ANALYSIS OF GROUNDWATER PRODUCTION COST

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Abstract

Over the years, the role of groundwater as a source of irrigation requirements, industrial requirements, human consumption and other domestic uses has been continuously increasing. With this widespread expansion in using groundwater, the economic factor related to its production cost has become of great importance.

This study deals with the cost analysis of pumped water from the groundwater storage considering the different variables affecting the unit cost. The approach used is an analytical one, which allows general conclusions to be drawn for all specific situations. The effect of change in different parameters such as diameter of well, discharge, entrance velocity, hydraulic conductivity, storativity, running hours, and static head, on the unit cost of pumped water is studied and the results are presented.

1. Introduction

Groundwater is the largest source of accessible fresh water on earth. The estimated amount of groundwater is around 8 million Km^3 (Wilson, 1983), half of which may be at depths less than 800 meters. This quantity is about 35 times the quantity of fresh water available on the surface of the earth and is about one third of the volume stored as ice in Polar Regions and mountain ranges (Garge, 1987). Therefore, groundwater constitutes a vast resource for satisfying water requirements of all kinds.

In arid and semi-arid regions groundwater storage is the major source of water and it has the utmost importance to any social and economic development. And, in humid regions where rivers and lakes have historically supplied much of the water needed, the value of groundwater has tended to be overlooked. As surface water supplies have become depleted or contaminated, groundwater has become a major source of water even in these regions. In some cases where surface water had to be pumped through long pipelines, groundwater has brought about considerable savings in cost of pipelines and treatment.

Effective methods and tools are now available for hydrogeological research and exploitation, and therefore for more understanding of groundwater. The greatly increased knowledge of geology and hydrology of the areas investigated, the more detailed understanding of the hydraulics of groundwater flow and recharge.

2. Purpose of the Study

The purpose of this study is to carry on design analysis of tube-wells and to describe the parameters affecting the cost function of groundwater and to show the effect of these parameters on the unit cost -**rather than the cost itself**- using an analytic approach, which allows general conclusions to be drawn when changing the design parameters, which apply to specific situation.

3. Economic Factor

The economic feasibility of using groundwater has led to rapid growth in its use. Water wells are increasingly used for both public and private exploitation, and may be particularly valuable for augmenting surface water supplied during short period of peak demand. Such systems based on wells can be brought into operation much more rapidly and efficiently than systems based on water treatment units, which may take a number of years to complete. Moreover, ground water development can be phased with demand avoiding costly excess capacity in early stages of development. For all these reasons, the widespread expansion of groundwater resources development is economically justified.

4. Production Cost Aspects

The total cost of pumping water from the groundwater storage is mainly influenced by two types of costs, namely the "*Fixed or Initial*" cost and the "*Recurrent or Variable*" cost.

Fixed cost includes the initial cost of data collection, exploration, analysis, drilling, and the cost of all types of installation (electrical and mechanical equipment). The main factors affecting this type of cost are the depth to the aquifer, aquifer parameters, diameter of well, well screen length, drilling costs which depend on the situation and the hydrogeological conditions of the site, design discharge, and groundwater level, and the drawdown. Other factors considered are the location of well, cost and availability of different types of energy. The latter is important for selection of the best type of pumps to be purchased, which, in turn, has a significant effect on the total fixed cost. For the same type of installation, cost of groundwater production will be lower in areas with favorable hydrogeological conditions and shallow water tables where materials and skills are available locally whereas in arid areas underlain with hard rock, deep water table; cost will be considerably high.

Recurrent include costs that are function of the duration of operation, like those of energy costs, labor costs for control and operation, plus costs derived from repairing equipment and installations. The costs of energy and labor and replacement (cost of spare parts) must be determined from the very beginning. If it is difficult to obtain any of these costs we may be faced in the future with a high recurrent cost to keep the equipment running properly. Where electricity is readily available the investment may be facilitated as opposed to remote areas where fuel would have to be transported to operate the pumps.

