PRACTICAL SKIMMING WELL DESIGN

WATER MANAGEMENT TECHNICAL REPORT NO.27

by

F. A. Zuberi

and

D. B. McWhorter

Prepared under support of

United States Agency for International Development

Contract No. AID/CSU

Water Management Research

in Arid and Sub-Humid Lands of the

Less Developed Countries

Colorado State University

Fort Collins, Colorado

CER 73-74 FAZ-BBM 23

F. A. Zuberi and D. B. McWhorter - Practical Skimming Well Design. CUSUSWASH Water Management Technical Paper No. 27. (Fort Collins, Colorado State University) December 4, 1973.

ABSTRACT

Well patterns and designs have been investigated in order to compare the technical performance and costs of several possible skimming facilities. It was established that, for aquifer properties typical in Pakistan, individual skimming wells can be expected to discharge in the range of 0.1 to 0.2 cfs. It is shown that several closely spaced wells can be pumped at a higher total discharge than a single isolated well, even though the individual wells in the battery are discharging at less than capacity. This results from the fact that distributed pumping produces a smaller maximum drawdown than does a single well pumping at the same rate. The discharge obtained by pumping in battery from closely spaced wells (i.e. 10 to 15 feet apart) is approximately 60 percent greater than for a single isolated well. The increased investment for the battery of wells is more than 60 percent higher than for a single well, however.

Costs estimates are contained in the report that indicate a single skimming well will cost approximately Rs. 2200. A typical private tubewell costs approximately Rs. 7000 for comparison. On a per unit discharge basis, the investment in a private tubewell is about Rs. 7000 per cfs and for a skimming well about Rs. 18,000 per cfs. Operating costs for electrically powered skimming wells is estimated to be about 15 percent of the operating cost for a typical private tubewell. On a per acre foot of water pumped, a skimming well will provide water at about Rs. 20 per acre foot compared with a cost of about Rs. 13 per acre foot for a private tubewell.

TABLE OF CONTENTS

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

THE INDUS PLAIN

THe Indus Plain of Pakistan is a vast land mass, about 50 million acres, which has been formed by the filling of a deep rift valley with alluvium brought down by the Indus River and it's tributaries through geologic times. The length of the plain from the Arabian Sea to the foot of the Himalayan Mountains is about 900 miles. The plain is a large flat area with a general slope of one foot per mile from the toe of the mountain to the sea.

CLIMATE

The Indus Plain is an area of scanty precipitation. Practically the whole area receives less than 15 inches of rain per year; the average being 5 inches per year and the lowest about 2 inches per year in some areas. The rainfall in the mountainous and semi-mountainous areas of the north, through which the rivers feeding the Indus Plain flow, is about 30 to 40 inches per year. The Indus Plain is thus semi-arid to arid, and its water wealth lies exclusively in the rivers and streams that flow through it and in the underground water.

Temperatures in the Indus Plain range from mean monthly minima of 40°F during December and January to mean monthly maxima in excess of 100°F during June and July. High summer temperatures exceeding 115°F are also not unusual.

LAND AND SOIL

In general terms the soils of the Indus Plain provide a satisfactory medium for plant growth. The majority of the soils have favourable textures and high potential productivity. Over most of the area they have characteristics favourable for irrigated farming, and even the lighter textured soils have relatively good moisture retention capacity. Soil texture tends to vary from loams to silt clays, with the heavier textured soils becoming more evident in the downstream areas of the doabs. Heavier textured soils are more common in the Southern Indus Plain than in the North. Where fine silts are present, weakly developed soil texture in the top layer (due to a lack of organic material in the soil) results in the formation of a crust which interferes with water infiltration.

There is a serious limitation on production due to the salinity of the soils. This condition arises from the upward capillary movement of moisture which contains salts and the evaporation of this moisture at or near the soil surface. Capillary action of this type is most likely to occur in areas where groundwater levels are high. However, soil salinity can be overcome by proper leaching techniques if the groundwater levels are maintained at a reasonable depth below the land surface and waterlogging is not allowed to occur. With the exception of some areas with alkali surface soils, the internal drainage characteristics of the soils are generally favourable and the aquifer is highly permeable. This means that, in the presence of an adequate drainage system, waterlogging will not present any real problems.

SURFACE WATER

The Indus Basin is served by the mighty Indus and its tributaries, principal of which are Kabul, Jhelum, Chenab, Ravi and Sutlej. The mean annual flow of these rivers is about 170 MAF (million acre feet), but under the Indus Basin Treaty, Pakistan has been allowed only 142 MAF for its use. Generally the flow of the rivers begins to increase in April, culminating in high peaks in July and August after which the flow abruptly declines, reaching a low fairly constant flow from October to April.

When compared with the present average canal head diversions of about 80-85 MAF, the combined mean discharge of 142 MAF available to Pakistan indicates the considerable potential that exists for future surface water conservation.

GROUNDWATER

The Indus Plain is underlain by a huge water bearing aquifer formed by alluvial deposits in a rift valley containing native saline water of the sea. The deep groundwater is highly brackish. In the upper portion, however, the freshwater has accumulated through seepage and deep percolation of water from rainfall, rivers, canals and field application of water for irrigation. This upper layer of fresh water is quite thick near the rivers, which historically are the source of fresh water percolation. But the fresh water lens is only about 100 feet (or less) thick in the center of the Doabs (lands lying between the rivers) where it has built up after the start of weir controlled canal irrigation.

Figure 1-A, taken from reference 1, shows a generalized hydrologic section (with vertical exaggeration of 169 times) along a line A-A' in Rechna Doab, which is typical for the Northern Indus Plain. The dashed lines represent the pre-irrigation water table. The arrows indicate the direction of flow. It can be seen from the cross-section that the thickness of the zone of fresh-water flow decreases along the flow path, from a maximum of about a thousand feet beneath the rivers to a minimum of less than a hundred feet at the low point of the water table.

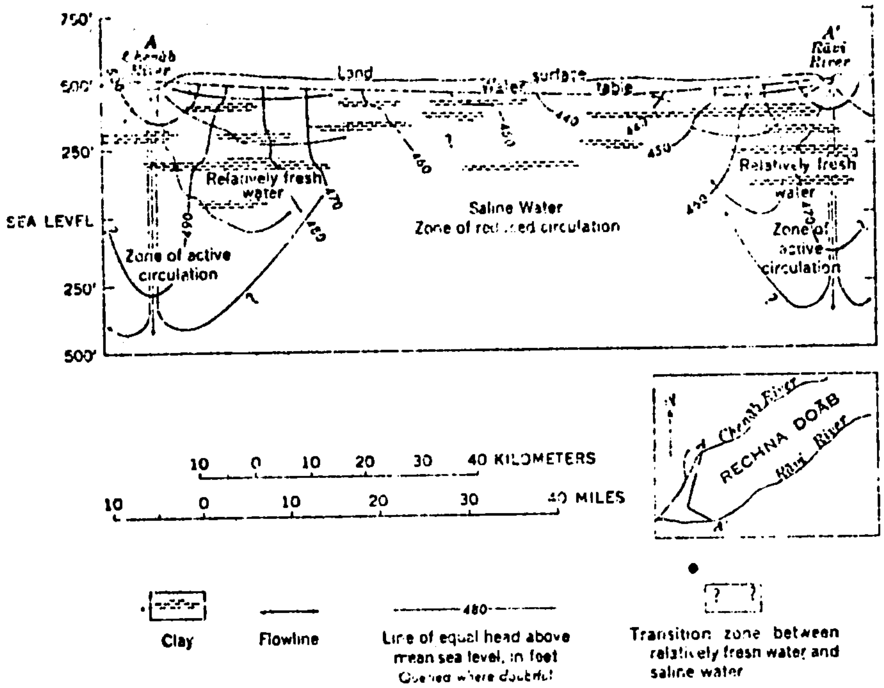


Figure 1A. Hydraulic profile for Rechna Doab for preirrigation period.

The interface between saline and fresh water, however, is not very distinct; the reason being that the two fluids (saline water and fresh water) are miscible and there is not a very large difference in their densities. In fact the two fluids are separated by a zone of dispersion with density decreasing with elevation. However, in this study it has been assumed that the dispersed layer is only a small fraction of the total thickness of the fresh water zone and therefore can be considered for all practical purposes as a boundary surface and has been referred to as an "interface".

Until recently there were no water storage dams in the Indus Basin and, therefore, attempts were made to irrigate large areas by the direct diversion of water from the rivers. Therefore, in terms of the depth of water applied, the supply of irrigation water to the plains is small. Moreover, losses are high from the irrigation system as the canals are unlined and seepage and evaporation rates are high. It has been estimated that 10% of the water diverted from the rivers is lost by evaporation and 30 to 40% by seepage. For 150% cropping intensity the average recharge has been estimated to be 1.5 cusecs per square mile for the northern region and 2 cusecs per square mile for the southern region. The drainable surplus, i.e. the amount of water to be removed annually for tubewell drainage, has been estimated to be 1.3 cusecs per square mile for the Northern Indus Plain and 1.8 cusecs per square mile for the Southern Indus Plain (2).

The quality of groundwater varies considerably throughout the irrigated area and much of it is too saline to be used for irrigation undiluted. On the other hand, the water from the Indus and its tributaries is of low salinity, being generally between 100 and 300 ppm TDS (total dissolved solids). Applying the criteria that water up to 1,000 ppm TDS can be applied directly to the crops without adverse effects and that water of 1,000 to 3,000 ppm TDS can be used after dilution with surface supplies, it has been estimated that out of 29.4 million acres of the irrigated area of the Indus Plain 14.2 million acres are underlain with fresh water, 4.6 million acres with water of intermediate quality, and the rest (10.6 million acres) with saline water (3).

IRRIGATION SYSTEM

Irrigation has been practiced in the Indus Plain since time immemorial. An ingenious, intricate and semi-automatic system of water control has its genesis in intensive cultivation of land supplied with water by the annual floods. The next step in the irrigation development was the construction of innundation canals, which drew water during summer when the rivers rose above the levels of their inlets and irrigated lands which otherwise would not have received water by natural flooding. Then came the canals. These are both perennial (i.e. having year round flow) and non-perennial and are supplied through diversion dams built on the rivers at strategic points. The innundation canals suffered from fluctuating river levels and, therefore, were converted to perennial or non-perennial canals receiving controlled supplies.

