© The Pakistan Development Review
52:4 Part I (Winter 2013) pp. 437–446

Energy-Cost Optimisation in Water-Supply System

FARRUKH MAHMOOD and HAIDER ALI

1. INTRODUCTION

Water, being the basic requirement of life, is important to all living organism, human health and food production. A positive correlation between economic growth and rate of water utilisation has also been observed in a growth model with water as a productive input for private producers [Barbier (2004)]. In addition, high per-capita consumption (PCC) of water is regarded as an indicator of the level of economic development where per-capita water consumption is defined as the average of water consumed by a person in a day. The declining availability of water supply, mainly due to global climate change, is one of the important issues faced by many developing countries at the present time. It is estimated that nearly two third of nations across the globe will experience water stress by 2025.[1] Thus, the safety and availability of clean water is an on-going concern within the global village.

In Pakistan, drinking water supplies are generally obtained from either surface water sources (i.e. rivers, streams, lakes) or the underground aquifers. Unfortunately, both sources are subject to pollution due to anthropogenic activities. Water supply systems (WSS) require energy in each of the stages of water production (pumping it from underground) and distribution chain. A number of studies [i.e., Abdalla (1990); Nguyen, *et al.* (2009); Khan, *et al.* (2012)] have analysed the economic and social cost of water degradation but a few studies at international level [Feldman (2009)] and no study in case of Pakistan, particularly after severe energy crisis, have analysed energy-cost optimisation in a WSS.

The most important factor in the design of a WSS is the estimation of water requirement for a community. The per-capita consumption of water varies from place to place and is affected by various factors i.e., climatic conditions, water pressure and quality, population size etc. There is no common understanding on the minimum per-capita water requirement for human health and economic and social development. According to World Health Organisation (WHO), minimum level of per-capita water consumption is twenty litre of water to take care of basic hygiene needs and basic food

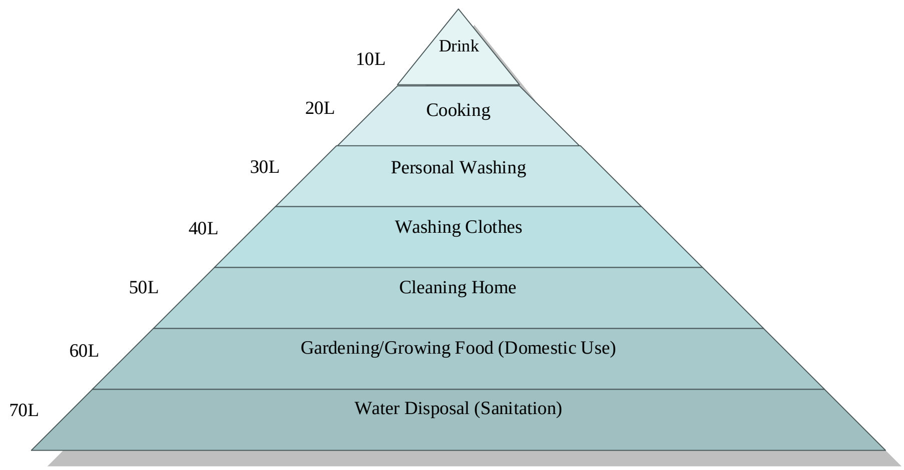
Farrukh Mahmood <farrukhmahmod_501@yahoo.com> is MPhil Student, Department of Economics and Finance, Pakistan Institute of Development Economics, Islamabad. Haider Ali <haider@pide.org.pk> is Lecturer, Department of Economics, Pakistan Institute of Development Economics, Islamabad.

[1]United Nations Environment Programme Report (2002).

hygiene. Laundering and cleaning would require more water. Taking into account that average household size of Pakistan is six;[2] a single unit of household requires a minimum of 120 litre of water per day for basic hygiene needs.

Figure 1 shows different categories of water need of an individual along with standard quantities of water requirement set by WHO to assess the accuracy of the per capita consumption of water for domestic use.

Fig. 1. Hierarchy of Minimum Water Requirements for Domestic Uses



Source: World Health Organisation Report (2006).