5. Unit Cost of Pumped Water

The total annual cost of pumped water equals to the annual capital cost plus the annual recurrent cost. These costs can be computed using the capital recovery factor(Beakley et.al.,1986) as follows,

a. **Annual Capital Cost (A):** $A = C\times(1+i)^n \times i / \{(1+i)^n - 1\}$ (1)

Where,

C = Total initial (or capital) cost,
A = Annual capital cost,
i = Rate of interest,
n = Life time of well in years

b. **Annual Recurring Costs:**

Assuming electric power supply, the power required to lift a certain amount of water to a given total head with the help of a lifting device (pump & motor) having a given efficiency is given by,

$$P = \gamma QH/\eta \tag{2}$$

Where,

P = Power,
γ = Specific weight(of water),
Q = Discharge,
H = Total head,
η = Overall efficiency of the pump.

The electric energy utilized during the period of operation will be,

$$E = P \times T_a \tag{3}$$

Where,

E = Electric energy utilized in Kilowatt-hour,
T_a = Annual period of operation in hours.

Hence, cost of energy will be,

$$C_e = E \times e_r \tag{4}$$

Where,
C_e = Annual energy cost
e_r = energy cost per Kilowatt-hour.

In case of fuel operated pumps same analysis is followed using the cost of fuel and oil consumption for the operation instead of cost of electric energy.
The maintenance and labor cost are generally computed as a percentage of the initial cost i.e.

$$M = C \times (K/100) \tag{5}$$

Where,
M = Annual maintenance cost,
K = Percentage of maintenance and labor cost.

The total annual cost (C_t) can be obtained by the summing up all annual costs. Finally, the unit cost of groundwater produced can be found by dividing the total annual cost by the number of units of water produced annually i.e.

$$C_t = A + C_e + M \tag{6}$$

And,

$$c = C_t / V_a \tag{7}$$

Where,
c = unit cost of groundwater produced (cost per cubic meter),
V_a = volume of water pumped per year,

$$= Q \times T_a \tag{8}$$

Q = Discharge in m^3/hour.

6. Design Aspects of Tubewells

A well is an intake structure to draw water from the underground reservoir. The well can also be used for disposal of industrial or sewage wastes, artificial recharge, relieving pressures under hydraulic structures, and draining out agricultural lands. A good design of tube-well should aim at efficient utilization of aquifer, long useful life, low initial cost, and low maintenance and operation costs. The main components of the well structure are:

a. **Well Casing:** the pipe used to support the hole during drilling (in cable tool method) or installed afterwards to complete the well assembly.
b. **Intake Portion:** Portion in which the water enters the well from the aquifer. This component requires hydraulic design from various considerations that influence its performance.

After a well is bored, the design procedure of a well involves the following steps (1):

i- Mechanical analysis of samples collected from various depths and preparation of a bore log.

ii- Selection of type of well-naturally or artificially packed.
iii- Determination of depth of housing pipe and its diameter.
iv- Selection of strata to be screened and fixing the length of the screen.
v- Determination of size of gravel for shrouding.
vi- Design of well screen-optimum diameter, length and material of screen.
vii- Selection of pumping set.

The hydraulic properties of the area permits the construction of deep wells of varied design which can harness different discharges ranging from 40 liters per second (lps) to 200 liters per second. The design of wells is worked out taking into account the hydraulic conductivity of the aquifer, total aquifer thickness, screen entrance velocity, total drawdown created in the well during pumping, depth and fluctuations of water table. Beside this, the design aspects are based on the available sizes of housing pipes, screens, standard thickness for each size, available power, and efficiency of pumps.

7. Determination of Production Cost

As mentioned before, the cost of water pumped from the groundwater storage is influenced by the *capital cost* including the cost of tubewell construction which varies with the size of the tubewell determined on the basis of water requirements for the intended use, and the cost of pumping set and its accessories. Whereas the *annual recurrent cost* includes the energy cost, operation and maintenance cost. The analysis of these costs has been carried out using the prevailing rates of labor and materials. The annualized cost is worked out using the capital recovery factor based on the following:

1. Rates of interest (i) used in the analysis are 8%, 10% and 12%.
2. Life of tubewell is 20 years.
3. Pump life is taken as 20000 hours.
4. Annual maintenance charges are taken as 7% of the capital cost.
5. overall efficiency of the pumping set is taken as 60%

Based on the above considerations, the total cost has been calculated and thence the cost of unit volume of water is obtained.

8. Cost Analysis

In order to study the effect of well and aquifer parameters on the production cost of groundwater, well capacities ranging from 40 lps to 200 lps are selected.