Now all the major canal systems receive controlled supplies, and the irrigation system commands a gross area of about 38 million acres, and comprises some thirty-eight thousand miles of canals. The main and link canals headworks are served from two storage dams: Warsak and Mangla (with a third called Tarbela under construction), sixteen barrages and three weirs. The total irrigated area is covered by 42 principal canal commands. The total CCA (Canal Commanded Area) is officially stated to be 33.5 million acres, but in practice about 25 million acres receive surface water supplies (2).

During the year 1965 about 85 MAF of surface water was diverted by the diversion dams and the supplies at watercourse heads were 58 MAF of surface water and 9.7 MAF of groundwater. The area cropped during the same year was 25.5 million acres (3).

WATERLOGGING AND SALINITY

Summer irrigation by means of innundation canals has been practiced in the Indus Plain for a long time. Near the rivers the water tables have always tended to approach the surface, but the configuration of the saturated zone in the alluvium, which over much of the area has a thickness of several hundred feet, was by and large stable. The depth to water table increased with the distance from the river and over a greater part of the Indus Plain groundwater tables were at a considerable depth below the groundwater surface. The infiltration from the rivers and the deep percolation of rainfall and the water supplied in the seasonal innundation irrigation within any particular area was in equilibrium with the discharge of groundwater by evapotranspiration and by movement out of the area toward the sea. This situation existed before the introduction of weir controlled irrigation systems.

As soon as water was brought from rivers by the large weir controlled canals, the dynamic equilibrium between the groundwater recharge and discharge was destroyed. The flow to the sea was not significantly increased because the area is a large flat plane with very little slope. The deep percolation and seepage from canals and from water supplied to the lands for irrigation formed a new increment of recharge which added to the normal recharge from the rivers and precipitation. The increase was greater than the rate at which water could be discharged from the aquifer, As a result, the water table started to build up; the rise varying between 0.5 feet and 2 feet per year.

As the water table rose, more and more land began to be adversely affected. The evaporation of water from the water table resulted in a steadily increasing accumulation of salts in the root zone of the crops. Because the application of water was not sufficient to leach down the salts, an environment was created which accelerated the salinization of lands.

The potential recharge of the groundwater reservoir in the canal irrigated areas has been estimated to be 49 MAF per year of which 34 MAF occurs in the areas where the underlying groundwater is of fresh and intermediate quality and 15 MAF in areas where the deep groundwater is saline (2). It has further been estimated that out of 27.6 million acres commanded by the canals (excluding the Peshawar Vale), 12.3 million acres are affected by waterlogging in different degrees and have water tables at a depth of less than 10 feet from the ground surface (3).

NEED FOR SKIMMING WELLS

As described previously the irrigated area of the Indus Plain can be divided into three zones on the basis of the quality of the underlying groundwater.

TABLE 1-A

Ground water Quality Zone	TDS of Deep Groundwater	Acres (million acres)
Fresh Water Zone	< 1,000 ppm	14.2
Intermediate Zone	1,000 - 3,000[1]ppm	4.6
Sub-total		18.8
Saline Zone	> 3,000[1]ppm	10.6[2]
Total		29.4

[1] A lower limit of 2,000 ppm TDS has been used for Lower Indus Region as it will receive more saline surface supplies.
[2] Out of this area only 7.5 million acres has aquifer suitable for well drainage.

The quality of deep groundwater and the area of each zone is given in Table 1-A which is taken from reference 2.

Even in the saline zones where the deep groundwater is highly brackish, the upper layer of water which has accumulated due to seepage from the irrigation system, etc. is of good quality and the same can be used for irrigation purposes. However, this upper layer of fresh water is only about 100 feet (or less) thick.

When a well in such an aquifer is pumped, the reduced head toward the well causes an upconing or mounding of the fresh-salt water interface under the well and eventually the well begins to draw the lowlying saline water, unless special care is taken in the design of the well and the rate of pumping. THe wells that are used for obtaining only fresh water in such situations are called Skimming Wells, as they are used to "skim" the fresh water from above the saline water with a minimum of mixing, either within the well or within the aquifer.

Skimming wells not only provide water for irrigation but do it in such a fashion that the mixing of fresh and saline waters in the aquifer is minimized. If the upper fresh water and the lowlying highly mineralized water are allowed to mix, the entire aquifer will eventually be ruined in terms of the quality of water.

The purpose of this report is to show how skimming wells can be utilized for irrigation purposes in the Indus Plain and other similar situations and to suggest practical designs for the same such that a most economic design can be selected for a particular area under the particular conditions. Different designs and patterns for skimming wells have been considered in this report and the cost of water obtained from each has been compared for the purpose of selection of an economic design.

CHAPTER II

DESIGN OBJECTIVES AND CONSTRAINTS

OBJECTIVES

For the purpose of exploiting the groundwater resource for agricultural use, it is necessary that water of acceptable quality be obtained at minimum cost. However, this should be done in such a fashion that the groundwater resource is neither exhausted nor ruined for future use, because it is a critically important resource in arid and semi-arid regions. Therefore the potential and limitations for development of the groundwater aquifer should be fully considered.

The safe yield of a groundwater basin is the amount of water that can be withdrawn annually without producing an undesirable result. The undesirable result can be depletion or complete extinction of the storage due to overdraft or degradation of water quality such that it no longer remains useful.

In the conditions that prevail in the Indus Basin, the various experts have always recommended a cautious approach in the development of groundwater, and have pointed out the importance of maintaining a favourable salt balance in the groundwater supply as pumpage on a large scale will create changes in the present hydrologic environment which in turn will influence the relationships of the quality of water in the aquifer. Several inherent factors in the tubewell system may tend to depreciate the quality of the groundwater in time (1). These are:

1. The leaching of the soil surface which will occur when full irrigation supplies are available will add appreciable amounts of salts to groundwater storage.
2. Reduction in volume of groundwater storage that will occur in

response to pumping will cause a proportional increase in the mineral concentration of the groundwater. As in the cycle of recirculation of water from the aquifer to the irrigated field and back to the aquifer, most of the salts will remain in solution where as most of the water will be lost to evaporation.

3. There will be an annual increment of salt derived from the surface irrigation supplies which will be transported down to the water table.
4. Chemical reaction between the percolating recharge water and the unwatered sediments will bring more salts into solution.

In the presence of so many factors which will tend to depreciate the quality of groundwater it would be unwise to allow mixing of saline and fresh waters in the aquifer.

In order to maintain the continuous availability of groundwater at acceptable standards of quality and at reasonable cost, the withdrawals should be limited by considerations of recharge, depth to the water table and the possibility of mixing fresh and saline waters. The major objective of the design of skimming wells is to obtain the maximum amount of fresh water at the least cost, while minimizing the water quality deterioration due to mixing.

CONSTRAINT IMPOSED BY SALT WATER MOUNDING

When a well, partially penetrating an aquifer containing fresh water overlying saline water, is pumped the reduced head near the well causes the underlying salt water to rise in the form of a cone in response to pumping; the apex of the cone being directly beneath the well. Under steady-state conditions the cone rises until its apex reaches a certain height depending on the drawdown in the well. However, in every field situation there is a drawdown at which the highest stable cone can occur. This drawdown is called the critical drawdown, and the discharge obtained from the well at critical drawdown is called critical discharge.

If the discharge of the well is less than the critical discharge, the brine cone will eventually reach a static condition provided the aquifer is large and the rate of discharge is steady. However, if the well is pumped too hard i.e. at a rate greater than the critical discharge, the cone becomes unstable. As a result the cone keeps rising and eventually the well starts to produce saline water. It is evident from the above description that deep, large capacity wells can not be employed for skimming fresh water from such aquifers when the fresh water layer is thin.

OTHER PHYSICAL CONSTRAINTS

Besides the above technical constraints on the installation of wells, other constraints such as the availability of construction material, including well casing pipe, strainers, pumps, motors, bricks, etc., have also to be taken into account. Private tubewells are very common in the Indus Plain and technical know-how for their installation is available even in remote areas. Besides the government agencies which install tubewells for the private owners, private companies also have been established. The construction material commonly used for private tubewells is mild steel casing pipe, jute or coir string wound - mild steel mesh strainers, horizontal type centrifugal pumps and electric or diesel motors. The string strainers have not been used for high capacity wells, but have been found to give satisfactory performance for wells of discharges of 2 cfs (cubic feet per second) and less. Both mild steel pipes and string strainers are made in Pakistan.

Centrifugal pumps up to 16 horsepower and electric motors for these pumps are also manufactured in Pakistan. Deepwell vertical turbine pumps of high capacities and fiber-glass casings and strainers, however, are not manufactured in Pakistan.

It is desirable that the design adopted for skimming wells will use materials manufactured in Pakistan. This will result in the establishment of more manufacturing industries and thus help in providing a sound industrial base for the country and at the same time provide jobs for the local population. Secondly, it will result in the saving of precious foreign exchange which will be utilized for other needs.

FINANCIAL CONSTRAINTS

Cost of construction and availability of funds are important constraints for the execution of any project. If the wells to be installed for irrigation are of small capacity and do not involve a great expenditure, the farmers will be able to get them installed at their own expense. However, if the cost is high, the farmers can not afford to install the wells at their own expense.

Financial constraints can be minimized by recommending a design which utilizes the farmers personal labor and skills to a maximum degree. The actual cost of construction to the farmer will only be that part of the job which he can not perform by himself, and the cost of the materials for construction. This factor should therefore be given full consideration in selecting the design of wells, and those designs which require more unskilled labor should be preferred over those which are equal in cost and technical performance otherwise.

OTHER FACTORS

Employment opportunities is another aspect which should be given consideration in the selection of well design. The design which will create more employment opportunities should be preferred over those which will not create employment opportunities for the local population. Designs which emphasize imported material and require technical personnel for construction and supervision should, therefore, not be adopted.

If those designs which use locally manufactured material are adopted, it will not only provide more job opportunities but will also provide an incentive to local production industry which will become established in time and will help provide a sound industrial base for the country.

Further, existing facilities and resources available in the area, such as the labor force and local technical talent, should be used extensively in any development project. Similarly, local customs and traditions should be given full consideration. The design that meets these standards will be more acceptable to the people and the farmers who are eventually going to utilize the facility.

CHAPTER III

BASIS FOR DESIGN

MATHEMATICAL EQUATION

The Indus Plain lies in semi-arid and arid zones. Water for irrigation is applied infrequently and rainfall is also infrequent. It is, therefore, not possible to construct wells in the Indus Plain which will hold the water table at a constant elevation, and recourse has to be made to unsteady-state solutions for the design of well systems and also for calculating the rise of the fresh-salt water interface. The optimum operation of skimming wells must certainly depend on the rate of upconing as effected by well discharge.