Primarily, there are two types of water-pumping systems for utilisation of underground aquifers. One is direct pumping system where the instantaneous demand is met by pumping water with no elevation storage provided. This direct pumping system is being phased out because of the operating costs. Severe load-shedding due to recent energy crisis is another reason why people are moving from this pumping system to other economical options. The second type is an indirect system in which the pumping station lifts water to an elevated storage tank which floats on the water system and provides system pressure by gravity. These days, majority of households (which utilise underground aquifers) use the indirect pumping system in Pakistan and have elevated storage tanks as this system does not require instantaneous energy supply for minute to minute water demand.

The underground WSS can be categorised into household and community water distribution system where the later implies a common elevated storage tank which flows water by gravity to each customer on the system. At household level, every household unit has to bear the fixed cost along with the variable cost of electricity consumption. Interestingly, the cost structure of the community WSS (capital investment in water infrastructure (reservoir and pipes) and operating and maintenance cost) is also not very

[2]Pakistan Statistical Bureau (2012).

different from that of household but due to large scale of production, it seems that average cost of producing water would be lower and all customers on community water system would incur a lower cost than otherwise. Under community WSS, number of customers and water pressure are negatively correlated. It implies that customers of community WSS have to face some additional cost to pump water from ground storage to elevated storage when lower pressure does not elevate the water. On the contrary, heights of the elevated-tank and water pressure are positively correlated.

The efficient operation of WSS is not just a technical issue. Prevailing energy crisis and focus of the government on demand-side energy policies (i.e., energy conservation) in Pakistan raises the need of using energy efficient techniques in every aspect of real life. Water supply systems are massive consumers of energy. Besides, the main life-cycle cost of a water pump is related to the energy spent in pumping, with the rest being purchase and maintenance cost of the equipments. Any optimisation in the energy efficiency of the water pump results in a considerable reduction of the total operational cost. Feldman (2009) asserts that energy efficiency can be achieved by; installing new technology, improving system design, installing variable speed of pump and reducing leakages.

Household WSS (individual unit) and community WSS (aggregate unit) are two major types of water systems in urban areas of Pakistan [Haydar, *et al.* (2009)]. This paper will examine whether community WSS relative to household WSS is more energy efficient or not. In other words, a single community WSS (assuming it consists of *'H'* number of household units) face less operational costs (energy consumption) than total operational cost faced by 'H' number of households when they work as individual entities. Besides, this study will determine the optimal threshold number of consumers under a single community elevated storage tank. This will allow determining the minimum number of customers required to make the option of building a given community WSS feasible.

The remainder of this paper is organised as follows. Section 2 contains the analytical framework and a brief description on data and variables. Section 4 includes discussion on the results of cost-benefit analysis of household and community water-supply systems. Finally, Section 4 concludes this study.

2. ANALYTICAL FRAMEWORK, DATA AND VARIABLES

Following Kim (1987), the theoretical framework to examine cost-structure of WSS is represented by:

$$C_i = C_i(p, y), \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (1)$$

where C_i is cost of producing water supply, $i = 1, 2$ index refers to household and community WSS, p is the vector of strictly positive input prices and y is the output. Thus, the cost function is given by:

$$C_i(p, y) = \min p.x,\ x \in v(y), \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (2)$$

where x is a vector of inputs and $v(y)$ is the input requirement set. From the cost function, it is possible to derive the cost minimising factor demand equations using Shephard's Lemma [Chambers (1989)].

$$\frac{\partial C(p,y)}{\partial p_i} = X_i(p,y). \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (3)$$

Scale economies (returns to scale) are important measurements for examining the potential for amalgamation and/or separation of (water) production units in view of the economic benefits. If there are economies of scale, larger firm (community WSS) can produce at lower average cost than smaller ones (household WSS). Scale economies are defined as the relative increase in output as a result of a proportionate increase in all inputs. In a nutshell, scale economies are measured by the relationship between average and marginal cost. Returns to scale (θ) are the inverse of the elasticity of output ε_{cy}.

$$\theta = \frac{c(p,y)}{MC*Y} = \frac{1}{\varepsilon_{cy}}. \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (4)$$

Where $\varepsilon_{cy} = \partial lnC/\partial lny_i$ and MC is the marginal cost $MC_i = C/Y_i \times \varepsilon_{cy}$. Economies of scale exist if $\theta > 1$, constant returns to scale exist if $\theta = 1$ and decreasing returns to scale exist if $\theta < 1$. The important implication of this is that marginal cost pricing is not sufficient to recover costs for industries with economies of scale.