Analyses are carried in details for finding the effect of change in the following parameters on the production cost:

a. Running hours,

b. Well diameter,
c. Hydraulic conductivity of the aquifer medium,
d. Storativity of aquifer,
e. Entrance velocity through the screen openings,
f. Static head,

The results of the analysis are given in the following paragraphs.

8.1. Effect of Running Hours

The number of running (*or operating*) hours affects the production cost. As the running hours increase, the running cost increases, and at the same time the volume of water produced also increases. To study the effect of change in running hours on the cost, a number of wells having different capacities are assumed to operate for a different number of hours taken as 1000, 2000, 3000, and 4000 hours per annum. The total cost, volume of water produced, and the unit cost are computed for each case. The results of this are shown in Fig. (1).

8.2. Effect of Well Diameter

To study the effect of change in well diameter on the production cost, the well is designed for different diameters based on the following assumptions:

i. For each diameter, the hydraulic conductivity is taken as 0.033 m/min., which is equal to that of the aquifer under consideration.
ii. For each diameter, the storativity is taken as 0.001, which is equal to that of the aquifer under consideration.
iii. Entrance velocity is taken as 0.02 m./s, and based on this, the length of screen is found using the relationship,

$$L = Q/(\pi \times d \times p \times v) \qquad (10)$$

Where

L = Length of screen in meters,
Q = Discharge of well in m^3/s,
d = Diameter of well in meters,
v = Velocity through the screen opening in m/s,
p = Ratio of effective screen area to the total open area(taken as 0.50)

iv. Static head, taken as 10 meters.
v. Running hours, taken as 3000 hours per year.
vi. As per the practice in the area under consideration, no water bearing strata is tapped within the first 30 meters from the ground level; therefore, the Length of housing pipe is taken as 30 meters. Moreover, it is assumed that for alluvial formations 50% of bore depth is non-water bearing.

Results of the analysis based on the above assumptions are given in Fig. (2) showing the variation of production cost per 1000 m^3 of pumped water, with the variation of well diameter.

8.3. Effect of Depth of Well

The total depth of well is obtained by adding up the lengths of housing pipe, screen, and blind pipe. Different lengths of screen are obtained for each well capacity by changing the diameter of the screen while keeping the entrance velocity constant (taken as 0.02 m/s). For calculating the drawdown, the values of the hydraulic conductivity, storativity, and static head are taken as 0.033m/min, 0.001, and 10 m respectively. Based on the above considerations the total capital cost for constructing the tubewells are obtained, and thereafter the annual fixed cost and running cost are determined. Finally, the unit cost of groundwater is found by using equation (7) based on 3000 working hours. The results are shown in Fig. (2).

8.4. Effect of Transmissibility

The coefficient of transmissibility *T* of an aquifer characterizes the capacity of an aquifer to transmit water through its thickness. This coefficient equals to the product of hydraulic conductivity *K* and the saturated thickness of the aquifer. Change in the value of *T* will change the aquifer loss given by:

$$S_a = \{Q/4\,\pi\,T\}\{\ln(2.25Tt/r^2S)\} \qquad (11)$$

Where

S_a = Aquifer loss in meters,
Q = Discharge in m^3/min,
T = Transmissibility in m/min,
t = Time of Pumping in minutes,
r = Radius of well in meters,
S = Storativity of the aquifer.

Due to change in aquifer loss, the total pumping head in the well, and finally the cost of production from groundwater storage will be affected. To study this effect in details, a number of wells of capacities of 40,70,80,and 100 lps are designed assuming different values of hydraulic conductivity, ranging between 0.005 m/min to 0.04 m/min for 70,80 and 100 lps wells, and between 0.01 to 0.055 for 40 lps well. For each value of K the wells are designed while keeping the following parameters constant:

i. Entrance velocity(taken as 0.02 m/s),
ii. Diameter of screen(taken as 23, 28, 30, and 33cm for 40, 70, 80, and 100 lps wells respectively),
iii. Storartivity (taken as 0.001),
iv. Static head(taken as 10 meters),

Base on these assumptions, the unit cost of groundwater production is found for each value of K and Q based on 3000 annual running hours. The results are shown in Fig. (3).

8.5. Effect of Storativity of the Aquifer

Storativity (or storage coefficient) of an aquifer usually denoted by *S,* is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface (Todd ,(1980)). Change in the value of storativity will change the aquifer loss and hence affects the total drawdown in the well.