Unfortunately, solutions describing the unsteady rise of fresh-salt water interface are few. Recently, McWhorter (6) has published a paper in which he has derived an approximate differential equation describing the behavior of fresh-salt water interface in response to pumping. The equation derived is

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} = \alpha \cdot \frac{\partial\psi}{\partial t} \qquad (1)$$

where $\alpha = \frac{\gamma_f \, S_y}{\Delta\gamma \cdot K_f \cdot \sqrt{\bar{\psi}}}$ $\quad TL^{-2}$ $\quad$ (2)

and $\psi = \{ \frac{m}{(1+\frac{\Delta\gamma}{\gamma_f})} - \xi \}^2$ $\quad L^2$ $\quad$ (3)

$\bar{\psi}$ = estimated weighted average of ψ

$= \{ \frac{m+(m-\xi)}{2} \}^2 = \{ \frac{2m-\xi}{2} \}^2$ $\quad L^2$

t = time after the start of pumping $\quad T$

γ_f = specific weight of fresh water $\quad ML^{-3}$

$\Delta\gamma$ = difference in specific weights of fresh and saline waters ML^{-3}

S_y = specific yield of the aquifer none

K_f = permeability of the aquifer LT^{-1}

m = thickness of freshwater zone L

ξ = interface elevation relative to original position - L

A large number of solutions to the above differential equation for various initial and boundary conditions are available in the literature.

Equation 1 was derived by assuming that a distinct and abrupt interface exists between the fresh water and the underlying saline water. Furthermore it was assumed that the effect of flow in the saline zone on the distribution of head on the interface is negligibly small, and the Ghyben-Herzberg approximation applies. In order to write the factor α in equation 1 as a constant, it was necessary to introduce $\bar{\psi}$, an estimated weighted average of ψ which varies in both time and space.

McWhorter's equation describes the time and spatial variation of ψ from which the value of ξ , the interface elevation, can be obtained. However, it does not predict any value of critical drawdown or critical rise of the cone after which the well will start to produce saline water. Further, as pointed out by McWhorter, his equation is untested at present and the magnitude of the error incurred by its application is not known. Therefore, an attempt has been made in this paper to establish the validity of this equation by applying it for the analysis of situations which have already been analyzed by other known methods and then comparing the results of the two analyses. It was found that McWhorter's equation can be used for the analysis of many practical engineering problems such as obtaining the solution to problems of distributed pumping, well interference, wells pumping near constant head boundaries and control of the lateral movement of saline water.

OPTIMUM PENETRATION

When a partially penetrating well in an aquifer containing fresh water overlying saline water is pumped, the saline water rises in the form of a cone in response to pumping; the apex of the cone being directly below the well. Under steady-state conditions the cone rises until its apex reaches a certain height, depending on the drawdown in the well. However, in every field situation there is a drawdown and the maximum rise of the cone which is called critical. If the drawdown exceeds this value the cone becomes unstable. As a result the cone keeps rising and eventually the well starts to produce saline water. Regardless of the well geometry and the aquifer and fluid properties, the highest stable cone never rises as high as the bottom of the well screen (5).

Recently, Sahni (5) studied the salt water coning beneath fresh water wells by means of an experimental model, and he developed a mathematical model for predicting the position of the cone in different situations. His results show that the critical discharge, i.e. the maximum discharge that can be obtained from the well before the cone becomes unstable, rapidly increases as penetration decreases, especially at shallow penetrations. The relationship between dimensionless critical discharge and well penetration presented by Sahni shows maxima in the neighborhood of 10 to 20% penetration.

This is an important discovery as Wang (7) had shown that maximum critical discharge is obtained at penetrations in the range of 30 to 40% . However, there are quite a few restrictive assumptions in Wang's analysis, while the results of Sahni's mathematical model agree with his experimental results.

Penetrations of 10 to 20% have therefore been adopted for the design of skimming wells.

CRITICAL CONE HEIGHT

The earliest work on coning under the wells seems to have been done by Muskat (8). Muskat defines the elevation of instability or the zone of accelerated rise for $\xi/d > 0.48$, where ξ is the elevation of the cone and d is the distance between the bottom of the well and the original position of the interface, and the critical elevation within the limits of ξ/d equal to 0.6-0.75 .

As reported by Schmorak and Mercado (9), the model experiments of Bear and Dagan (1964) show that for values of ξ/d greater than one-third to one-half, the rate of rise of the cone is accelerated and above a certain critical rise, it reaches the bottom of the pumping well with a sudden jump. The field experiments of Schmorak and Mercado (9) show that the critical rise of the cone is rather constant and lies between 0.4 and 0.6 .

McWhorter (6) has suggested that, from the considerations of a factor of safety, the salt water interface should not be allowed to rise above one-half the distance between the original interface position and the bottom of the well. This seems to be a reasonable criterion considering the findings of Muskat, Bear and Dagan, and Schmorak and Mercado as reported above and has therefore been adopted for this study.

TEST FOR VALIDITY

McWhorter's unsteady-state equation can be written in the radial coordinates as

$$\frac{\partial^2\psi}{\partial r^2} + \frac{1}{\ } \frac{\partial\psi}{\partial r} = \alpha \cdot \frac{\partial\psi}{\partial t} \tag{4}$$

A large number of solutions to the above equation for various initial and boundary conditions are available in the literature.

The solution of the above equation for the initial and boundary conditions

$$\lim_{r \to o} \; r \frac{\partial\psi}{\partial r} = \frac{Q}{\pi \frac{\Delta\gamma}{\gamma_f} (1+\frac{\Delta\gamma}{\gamma_f}) K_f}$$

$$\psi(\infty,t) = \{ \frac{m}{(1+\frac{\Delta\gamma}{\gamma_f})} \}^2 = \psi_\infty$$

$$\psi(r,o) = \{ \frac{m}{(1+\frac{\Delta\gamma}{\gamma_f})} \}^2 = \psi_\infty$$

where Q is the discharge of the well, is presented by McWhorter (6) as,

$$\psi = \psi_\infty - \frac{Q}{2\pi \frac{\Delta\gamma}{\gamma_f} (1+\frac{\Delta\gamma}{\gamma_f}) K_f} W(u) \tag{5}$$

$$= \psi_\infty - k\,Q\,W(u) \tag{6}$$

where

$$W(u) = \int_{\frac{r^2\alpha}{4t}}^{\infty} \frac{e^{-u}}{u} du \tag{7}$$

$$k = 1/2\pi \frac{\Delta\gamma}{\gamma_f} (1+\frac{\Delta\gamma}{\gamma_f}) K_f \tag{8}$$

The function W(u) is the exponential integral which is tabulated in several standard mathematical tables.

The above solution in ψ (equation 5 above) describes the time and spatial variation of ψ to the interface elevation as given by equation 3.

An attempt was made to establish the validity of equation 4 by comparing the solution (equation 5) with the results obtained by Sahni (5) experimentally. The pertinent system parameters for Sahni's steady-state experiment are:

γ_f = 0.755 gm/cc

$\Delta\gamma$ = 0.245 gm/cc

$r\omega$ = 2.38 cm

K_f = 2.6 cm/sec

S_y = 0.35

Strictly speaking, equation 5 (or equation 6) does not reduce to a steady-state equation at large times. The distribution of ψ at approximately a steady-state can be deduced, however, by expanding W(u) as a series and introducing the Taylor-Rainville criteria.

Equation 6 is

$$\psi = \psi_\infty - k\,Q\,W(u)$$

where

$$W(u) = \int_{\frac{r^2\alpha}{4t}}^{\infty} \frac{e^{-u}}{u}\,du = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \cdots\cdots$$

where $u = \dfrac{r^2\alpha}{4t}$.

We see that $u \to o$ as t gets large. In such a situation the series expansion can be closely approximated by the first three terms. Therefore, for two observation wells at radii r_1 and r_2 ,

$$\psi_1 = \psi_\infty - k\,Q\,W(u_1)$$

$$\psi_2 = \psi_\infty - k\,Q\,W(u_2)$$

subtracting

$$\frac{\psi_2-\psi_1}{k\ Q} = W(u_1) - W(u_2)$$

$$= -0.5772 - \ln u_1 + u_1 + 0.5772 + \ln u_2 - u_2$$

$$= \ln\left(\frac{u_2}{u_1}\right) + (u_1 - u_2)$$

$$= \ln\left(\frac{r_2^2\alpha}{4t} / \frac{r_1^2\alpha}{4t}\right) + \left(\frac{r_1^2\alpha}{4t} - \frac{r_2^2\alpha}{4t}\right)$$

$$= \ln\left(\frac{r_2^2}{r_1^2}\right) + \left(\frac{r_1^2\alpha}{4t} - \frac{r_2^2\alpha}{4t}\right)$$

$$= 2\ln\left(\frac{r_2}{r_1}\right) + \left(\frac{r_1^2\alpha}{4t} - \frac{r_2^2\alpha}{4t}\right)$$

or
$$\frac{\psi_2-\psi_1}{2k\ Q} = \ln\left(\frac{r_2}{r_1}\right) + \tfrac{1}{2}\left(\frac{r_1^2\alpha}{4t} - \frac{r_2^2\alpha}{4t}\right)$$

For t sufficiently large,

$$\frac{\psi_2-\psi_1}{2k\ Q} = \ln\left(\frac{r_2}{r_1}\right)$$

Therefore, the criterion for approximate steady-state used in this work is that the term $\tfrac{1}{2}\left(\frac{r_1^2\alpha}{4t} - \frac{r_2^2\alpha}{4t}\right)$ be less than 1% of $\ln(r_2/r_1)$. The time at which the conditions can be assumed to be steady is obtained from:

$$\tfrac{1}{2}\left\{\frac{r_2^2\alpha}{4t} - \frac{r_1^2\alpha}{4t}\right\} = \frac{1}{100}\ln\left(\frac{r_2}{r_1}\right)$$

or
$$\frac{1}{8t}\{\alpha\ (r_2^2 - r_1^2)\} = \frac{1}{100}\ln\left(\frac{r_2}{r_1}\right)$$

or
$$t = \frac{100\ \alpha\ (r_2^2 - r_1^2)}{8\ln(r_2/r_1)}$$

or $$t = \frac{12.5\ \alpha\ (r_2^2 - r_1^2)}{8 \ln\ (r_2/r_1)} \qquad (9)$$

The above equation gives the time at which the solution to the transient problem approximates the steady case. Discharges at various cone heights were computed from equation 5 at the time computed from equation 9 for the conditions in Sahni's steady-state experiments. The measured and computed discharges are compared in Table 3A. It is seen from the table that the discharges obtained by the unsteady-state equation are about 27% less than that obtained in the experiment. It means the results obtained by use of the unsteady-state equation are conservative and can be used with confidence.