Total cost of installing a WSS consists of fixed cost and variable cost where the later varies with the level of output. Fixed cost of household WSS includes cost of tank, cost of motor, cost of water pipes, boring (drilling) cost, cost of wire, cost of joints for pipe and some miscellaneous expenses (i.e. cost of grease, cost of making holes in outer pipe etc.). Drilling cost depends positively on depth as well as radius of the earth bore while motor cost depends directly on the capacity (horse power) of the motor and indirectly on the depth of the bore (Data on prices of all variables used are given in Appendix 1). It is important to explain, here, that water-tank cost in case of individual household is taken for water-tank of three hundred gallon capacity (300*3.78=1134 litres) that is minimum size of tank available in the market. One rational is that this study pivots around WHO daily per-capita water requirements that vary from 120 litres (minimum) to 420 litres (maximum) per household.

The variable cost is basically the operational cost and is sum of cost of energy consumption and cost of wear and tear of capital.[3] Energy (mainly electricity in our study) cost is a product of units consumed times tariff rate whereas consumption of energy units depends on the (horse) power of motor and total time duration when motor works.

In community WSS, only fixed cost structure is a little different as it includes all those expenses incurred in household WSS plus compensation of water-supply staff. It is important to note that in the long run, the households can change the level of water consumption. Since acquiring a WSS is a decision of long-run planning horizon, households have to make decision either they should use independent or the community WSS.

Primary data on five community and fifty households WSS have been taken randomly for cost-benefit analysis from Islamabad/Rawalpindi district as it mainly consists of well-planned Government and private housing societies. Data on variables of cost of water tank, cost of motor, cost of water pipes and cost of joints for pipes have been taken from whole sellers and retail sellers while data on boring cost is taken from

[3]We are assuming a zero wear and tear cost to keep our analysis simple. This assumption does not invalidate our results.

private contractors. Data of electricity tariff are taken from Islamabad Electricity Supply Corporation (IESCO). Data are taken on market prices of water tank installed per gallon, capacity of motor (Horse Power), billing cost (price times units consumed) and cost of boring, water pipes and wire per feet. Same variables are also observed for elevated water supply system including construction rate of elevated water supply system.

3. RESULTS AND DISCUSSION

All variables are explained in three scenarios where the cost is estimated for depth of 150, 200 and 300 feet of earth bore. Household WSS usually has bore of 150 feet while community WSS can have either 200 or 300 feet earth bore. Descriptive statistics for the data on fixed variables are shown in Table 1.

Table 1

Descriptive Statistics (Fixed Cost Variables)

Variables (Feet)	Bore Depth	Minimum	Maximum	Average	S.D
Inner Pipe	150	165	170	167.5	3.53
	200	200	220	210	14.14
	300	300	320	310	14.14
Outer Pipe	150	150	155	152.5	3.53
	200	200	205	202.5	3.53
	300	300	305	302.5	3.53
No. of Joints	150	15	16	15.5	0.70
	200	20	21	20.5	0.70
	300	30	31	30.5	0.70
Rope	150	155	160	157.5	3.53
	200	205	210	207.5	3.53
	300	310	320	315	7.07
Electric Wire	150	160	170	165	7.07
	200	10	20	15	7.07
	300	10	20	15	7.07
Miscellaneous Expenses (Rs)	150	600	800	700	141.42
	200	11000	12000	11500	707.10
	300	17000	18000	17500	707.11

It can be seen from Table 1 that all variables depend positively on the depth of earth bore. One anomaly is seen in case of wire per feet where increased depth of earth bore reduces the length of wire. It is because increased depth of bore needs high-power motor for water suction (which simultaneously pumps water from underground aquifer and throw it into the system), that precludes need of a separate water pump. Therefore, wire is required just to connect the motor with electricity source. Sum of market values of all these above variables along with water-motor cost, drilling (boring) cost, water-tank cost and working staff (in case of only community WSS) yield total fixed cost for community and household water supply systems. Table 2 below presents a brief picture of total fixed cost for both WSS.