To study the effect of this parameter on the production cost, a number of wells having different capacities are designed assuming different values of storativity ranging between 0.00001 to 0.01 while keeping constant the values of hydraulic conductivity, static head, and entrance velocity. The results are shown in Fig. (4).

8.6. Effect of Screen Entrance Velocity

The screen entrance velocity denoted by v, has a significant role in ensuring a long service life of wells. Besides this, it is an important parameter which affects the cost of production of groundwater. Change in the value of entrance velocity will change the length of screen (equation (10)) and hence affects initial and running costs.

To study the effect of this parameter on the production cost, a number of wells having different capacities are designed assuming different values of entrance velocity ranging between 0.005 m/s to 0.04 m/s while keeping constant the values of hydraulic conductivity, static head, and storativity. The results showing this effect are presented in Fig. (5).

8.7. Effect of Static Head

Change in static head will change the total head over which water is pumped from the groundwater storage. This total head affects the running cost as well as the initial cost.

In order to study the effect of this parameter on the production cost, a number of wells having different capacities are designed assuming different values of static head ranging between 0 to 20 m while keeping constant the values of hydraulic conductivity, storativity, and entrance velocity. The results showing this effect are presented in Fig.(6).

9. Results and Discussion

From Fig. (1), it is observed that the unit cost of production decreases with the increase in annual pumping hours. It is also noticed that for capacities higher than 100 lps the plot is almost horizontal i.e. increase in well capacity will not bring significant savings in the unit cost. However, for well capacities less than 60 lps there is a noticeable increase in production cost with the decrease in well capacity.

A perusal of Fig. (2) indicates that for each well capacity there is an optimum diameter with minimum unit cost of pumped water as in the following table,

Well Capacity (lps)	40	70	80	100
Optimum Diameter (cm)	23	25-28	28-30	30-33

From Fig. (3), it is noticed that with the increase in the value of Transmissibility (T), the production cost decreases. It is also seen from the figure that the rate of change decreases with the increase in T.

From Fig. (5), it is observed that with the increase in the value of Storativity (S), the production cost decreases. The decrease in cost is linear on a semi log. scale (the value of S being on the log scale).

From Fig. (6), it is noticed that there is an optimum value of screen entrance velocity (v) which gives the minimum production cost. The values are shown in the following table,

Well Capacity (lps)	40	70	80	100
Optimum Entrance Velocity(m/s)	0.018	0.018	0.018	0.02

The change in entrance velocity affects both the fixed and running cost in a certain manner. Plotting values of v (starting from 0.005 m/s) versus cost, it is seen that the running cost initially decreases with the increase in entrance velocity then starts to increase for values of v greater than 0.01m/s. The fixed cost decreases (with a decaying rate) with the increase in the in the value of entrance velocity.

A perusal of Fig. (7) indicates that the cost of water increases with the increase in static head. The relationship between the unit cost and the depth to water table is nearly linear.

10. Conclusion and Recommendations

1. Large scale development of groundwater calls for optimum design of wells which would concentrate on delivering water with the minimum cost. In order to obtain the optimum design it is essential to carry on cost analysis for a number of wells having different capacities.
2. For each design, it is important to study the effect of change of well and aquifer parameters on the unit cost. By doing this, we can obtain better design with suitable capacity,
3. For further research in well design aspects, it is recommended to study the effect of changing a number of parameters at a time. This may lead to more refinement in the design of wells and reduce the unit cost of pumping from the groundwater storage.

References

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Fig.(1) Variation of Cost with Running Hours and Well Capacity