Discharges computed by the unsteady-state equation and Muskat's formula for the same cone height show that Muskat's formula predicts discharges 43% higher than the unsteady-state equation. Similarly, discharges obtained from the unsteady-state equation and Wang's formula for the same cone height show that Wang's formula predicts discharges 47% higher than the unsteady-state equation.

TABLE 3A

Case #	m (cm)	d (cm)	% Penetration	ξ^1 (cm)	$Q_E{}^2$ (cc/sec)	Q^3 (cc/sec)	Q_E-Q	% of Q_E
1	24.90	18.50	74.3	6.10	180	137	43	23.9
2	24.90	15.81	63.5	8.45	254	175	79	31.1
3	24.90	14.14	56.8	9.74	276	193	83	30.1
4	24.90	11.21	45.0	11.30	295	212	83	28.1
5	25.50	13.80	54.1	9.90	276	208	68	24.7
6	26.00	17.16	66.0	7.50	223	170	53	23.8

Average = 26.9

[1] Coning obtained in Sahni's experiment and also used in McWhorter equation.

[2] Discharge obtained in Sahni's experiment.

[3] Discharge obtained by McWhorter equation.

CHAPTER IV

INVESTIGATION OF DESIGN ALTERNATIVES

EFFECT OF DIFFERENT PATTERNS AND WELL SPACING

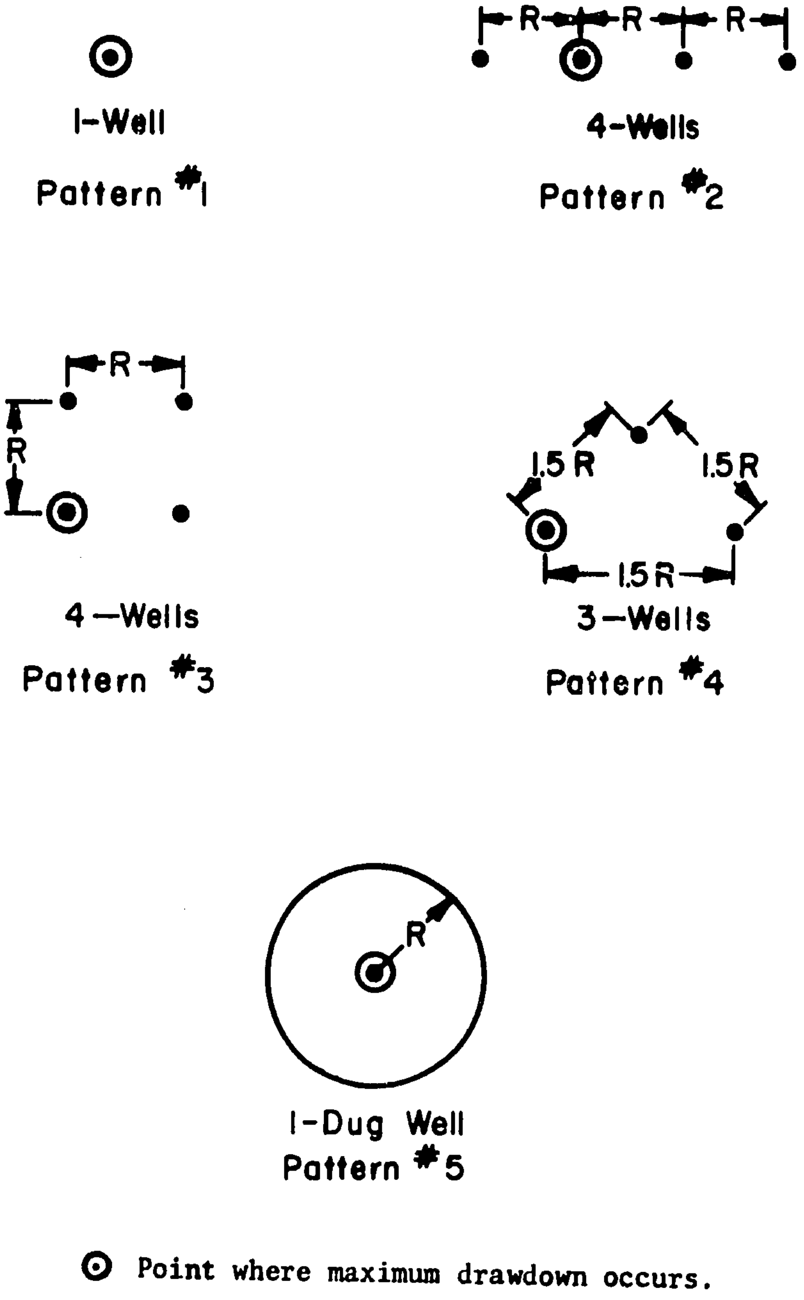
It is clear from the nature of saline water coning that although coning is not directly proportional to drawdown, nevertheless, smaller mounding occurs for smaller drawdown and greater mounding occurs for greater drawdown. This leads us to the conclusion that if we want to limit the coning we will have to limit the drawdown.

The principle of superposition of potentials tells us that if we have two wells in the same field, each pumping half the discharge that we could obtain from a single well, the total discharge in the two cases will remain the same, but the drawdown at each well obtained for the two well system will be less than what it was for one well. This leads us to the conclusion that if we employ a combination of wells to obtain the same discharge as is obtained from one well, the mounding of the saline water will be less for the combination of wells than it is for a single well. Similarly if we keep the mounding the same for the two cases, we will be able to obtain greater discharge for a combination of wells than from one well.

It is proposed, therefore, to study the production of fresh water from a number of possible patterns of the combination of wells in a given fresh water aquifer underlain by saline water. The following possible patterns are studied:

Pattern #1: One well only, pumping at a great distance from other wells.

Pattern #2: Four wells in a row, at a distance of R feet from one another.



1-Well
Pattern #1

4-Wells
Pattern #2

4 —Wells
Pattern #3

3 —Wells
Pattern #4

1-Dug Well
Pattern #5

⊙ Point where maximum drawdown occurs.

Figure 4A.

Pattern #3: Four wells in a square pattern, side of the square being R feet.

Pattern #4: Three wells in a triangular pattern, side of the triangle being 1.5 R feet.

Pattern #5: One big diameter dug well, diameter of the well being R feet.

The following values of the aquifer constants and other variables have been used for the purpose of these calculations:

$\gamma_f = 1.00$ gm/cc   Penetration $d = 20$ ft., for single wells
$\gamma_b = 1.02$ gm/cc $= 15$ ft., for combination of wells and dug wells.
$\Delta\gamma = 0.02$ gm/cc
$m = 100$ feet $K_f = 0.003$ ft/sec
$S_y = 0.14$
$t = 5$ years

From the above we can calculate the following:

$$k = \frac{1}{2\pi \frac{\Delta\gamma}{\gamma_f}\left(1+\frac{\Delta\gamma}{\gamma_f}\right)K_f}$$

$$= \frac{1}{2\pi\cdot\frac{1}{50}\cdot\frac{51}{50}\cdot 0.003} = \frac{50\cdot 50}{2\pi\cdot 51\cdot 0.003} = 2.601\ \frac{\text{sec}}{\text{ft}}$$

$$\sqrt{\psi_\infty} = \frac{m}{1+\frac{\Delta\gamma}{\gamma_f}} = \frac{100}{51/50} = 98.04\ \text{ft.}$$

$$\psi_\infty = (98.04)^2 = 9{,}611.84\ \text{ft}^2$$

TABLE 4A

EFFECT OF PATTERN AND WELL SPACING

Pattern #	R(ft)	$r\omega$(ft)	d(ft)	ξ(ft)	$\sqrt{\psi_{r\omega}}$[1](ft)	$\psi_\infty - \psi_\omega$	$\Sigma W(u)$[2]	Q[3](cfs)	Total Q (cfs)
1	0	0.25	20	40	58.04	6,243.20	19.08	0.126	0.126
2	0	0.25	20	40	58.04	6,243.20	19.08	0.126	0.126
	5	0.25	15	42.5	55.54	6,527.15	56.95	0.0441	0.176
	10	0.25	15	42.5	55.54	6,527.15	52.75	0.0476	0.190
	15	0.25	15	42.5	55.54	6,527.15	50.33	0.0499	0.200
3	0	0.25	20	40	58.04	6,243.20	19.08	0.126	0.126
	5	0.25	15	42.5	55.54	6,527.15	57.65	0.0435	0.174
	10	0.25	15	42.5	55.54	6,527.15	53.44	0.0470	0.188
	15	0.25	15	42.5	55.54	6,527.15	51.03	0.0492	0.197
4	0	0.25	20	40	58.04	6,243.20	19.08	0.126	0.126
	7.5	0.25	15	42.5	55.54	6,527.15	43.60	0.0570	0.173
	15.0	0.25	15	42.5	55.54	6,527.15	40.84	0.0614	0.184
	22.5	0.25	15	42.5	55.54	6,527.15	39.20	0.0640	0.192
5	3.0	1.5	15	42.5	55.54	6,527.15	15.49	0.1620	0.162
	5.0	2.5	15	42.5	55.54	6,527.15	14.46	0.1735	0.174
	8.0	4.0	15	42.5	55.54	6,527.15	13.52	0.1856	0.186
	10.0	5.0	15	42.5	55.54	6,527.15	13.10	0.1916	0.192

[1] $\sqrt{\psi_{r\omega}} = \sqrt{\psi_\infty} - \xi$

[2] $\alpha = \dfrac{\gamma_f \, S_y}{\Delta\gamma \cdot K_f \cdot \sqrt{\psi_f}}$, $u = \dfrac{r^2\alpha}{4t}$

$\Sigma W(u)$ = Summation of W(u) for all wells of the pattern at the point of maximum drawdown shown as ⊙ in figure 4A.