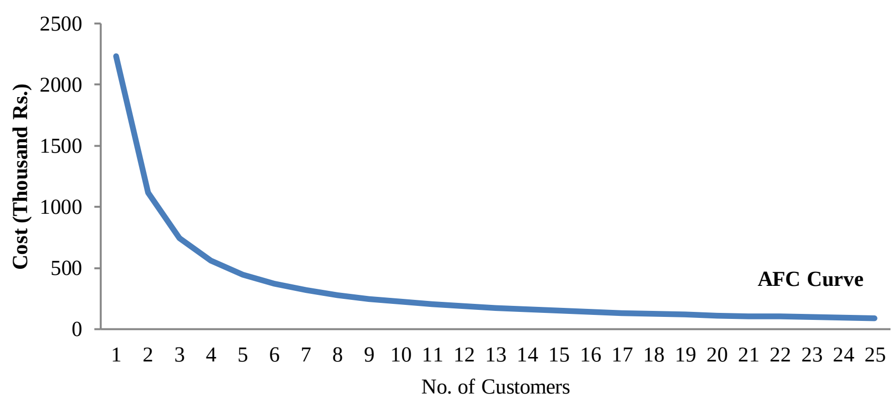
Table 2

Total Fixed Cost (Thousand Rs) of Water Supply Systems

Bore Depth (Feet)	Household WSS	Community WSS
150	88.812	1651.225
200	154.373	1732.000
300	472.848	2232.500

The major difference in fixed cost of both systems is primarily due to construction cost of elevated water tank in case of community WSS. Fixed cost of community WSS includes cost of elevated water tank of 8000 gallon (8000*3.78 = 30240 litres) capacity. This construction cost alone is higher than total cost of a single household WSS under 150 bore depth (See Appendix). Besides, the motor cost of community WSS is also much higher than the cost of motor used in household WSS. But, this huge fixed cost of community WSS can be divided among customers of this system to bring the per-head cost down to the fixed cost faced by an individual in case of 150 bore depth (as household usually utilises water up to 150 bore depth). The diagram below shows how average fixed cost responds to increase in number of customers.

Fig. 2. Average Fixed Cost (AFC) of Community WSS



The depth of boring for individual household cannot go beyond 150 feet due to the low capability of the machine used in household WSS while, for community WSS, it can be 300 feet as the machines used in this system is highly powerful. It can be deduced from Table 2 that it is not beneficial to develop community WSS unless number of houses exceed 25 (2232.500/88.812 = 25.137). Interestingly, a community WSS can serve much greater number of households than just twenty five and, in that case, average fixed cost would be even further lower. If we take 420 litres of daily water consumption by a housing unit (WHO standard); a community WSS, in this case, can serve seventy two household units with average fixed cost that is one-third of total fixed cost incurred under household water supply system.

The remaining part of total cost is variable cost which includes operational cost of a WSS whereas daily operational hours of motor depend on the daily water requirement of a household. Table 3 below presents electricity units consumed and energy cost for WHO's established hierarchy of minimum water requirement under both household and community WSS.

Table 3

Variable (Operational) Cost of Water Supply Systems

			Households Daily Water Requirement (Litres)				
		Bore Depth	120	180	240	360	420
Electricity Units Consumed	Household	150	51.874	77.811	103.748	155.621	181.558
		200	142.653	213.979	285.306	427.959	499.285
		300	1141.224	1711.836	2282.448	3423.671	3994.283
	Community	150	22.824	34.237	45.649	68.473	79.886
		200	51.874	77.811	103.748	155.621	181.558
		300	163.032	244.548	326.064	489.096	570.612
Billing Cost (Rs)	Household	150	300.349	450.524	841.393	1262.090	1472.438
		200	1156.916	2638.367	3517.822	5276.734	6156.189
		300	17198.243	25797.364	34396.485	51594.728	60193.850
	Community	150	132.154	198.231	370.213	555.320	647.873
		200	420.697	631.045	841.393	1918.812	2238.614
		300	2010.184	3015.276	4020.368	6030.553	7035.645

Table 3 explains that electricity cost is positively correlated with daily water requirement as well as depth of earth bore. An increase in daily water requirement increases operational time of the motor required filling the tank; hence, resulting in higher billing cost. An increase in depth of bore raises operational cost in two ways. First, it reduces the suction rate of the pump, hence, increasing the time of motor working (for details on suction rate and bore; see, Table A2 in Appendix). Second, increased bore depth requires more energy to pump water from underground aquifer and throw it into the system; that in turn requires water motor of higher capacity (which bears higher cost). That is why billing cost of community WSS is lower than billing cost of individual WSS. On the other hand, the billing cost of household WSS is much higher than that of community WSS.