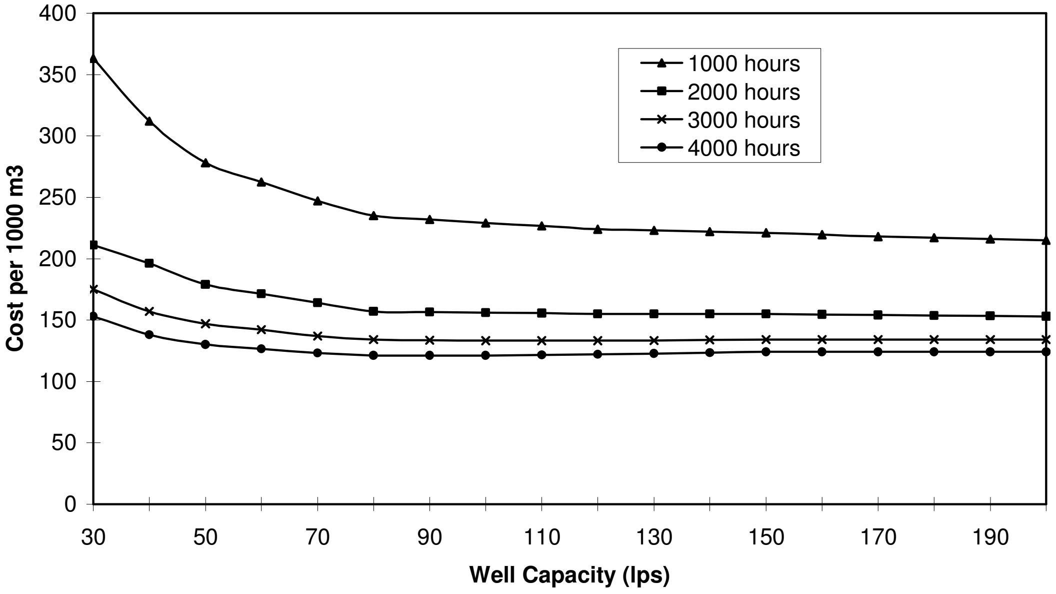

Fig.(2) Variation of Cost with Well Diameter

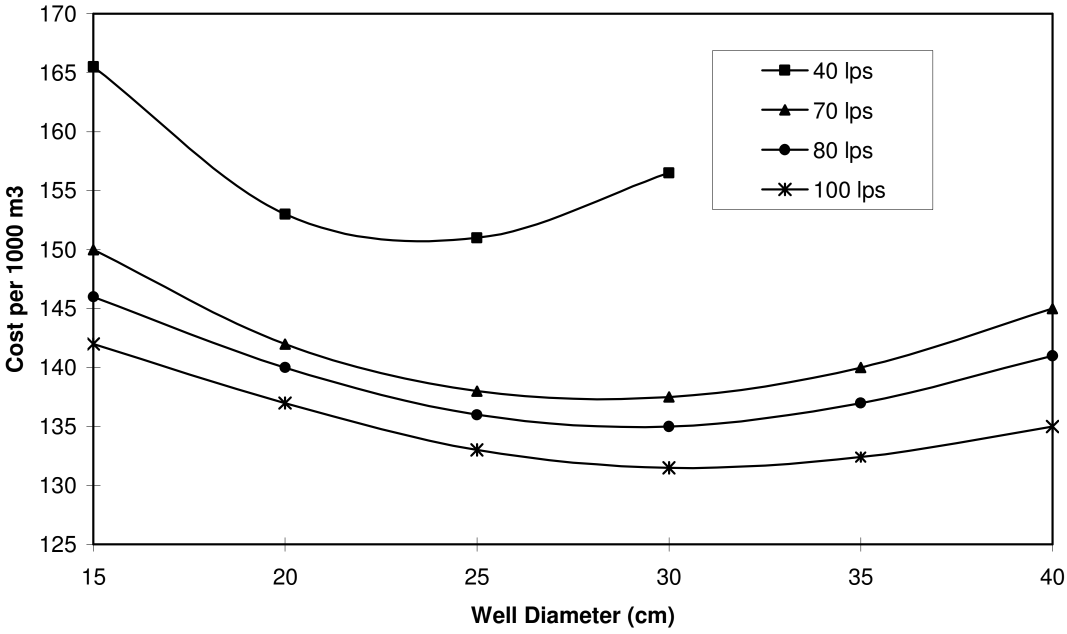

Fig.(3) Variation of Cost with Transmissibility