[3] $Q = \dfrac{\psi_\infty - \psi_{r\omega}}{k \, W(u)}$

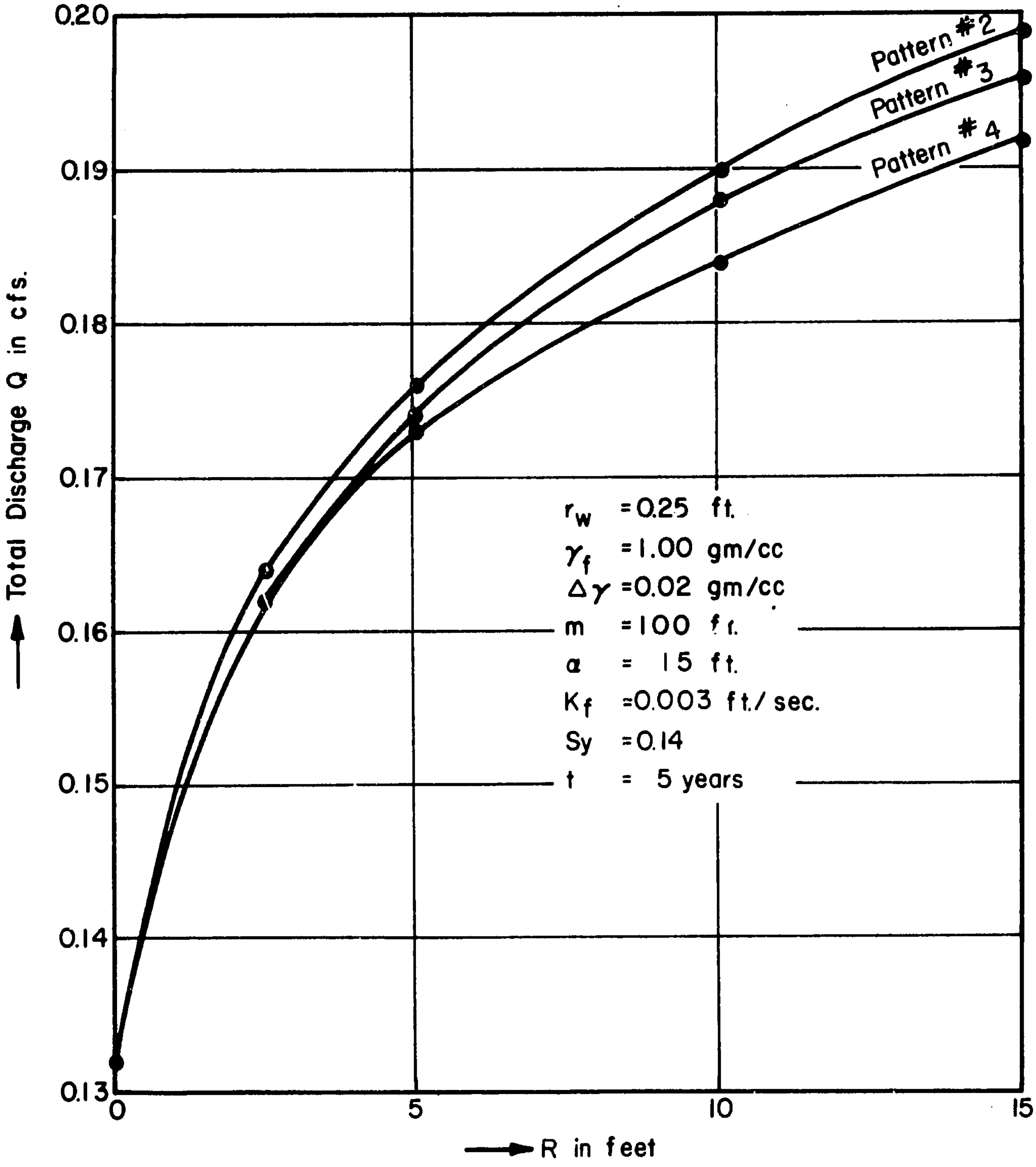


Figure 4B. Variation of Discharge With Pattern and R .

Sketches of the different patterns studied are given in figure 4A. Calculations for the maximum fresh water discharges that can be obtained from each pattern for different spacings are presented in Table 4A, and the results have been plotted in figure 4B.

It is clear from Table 4A and figure 4B that greater discharge can be obtained as the value of R , the distance between the wells or the diameter of the dug well, is increased. Since discharges obtained from individual tubewells are very small, it will be economical to pump several wells by one centrifugal pump. This imposes a practical limit on the distance at which the wells in patterns #2,3 and 4 can be located. The distance between the wells should be such that the net positive suction head requirement of the pump is met. However, as this is only a comparative study, distance between wells R has been taken equal to 5 feet for patterns #2 and 3 and 7.5 feet for pattern #4. It will be noted that these different values have been assumed because only then the length of the connecting pipe for the different patterns shall be equal and, therefore, approximately the same losses will occur in the different patterns.

EFFECT OF WELL DIAMETER

Figure 4C shows that for any penetration of the well, the discharge increases as the diameter of the well is increased. This increase in discharge is very sharp for small diameters. For a penetration of 20%, the discharge increases from 0.126 cfs to 0.183 cfs i.e. an increase of about 45% , when the diameter of the well is increased from 0.5 feet to 10 feet . If the diameter is now increased from 10 feet to 20 feet, the increase in discharge is from 0.183 cfs to 0.205 cfs , a rise of about 12%. Further increase in the diameter of the well from

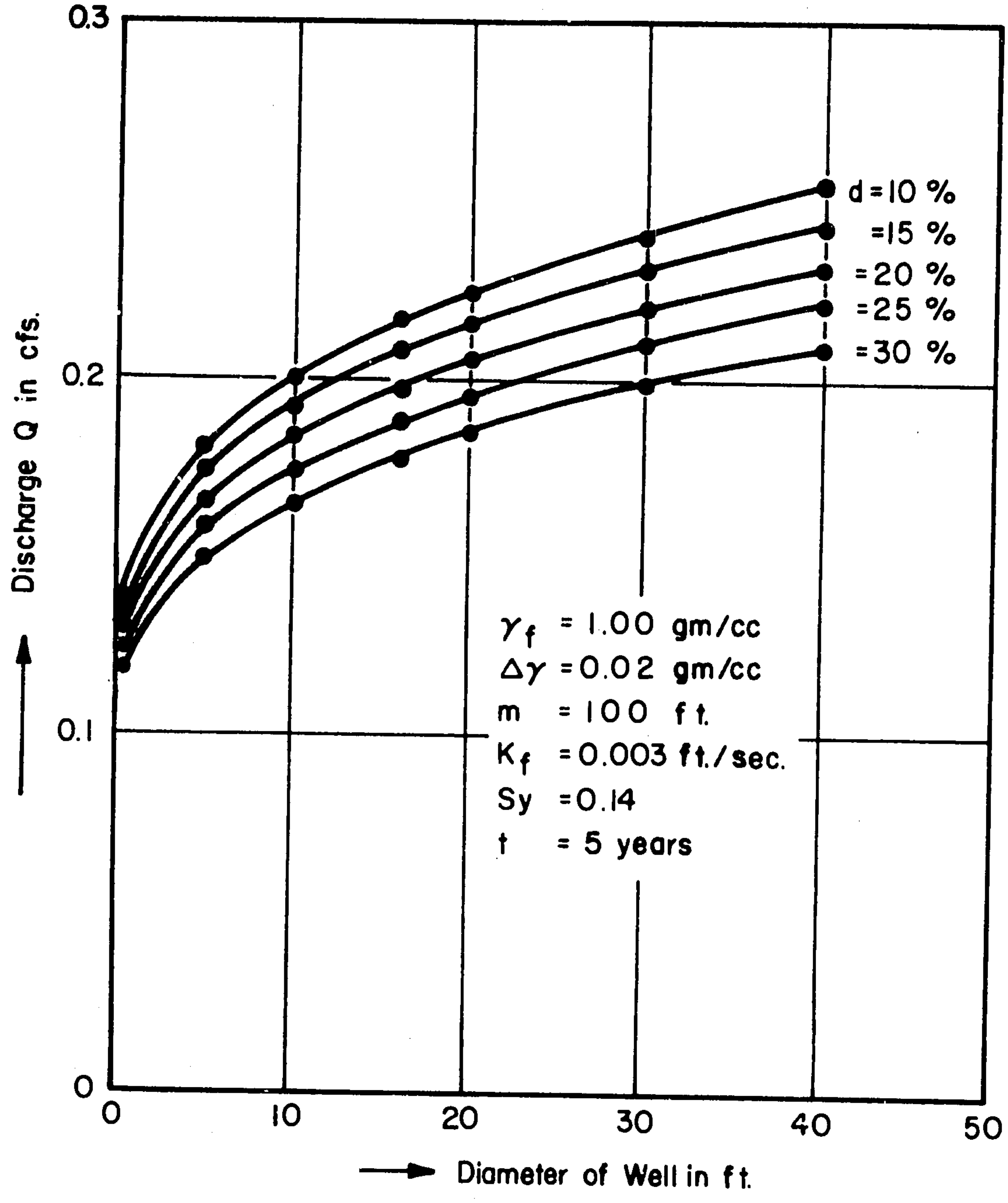


Figure 4C. Variation of Discharge With Diameter and Penetration.

20 feet to 30 feet will increase the discharge from 0.205 to 0.220 cfs i.e. an increase of about 7.3% only.

CHAPTER V

WELL CONSTRUCTION AND COST

Several possible patterns in which the wells can be installed for skimming fresh water from an aquifer underlain with saline water have been discussed in the previous chapter. The adoption of any of these patterns in the field will depend on many other considerations such as:

1. Cost of water pumped.
2. Availability of funds.
3. Source and availability of construction material.

Besides the above economic factors, social aspects should also be given full consideration. Social factors which need to be considered in this connection are:

1. Existing traditions and facilities.
2. Impact on local employment level.

All the above factors as they influence the selection of well design are discussed below.

COST OF WATER PUMPED

Cost of the water pumped is probably the most important consideration in selecting any of the skimming methods.