To compare the operational (variable) cost between the two systems, it is realistic to compare billing cost of household WSS at 150 earth bore with billing cost of community WSS at 300 earth bore. Billing cost of community WSS is then divided among 25 households (for the reason discussed above that a community WSS can only be built if there are at least 25 households to share its total fixed cost) for a better appraisal of average household cost under community WSS. This will give correct apportionment of the difference of energy cost (and, hence, energy consumption) between the two WSS. Besides, this analysis will also be extended for 72 household units as it has been estimated that a community water tank of 8000 gallon capacity can serve 72 households for daily water requirement of 420 litres.

Figure 2 below depicts trends in billing cost with respect to daily water requirements for both water supply systems whereas trend in cost of community WSS is shown for an average unit under community WSS; first assuming it has 25 customers and, then, by assuming it has 72.

Fig. 3. Billing Cost of Household and Community WSS

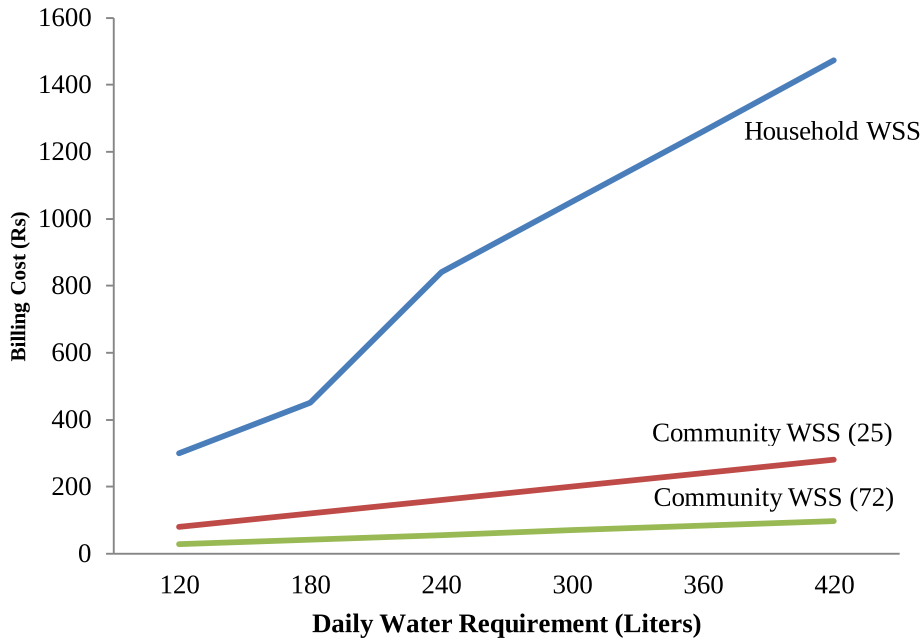


Figure 2 shows that household WSS is a massive consumer of electricity as compared to community WSS. Besides, the gap is increasing at increasing rate with increase in demand of water for daily requirements (that depends on household size and water-consuming habits). The operational cost under community WSS gets further lower in case of increased units of households (72 units). One of the possible reasons of this lower operational cost under community WSS is economies of scale where a centralised system with greater scale of production can utilise better inputs resulting in decreasing cost. These results suggest that building of community WSS (if and only if there are, at least, more than twenty five housing units) not only reduces fixed cost but also results in lower operational cost of water system. In addition, community system supplies cleaner drinkable water relative to individual water system as the former sucks water 300 feet under the earth surface.