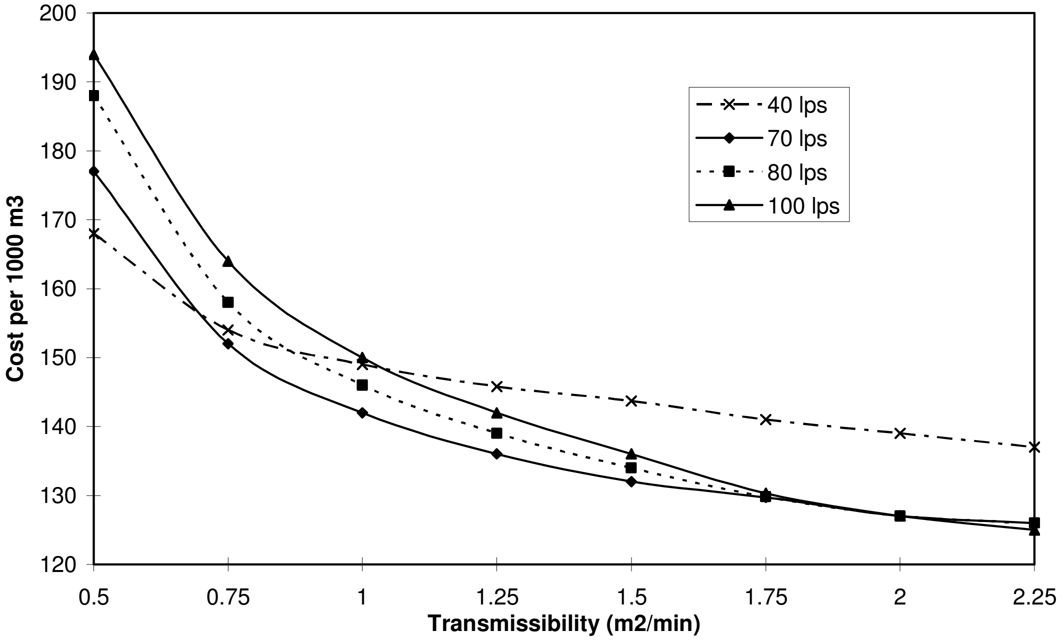

Fig.(4) Variation of Cost with Storativity

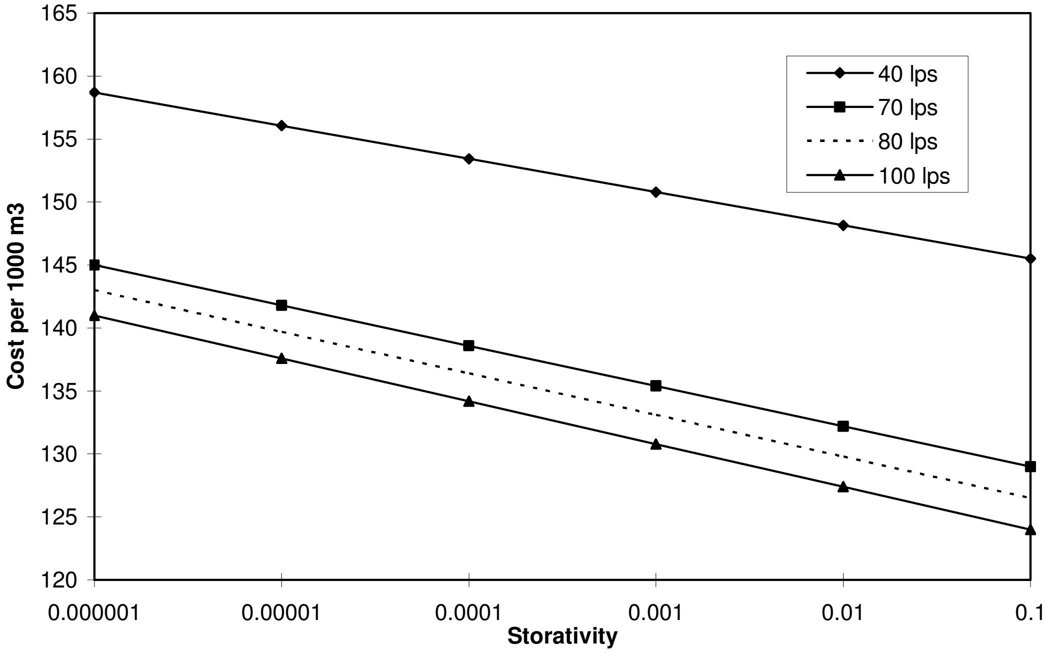

Fig.(5-a) Variation of Cost with Screen Entrance Velocity