Figures 5A and 5B give the designs of skimming tubewells which can be adopted for the purpose. In selecting the design full consideration has been given to the availability of technical know-how at places remote from the cities and to the existing traditions and the availability of construction materials etc.. The design is based on the design of private tubewells presently being used by the farmers in the villages in the Indus Plain. The mild steel casing pipes, string strainers, galvanized

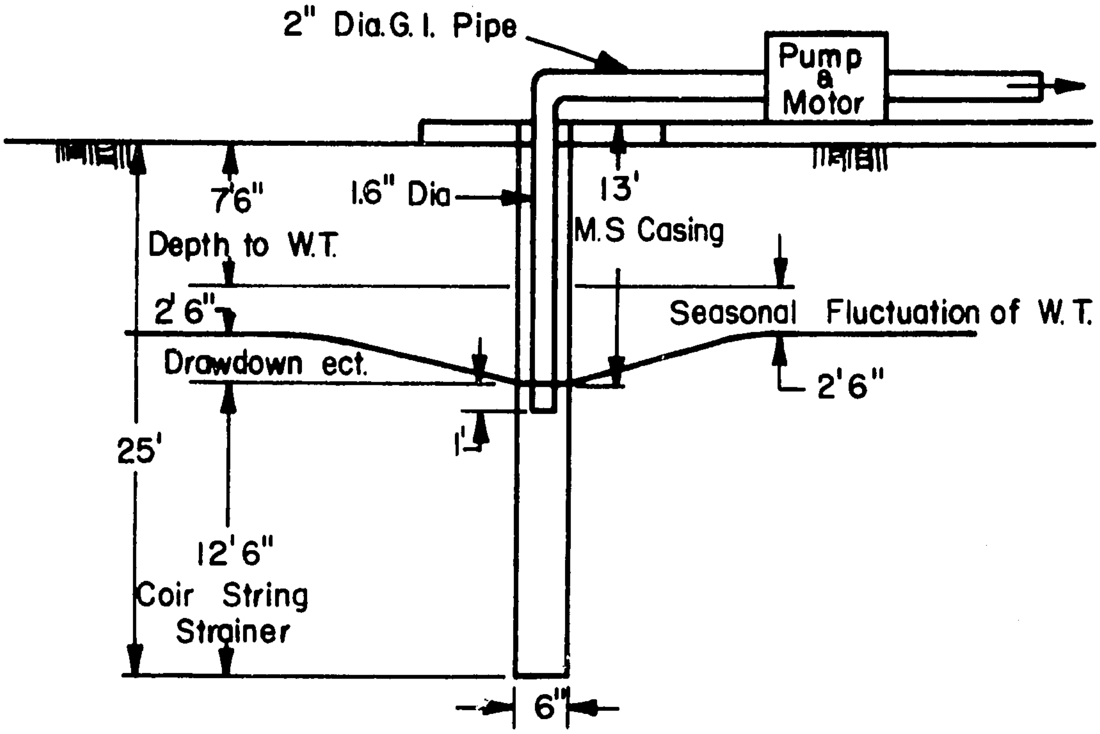


Figure 5A. Design of a Typical Skimming Well (Type A)[1]

---

[1] To be used as a single well of Pattern #1.

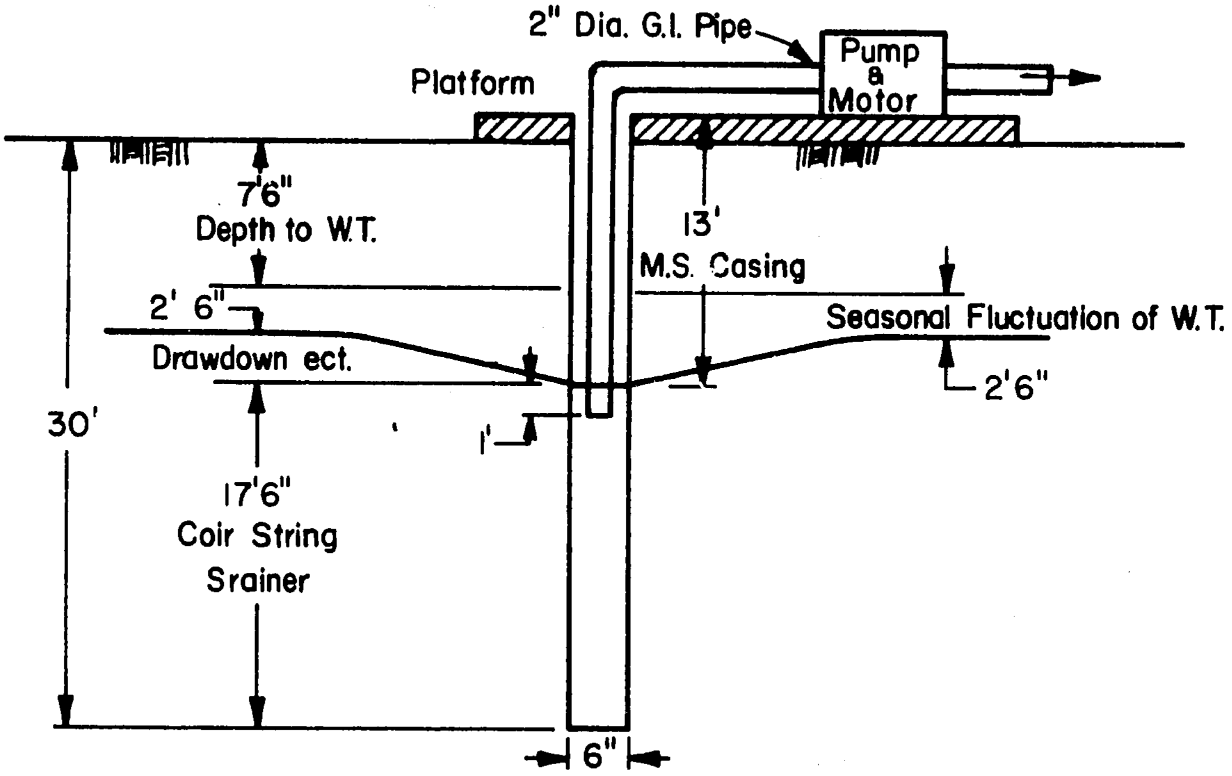


Figure 5B. Design of a Typical Skimming Well (Type B)[1]

[1] To be used in groups of 3 or 4, as per the adopted Pattern #2,3 or 4.

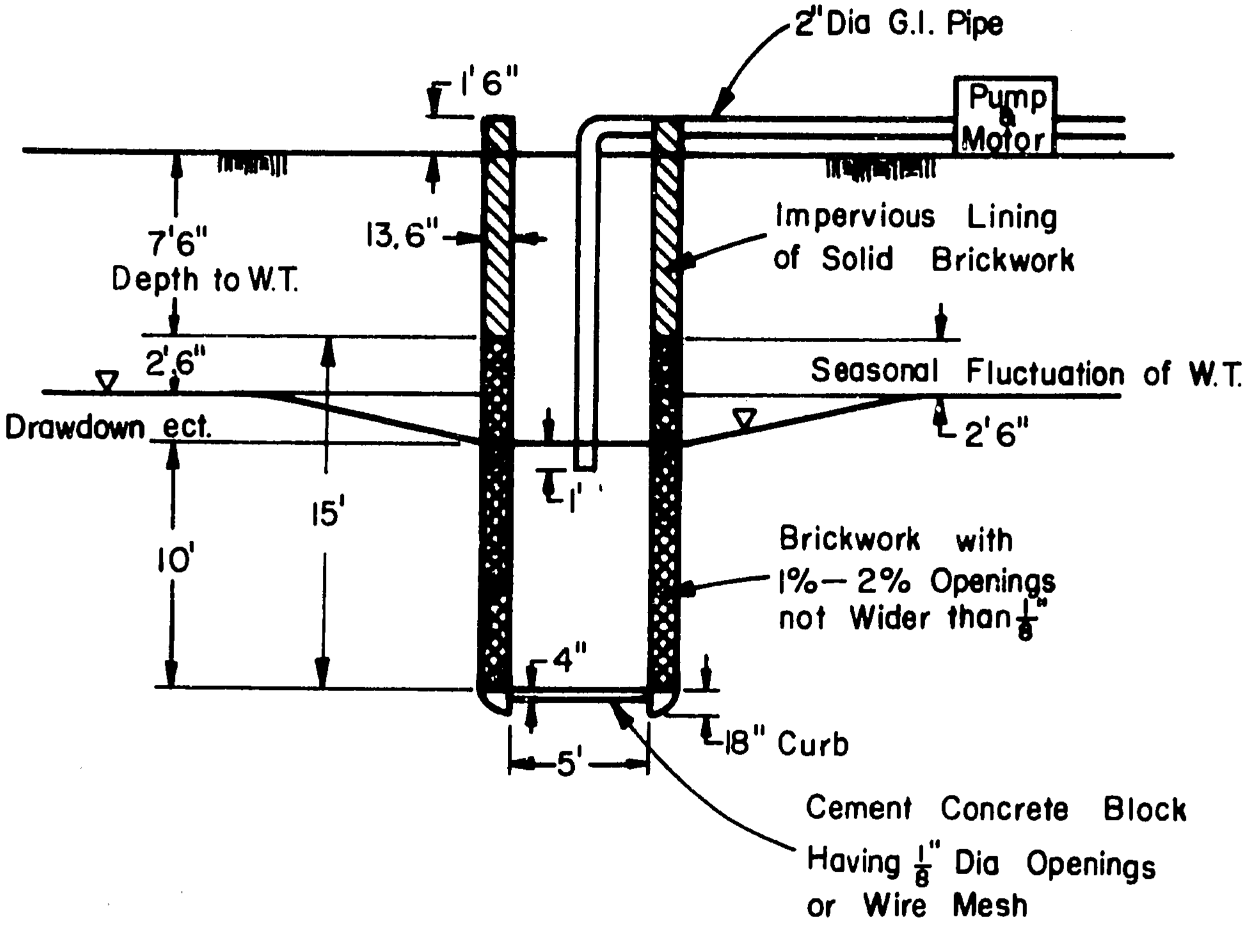


Figure 5C. Design of a Typical Dug Well[1]

---

[1] To be used as a single well in Pattern #5.

iron pipe, small capacity horizontal type centrifugal pumps and the electric motors are all manufactured locally in Pakistan. The wells are only 25 to 30 feet deep and, therefore, can be installed without much difficulty.

Design of a dug well which can be used for skimming purposes is given in figure 5C. The well has an internal diameter of 5 feet. Less penetration is needed as the diameter of the well is large. From figure 4C we find that for a penetration of 15% a safe discharge of 0.174 cfs can be obtained from this well.