4. CONCLUSION

Recent energy crisis in all most all developing countries and particularly in Pakistan forced government agencies to focus on demand-side energy policies, especially energy conservation, as a short-term solution. This study presents a view on how individual water supply systems are bulk consumers of electricity while community water supply systems can provide daily water requirements at much lower consumption rate of electricity; hence, resulting in twofold benefit of lower consumption of electricity and lower total cost (in monetary terms) of per-capita water.

This study also reveals that a minimum of twenty five households are required to bear the fixed cost of building a community water supply system. If the number of customers in community water supply system rises to seventy two, this fixed cost comes down to almost one-third of the cost an individual household incurred for developing his own water system. Besides, the results show that average billing cost goes down to less than hundred if community water supply system includes seventy housing units. In addition, community system supplies cleaner drinkable water relative to individual water system as the former sucks water 300 feet under the earth surface. Based on these results, it is suggested that community water system should be made compulsory for developing housing colonies. Municipal authorities of Islamabad/Rawalpindi region can develop community water systems in those sectors where tube wells are supplying water but elevated tanks are not constructed. This will incur less operational cost to each household due to less consumption of electricity as elevated tank precludes electricity requirement for throwing water from ground tank to elevated tank.

APPENDIX

Table A1

Market Price of Inputs for Household and Community WSS

		Price (Rs)/Unit	
Variable	Unit	Household WSS	Community WSS
Inner Pipe	Feet	12	950
Outer Pipe	″	235	950
Rope	″	10	–
Wire	″	25	200
Drilling Cost	″	100	120
Joints	No.	230	1250
Motor Cost	2 Horse Power	20000	–
	5 Horse Power	70000	–
	20 Horse Power	350000	350000
Plastic Tank Cost	300 Gallon	6000	–
	400 Gallon	8000	–
Cement Tank	Cubic Feet	–	120*
Working Staff	Rs	–	6000

*Cost of building an elevated water tank of 8000 Gallon capacity at this rate requires (on average) 1.2 Million Rupees.

Table A2

Water Suction (Litre per Hour) Capability of the Motor

	Motor Capacity (Horse Power)	
Depth of Bore (Feet)	2 HP	20 HP
150	8327.902	189270.5
200	3028.328	83279.02
300	378.541	26497.87

Source: Pakistan Engineering Council, Islamabad.

Table A3

Tariff Rate for Electricity

Bracket	Unit	Tariff (Rs)
I	1-50	2.00
II	51-100	5.79
III	101-300	8.11
IV	301-700	12.33
V	Above 700	15.07

Source: IESCO (2013).

REFERENCES

Abdalla, C. W. (1990) Measuring Economic Losses from Ground Water Contamination: An Investigation of Household Avoidance Costs. *Water Resources Bulletin* 26:3, 451–462.

Barbier, Edward B. (2004) Water and Economic Growth. *Economic Record* 80:1, 1–16.

Chambers, R. K. (1989) *Applied Production Analysis: A Dual Approach*. Cambridge University Press, USA.

Feldman, M. (2009) *Aspects of Energy Efficiency in Water Supply Systems*. Carlamani Conference and Events, Tel Aviv, Israel.

Haydar, S., M. Arshad and J. A. Aziz (2009) Evaluation of Drinking Water Quality in Urban Areas of Pakistan: A Case Study of Southern Lahore. *Pakistan Journal of Engineering and Applied Sciences* 5, 16–23.

Khan, S., *et al*. (2012) Drinking Water Quality and Human Health Risk in Charsadda District, Pakistan. *Journal of Cleaner Production*, doi:10.1016/j.jclepro.2012.02.016.

Kim, H. Y. (1987) Economies of Scale in Multi-Product Firms: An Empirical Analysis. *Economica* 54:214, 185–206.

Nguyen, Van Anh, S. Bang, P. Hung, and K. W. Kim (2009) Contamination of Groundwater and Risk Assessment for Arsenic Exposure in Ha Nam Province, Vietnam. *Environment International* 35, 466–472.

United Nations Environment Programme (2002) *Vital Water Graphic: An Overview of the State of the World's Fresh and Marine Waters*. Nairobi: United Nations.

World Health Organisation (2006) *Guidelines for Drinking-water Quality: Incorporating First Addendum* (3rd ed). Geneva: World Health Organisation.