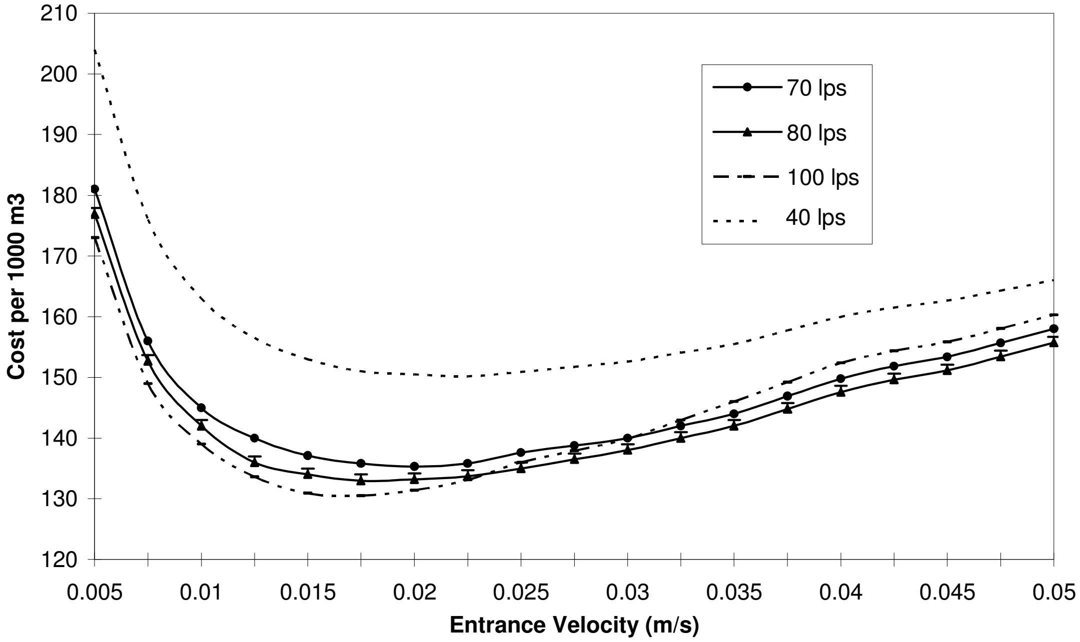

Fig.(5-b) Variation of Cost with Entrance Velocity (Well Capacity 100 lps)

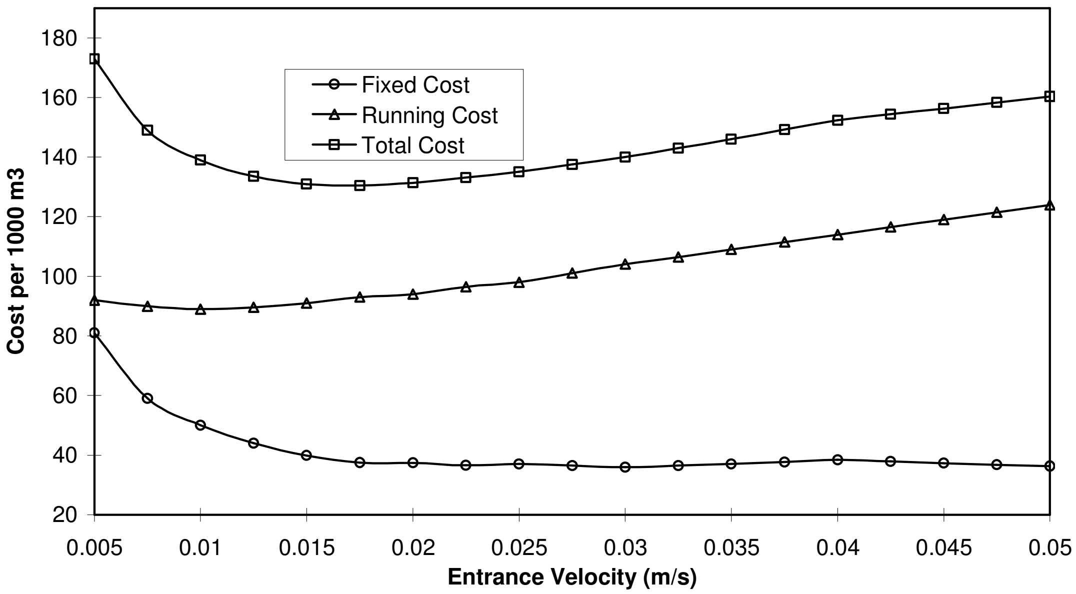

Fig.(6) Variation of Cost with Static Head