Tables 5A, 5B, 5C and 5D give the cost of construction of the wells for each of the five patterns. Costs for patterns #2 and 3 are the same, but the discharge for pattern #2 is slightly higher than the discharge of pattern #3. Table 5E gives the cost of construction of a skimming Persian wheel. Table 5F gives the comparison of the cost of construction of the six patterns. Costs per cubic foot of discharge have also been calculated for the purpose of quick comparison. Costs of WAPDA constructed tubewells and private tubewells are also given in the same table for comparison purposes.

It is seen from the above Table that the cost of skimming facilities per cusec discharge are about double the cost of the tubewells being installed by WAPDA and about three times the cost of private tubewells. Comparing among the skimming facilities we find that the cost per cusec discharge of pattern #5A is the highest, while the costs of patterns #1 and 5 are the lowest and are roughly equal.

The above costs have been worked out on the basis of using electric motors for the pumps. However, at places where electricity is not available, diesel motors will have to be used. Costs of diesel operated wells

TABLE 5A

COST OF A SKIMMING WELL - TYPE A

Pattern #1

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Boring 8"	rft.	30	5.00	150.00
2	Strainer, Coir String 6"	rft.	17.5	8.00	140.00
3	Casing Pipe, M.S. 6"	rft.	13	16.00	208.00
4	Pump, Motor (.75HP) & Control	No.	1	L.S.	1400.00
5	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
6	G.I. Pipe incl. bands 2"	rft.	20	3.00	60.00
7	Discharge Box	No.	1	L.S.	60.00
8	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				2218.00

TABLE 5B

COST OF A SET OF FOUR SKIMMING WELLS - TYPE B

Patterns #2 and 3

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Boring 8"	rft.	100	5.00	500.00
2	Strainer, Coir String 6"	rft.	50	8.00	400.00
3	Casing Pipe, M.S. 6"	rft.	52	16.00	832.00
4	Pump, Motor (1.25 HP) & Control	No.	1	L.S.	1800.00
5	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
6	G.I. Pipe incl. bands 1½"	rft.	70	2.00	140.00
	2"	rft.	10	3.00	30.00
7	Discharge Box	No.	1	L.S.	60.00
8	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				3962.00

TABLE 5C

COST OF A SET OF THREE SKIMMING WELLS - TYPE B

Pattern #4

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Boring 8"	rft.	75	5.00	375.00
2	Strainer, Coir String 6"	rft.	37.5	8.00	300.00
3	Casing Pipe, M.S. 6"	rft.	49	16.00	784.00
4	Pump, Motor (1.25 HP) & Control	No.	1	L.S.	1800.00
5	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
6	G.I. Pipe incl. bands 1½"	rft.	55	2.00	110.00
	2"	rft.	10	3.00	30.00
7	Discharge Box	No.	1	L.S.	60.00
8	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				3659.00

TABLE 5D

COST OF A DUG WELL - 5 FT. INTERNAL DIAMETER

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Excavation - dry soil, up to 7.5' depth	1000 cft	0.31	60.00	18.60
2	Excavation - slush, incl. lift 7.5' to 25' depth	1000 cft	0.62	90.00	55.80
3	Brickwork (2nd. Class) in cement mortar	100 cft	0.53	200.00	1060.00
4	Curb	No.	1	L.S.	80.00
5	Pump, Motor (1.25 HP) & Conrtol	No.	1	L.S.	1600.00
6	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
7	G.I. Pipe incl. bands 2"	rft.	20	3.00	60.00
8	Discharge Box	No.	1	L.S.	60.00
9	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				3134.40

TABLE 5E

COST OF A PERSIAN WHEEL - 8 FT. INTERNAL DIAMETER

Pattern #5A

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Excavation - dry soil, up to 7.5' depth	1000 cft	0.62	60.00	37.20
2	Excavation - slush, incl. lift 7.5' to 25' depth	1000 cft	1.24	90.00	111.60
3	Brickwork (2nd. Class) in cement mortar	100 cft	7.80	200.00	1560.00
4	Curb	No.	1	L.S.	125.00
5	Steel Chain with G.I. sheet buckets	rft.	40	60.00	2400.00
6	G.I. Water Collecting Pan	No.	1	L.S.	80.00
7	Steel Bucket Wheel, axle, gears, main wheel incl. dr. arm	No.	1	L.S.	1000.00
8	Main Beam (wooden) incl. supporting wheel	No.	1	L.S.	125.00
9	Discharge Box	No.	1	L.S.	100.00
10	Development of Well	No.	1	L.S.	150.00
11	Bullocks to Drive	No.	2	L.S.	2000.00
	TOTAL COST (cost of any shelter not incl.)				7688.80

TABLE 5F

COMPARISON OF COST OF VARIOUS SKIMMING FACILITIES

S.No.	Type of Well	Discharge (cfs)	Cost (Rs)	Cost/cfs (Rs)
1	WAPDA Tubewells[3]	4.0	45,000[1]	11,250
2	Private Tubewells[3]	1.0	6,850[2]	6,850
3	1 Tubewell (Pattern #1)	0.126	2,218	17,600
4	4 Tubewells (Pattern #2)	0.176	3,962	22,510
5	4 Tubewells (Pattern #3)	0.174	3,962	22,770
6	3 Tubewells (Pattern #4)	0.173	3,659	21,150
7	1 Dug Well (Pattern #5)	0.174	3,135	18,020
8	1 Persian Wheel (Pattern #5A)	0.186	7,689	41,338

[1] From "Regional Plan for Northern - Indus Plain" by WAPDA and T & K Inc. (1967).

[2] From "A Study of the Contribution of Private Tubewells in the Development of Water Potential in Pakistan" by University of Engineering and Technology, Lahore (June 1970).

[3] These figures are presented only for comparison purposes and are not part of skimming facilities.

TABLE 5G

LIFE OF DIFFERENT COMPONENTS OF SKIMMING FACILITIES

	Component	Assumed Life
1	Tubewell	
	Well Construction	10 years
	Pump Motor, etc.	10 years
2	Dug Wells	
	Well Construction	30 years
	Pump Motor, etc.	10 years
3	Persian Wheel	
	Bullocks	10 years
	Well Construction	30 years
	Iron Chain, Wheel, etc.	30 years

TABLE 5H

ANNUAL OPERATION COST OF SKIMMING FACILITIES

S.No.	Item	Hours Operated Per Year	Operation Cost (Rs)
1	Tubewell	2130[1]	
	Cost of Power		1430[2]
2	Skimming Tubewell	2130	
	Cost of Power		180
3	Skimming Dug Well	2130	
	Cost of Power		250
4	Persian Wheel	2130	
	Bullock Feed @Rs.1'50/day/bullock		540
	Pay of one boy laborer @Rs.60'/month		360

[1] It is assumed for the annual cost calculations that the well is operated for 50% of the time for six months.

[2] Power cost has been taken from Table 6.5 of "A Study of the Contribution of Private Tubewells in the Development of Water Potential in Pakistan" conducted by W. P. University of Engineering and Technology, Lahore (June 1970).

TABLE 5I

ANNUAL COST OF WATER

(All figures are in Rupees)

Item	Private Tubewell	Skimming Tubewell Pat. #1	Skimming Dug Well Pat. #5	Persian Wheel Pat. #5A
Operation Cost	1430	180	250	920
Replacement & Repairs	375	120	150	201
Amortization of Capital Cost	520	170	150	224
TOTAL ANNUAL COST	2325	470	550	1345
Capacity of Wells (cfs)	1.0	0.126	0.174	0.186
Annual Working Hours	2130	2130	2130	2130
Water Pumped Annually (AF)	176	22.2	30.6	32.7
Cost/Acre Foot	13.2	21.2	18.0	41.2

will be about 40% higher than the cost of electric operated wells.

Annual cost of water pumped has also been calculated for water obtained from Private Tubewell, Skimming Tubewell (Pattern #1), Skimming Dug Well (Pattern #5) and Persian Wheel (Pattern #5A). Cost of water obtained from the Persian Wheel is found to be very high. Cost of water obtained from Skimming Tubewells and Dug Wells are nearly the same but the cost of water from the Dug Well is the lesser.

ABILITY TO FINANCE WELLS

Although the cost of skimming facilities are high in terms of unit discharge, the cost of one individual skimming well (or set of wells) is not very great. The cost of one skimming tubewell is about one-third the cost of a private tubewell and, therefore, more farmers can afford to have a skimming tubewell of their own. It is, therefore, possible that by proper publicity the construction of skimming wells can be carried out in the private sector.

SOURCE AND AVAILABILITY OF CONSTRUCTION MATERIAL

As described earlier the construction material specified for the skimming wells are all manufactured locally. For tubewells mild steel casing pipe, string strainers, galvanized iron pipe, small capacity horizontal type centrifugal pumps and small horse power electric motors have been specified. All of these are manufactured locally. At places where electricity is not available, diesel engines will have to be used. but these are also manufactured locally. However, diesel oil which is needed for their operation is imported. Dug wells also use locally available material for construction. Pumps and motors used are the same as used for the tubewells.

EXISTING TRADITIONS AND FACILITIES

Dug wells have been used in Pakistan for thousands of years. The technical know-how of constructing dug wells is wide spread and is available even in remote villages. However, the water from the wells is lifted by means of animal labor, which also requires the presence of human beings to exercise control on the animals and also for pushing the water out of the bucket after it has been lifted by the animals. However, in the past 30-40 years the cost of animals has increased and animal feed is also in short supply. The cost of pumping water with animal labor is, therefore, much higher and much less dependable than by means of motors. Electric motors have been provided in the design.

In the last two or three decades a large number of private tubewells have been installed in the Indus Plain. A study of private tubewells made by W. P. University of Engineering and Technology, Lahore, shows that there are about 80,000 tubewells in Pakistan. The great majority of which are located in the Indus Plain. The technical know-how for the construction of the private tubewells is available easily. Private well drillers are available in all the marketing towns in the areas where private wells are being drilled. Some government agencies in the area also do well drilling for the private owners.

It is believed, therefore, that no difficulty will be experienced in acceptance of these designs by the village people at large.

IMPACT ON LOCAL EMPLOYMENT LEVELS

As described previously, the designs proposed for well construction are already well known in the villages and do not involve a great deal of technicalities. Most of the labor required for the job shall be semi-skilled who in turn will develop into skilled labor as the program advances. Therefore, more employment opportunity for the village labor force will be provided by this method of well construction than is done by the public tubewells, where most of the people involved in construction and supervision are technical.

