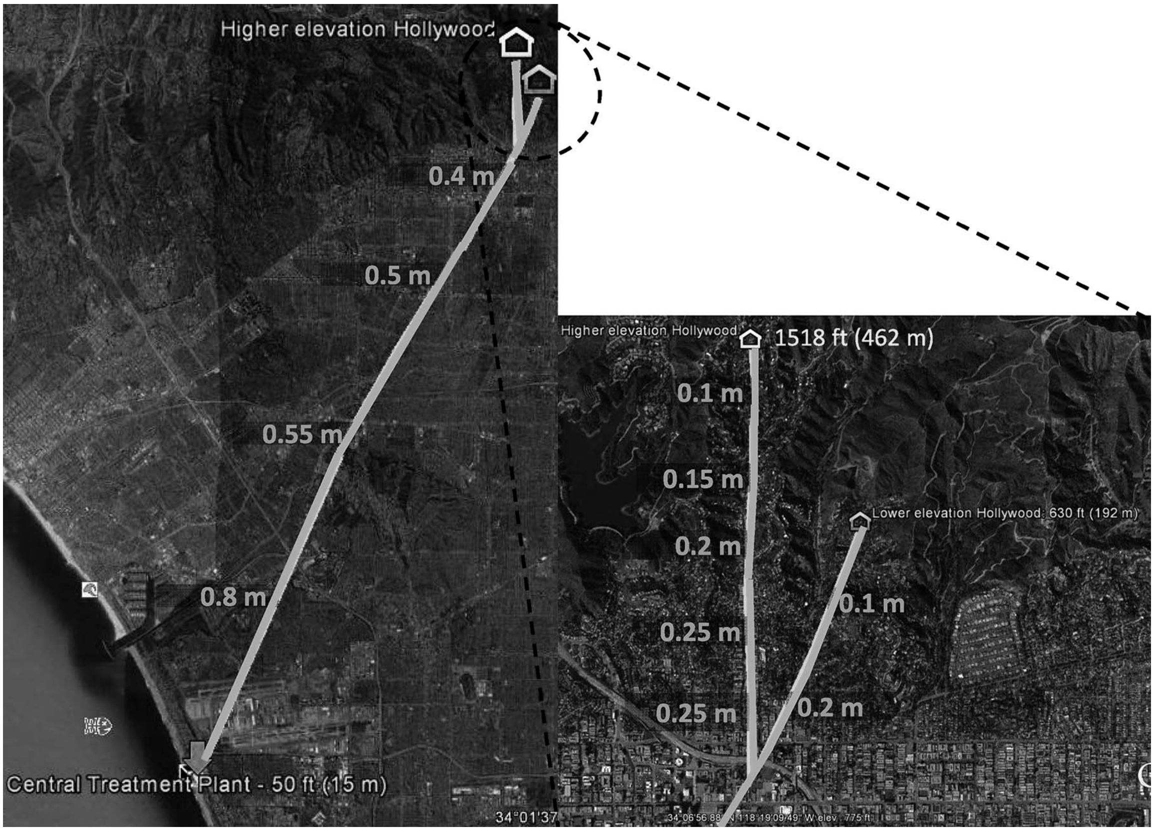

Figure 8—Sewer size for collection network (Google Earth© 7.0.2 2013)

similar to the one demonstrated in this study which also incorporates the economy of scale in terms of capital and operational cost.

An alternative to pumping back reclaimed water from decentralized reclamation plants to end users is to construct reclamation plants near spreading grounds or points of injection into the groundwater basins. This solution too is more easily achievable with decentralization. Pumping back reclaimed water incurs high expenditure in the form of pumping power, piping infrastructure, and dual fixtures and connections. For example, in Los Angeles County, except in areas without access to groundwater basins, using reclaimed water to recharge groundwater basins is being preferred to pumping back reclaimed water due to the above reasons.

Decentralized systems can be advantageous in remote, high economy communities. Residents of such communities are usually reluctant towards installation of large treatment plants to avoid community expansion and high population and residential density. A staunch aversion to reside in proximity to any wastewater treatment plant also hinders wastewater management in these communities. For example, the Malibu locality in Los Angeles County, CA, still relies on individual household based septic tank systems. With increase in demand, such systems are bound to reach capacity exhaustion, due to their dependence on leach fields. Smaller, modular treatment units can be more appealing to these residents on account of their low physical footprint and capital investment.

Most importantly, decentralized systems can be cost-effective in terms of installation (capital cost) and pumping energy (operational costs). As the unit processes are more modularized and do not have extremely conservative estimates for future demands, widespread wastewater management is more probable with such cost-effective configurations. A previous study by the authors analyzed the improvement in public health due to wastewater treatment independent of economic growth or other demographic development (Naik and Stenstrom, 2012). It concluded that wastewater treatment availability significantly benefits public health, irrespective of growth in health care or national income. This variation was observed at different levels of human development and also conditions of complete sanitation. It demonstrates that wastewater treatment is not a luxury for the developed nations but is a vital service for public health protection and improvement independent of the nation's economic standing.

Conclusions

Pump-back power consumption of recycled water, expansion cost of sewer lines and central treatment plant facilities determine the feasibility of installing a decentralized system for a new/remote region. Pump-back power consumption is a large fraction of the total treatment power consumption and can surpass aeration energy consumption. With the demand for recycled water on the rise, pump-back power consumption has to be controlled to make water reclamation more practical and economical. In addition to complex reclaimed water distribution networks, installing pump stations can be a significant part of the capital investment. A decentralized wastewater system can be more economical than sewer expansion and capacity expansion of the central system to accommodate the increased demand. Thus, decentralized treatment can be an extremely practical and economic alternative for expanding communities and urban areas. Furthermore, it ensures access to wastewater treatment for remote regions. This study establishes the need to further model the decentralized configuration consisting of multiple systems and determine an optimal solution set in terms of capacity, number of units and location.

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