Dug wells will require a large number of unskilled labor for the digging of the wells and for brickwork. Both the designs will provide more opportunities of employment for the village labor force.

CHAPTER VI

DESIGN PROCEDURE

The calculations for the rise of the salt water cone and the discharge of the well given in Chapters IV and V are based on the average values of the permeability and storage coefficient as found by Bennett, et al. (1) by aquifer tests in the northern Indus Plain. The specific weight of the saline water has been assumed to be 1.02 gm/cc . The thickness of the fresh water layer in the so-called saline zones i.e. where the upper fresh water layer is not very thick, is reported to be varying between 60 to 120 feet . A thickness of 100 feet was, therefore, assumed for the purpose of calculations in the above chapters.

However, for real situations in the field different designs will have to be prepared for different areas taking into account the actual values of the aquifer constants for that area, the thickness of the fresh water layer as found in that area, the density of the deep saline water and also the quality and characteristics of the construction material, as the perforated area per foot length of the strainers, pipe, etc..

The design procedure for different situations is, therefore, discussed in the present chapter and an example calculation is also presented to illustrate the design procedure. The following dimensionless parameters have been used for drawing the design graphs (figure 6A) so that they may have general applicability.

1. Dimensionless Penetration $\dot{d} = \frac{d}{m}$
2. Dimensionless Rise of Cone $\dot{\xi} = \frac{\xi}{m}$
3. Dimensionless Discharge $\dot{Q} = \frac{k \cdot Q}{\psi_{\infty} - \psi_{r\omega}}$

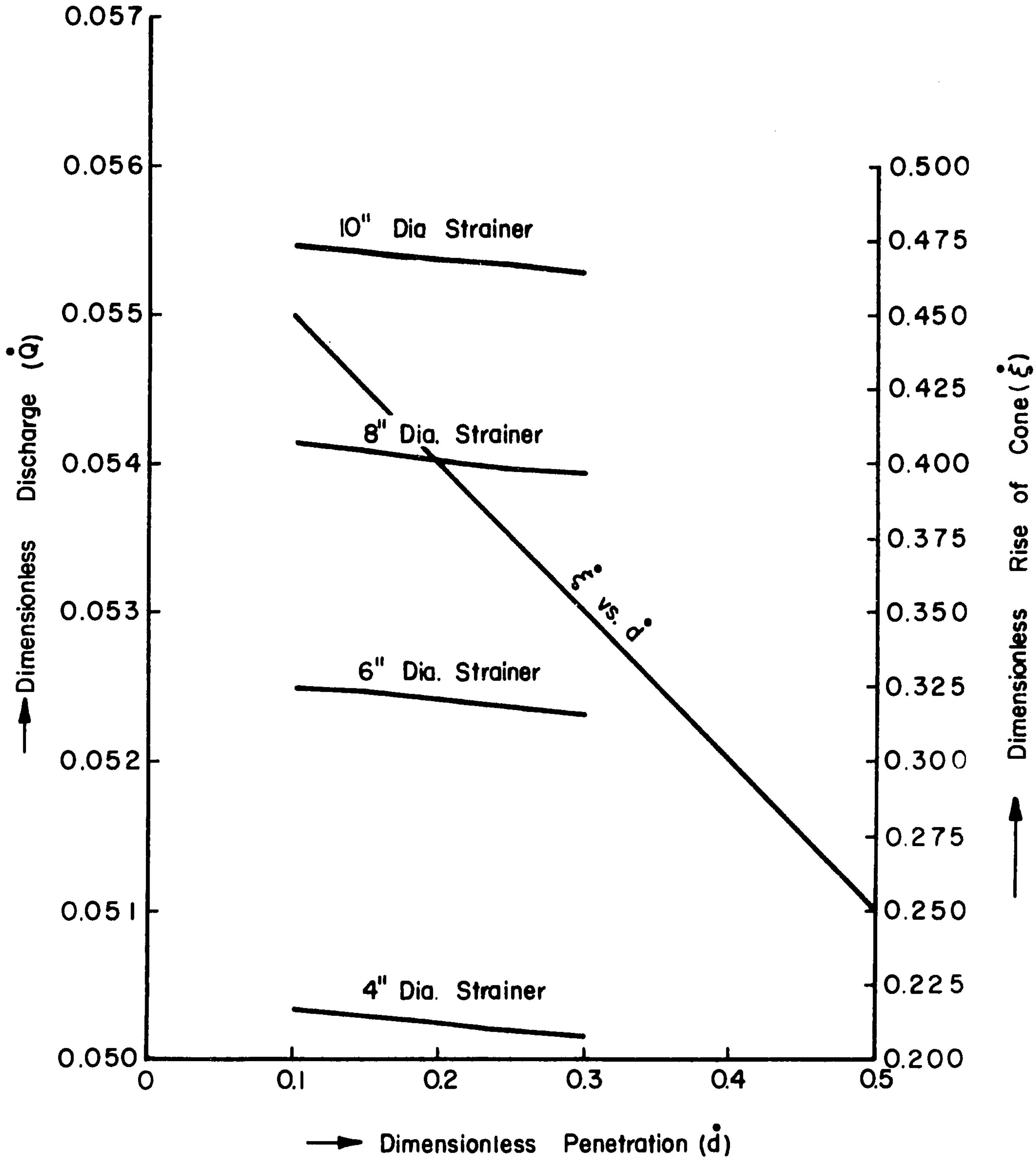

0.057
0.056
0.055
0.054
0.053
0.052
0.051
0.050
→ Dimensionless Discharge ($\dot{Q}$)
0.500
0.475
0.450
0.425
0.400
0.375
0.350
0.325
0.300
0.275
0.250
0.225
0.200
→ Dimensionless Rise of Cone ($\dot{\xi}$)
10" Dia Strainer
8" Dia. Strainer
6" Dia. Strainer
4" Dia. Strainer
$\dot{\xi}$ vs. $\dot{d}$
0
0.1
0.2
0.3
0.4
0.5
→ Dimensionless Penetration ($\dot{d}$)

Figure 6A.

DATA REQUIRED

The following data will have to be obtained from the field for any area for which the wells have to be designed:

1. Thickness of fresh water zone m .
2. Average specific weight of the upper fresh water layer γ_f .
3. Average specific weight of the underlying saline water γ_b .
4. Permeability of the aquifer K_f .
5. Specific yield of the aquifer S_y .

EXAMPLE DESIGN

(A) TUBEWELL:

An example calculation illustrating the design of a single skimming well is presented below.

The values of the following coefficients are to be determined in the field, for a particular area. The values being used here represent the general conditions prevailing in the saline zones of the Northern Indus Plain:

$\gamma_f = 1.00$ gm/cc

$\gamma_b = 1.02$ gm/cc

$\Delta\gamma = 0.02$ gm/cc

$K_f = 0.003$ ft/sec

$S_y = 0.14$

$m = 100$ feet .

Now assume some value of penetration d . The first assumption may be 20% of fresh water aquifer thickness as maximum discharge is obtained at 10% to 20% penetration. Using figure 6A for the dimensionless penetration $\dot{d}$ equal to 0.2 , we get the following values for dimensionless discharge and the dimensionless rise of the cone:

$$\dot{Q} = \frac{k \cdot Q}{\psi_{\infty} - \psi_{r\omega}} = \left[\begin{array}{ll} 0.05023 & \text{for } 4'' \text{ diameter strainers} \\ 0.05241 & \text{for } 6'' \text{ diameter strainers} \\ 0.05402 & \text{for } 8'' \text{ diameter strainers} \end{array} \right. \qquad (1)$$

and

$$\dot{\xi} = \frac{\xi}{m} = 0.4 \qquad (2)$$

From equation 2 we get:

$$\xi = 0.4m = 0.4 \times 100 = 40 \text{ feet}$$

Also

$$k = 1/2\pi \frac{\Delta\gamma}{\gamma_f} (1 + \frac{\Delta\gamma}{\gamma_f}) K_f = \frac{1}{2\pi \frac{1}{50} \cdot \frac{51}{50} \cdot 0.003} = 2{,}601 \frac{\text{sec}}{\text{ft}}$$

$$\psi_{\infty} = \left(\frac{m}{1 + \frac{\Delta\gamma}{\gamma_f}} \right)^2 = \{ \frac{100}{51/50} \}^2 = (98.04)^2 = 9{,}611.84 \text{ ft}^2$$

$$\psi_{r\omega} = \left(\frac{m}{1 + \frac{\Delta\gamma}{\gamma_f}} - \xi \right)^2 = \{98.04 - 40\}^2 = (58.04)^2 = 3{,}368.64 \text{ ft}^2$$

$$\frac{\psi_{\infty} - \psi_{r\omega}}{k} = \frac{9611.84 - 3368.64}{2601} = \frac{6243.20}{2601} = 2.40$$

For a 4" strainer:

$$Q = 0.05043 \times \frac{\psi_{\infty} - \psi_{r\omega}}{k} = 0.05043 \times 2.40 = 0.121 \text{ cfs.}$$

Looking at Table 6A for a discharge of 0.1 cfs we find that a length of 22.5 feet of 4" diameter strainer is required while the assumed penetration is only 20 feet. It means we can not draw 0.121 cfs from the available length of the strainer.

TABLE 6A

LENGTH OF COIR STRING STRAINERS FOR DIFFERENT DIAMETERS AND DISCHARGES

Dia. of Strainer	Length of Strainer in Feet					
	1 cfs	0.2 cfs	0.15 cfs	0.125 cfs	0.1 cfs	0.06cfs
4"	150	40	32.5	27.5	22.5	17.5
6"	100	27.5	22.5	17.5	15	12.5
8"	80	22.5	17.5	15	12.5	10
10"	70	20.0	15	12.5	10	10

Note: Table 6A has been prepared for easy and quick selection of the well diameter in the design of wells. The lengths given for different discharges are derived from the lengths being commonly used in private tubewells. The private tubewells are generally of 1 cfs capacity. The lengths for lower discharges have been obtained by proportionate decrease of the length according to discharge and then increasing the same by a certain percentage, as smaller lengths will not be able to give the same discharge per unit length as longer strainers. The percentage increase in length, therefore, becomes greater as the discharge gets smaller.

The table is only a first guess guide for a new designer. An experienced designer may use his own knowledge and judgement. Until the string strainers are standardized and similar tables are available from the manufacturers, tables like Table 6A will have to be relied upon for the first guess.

For a 6" strainer:

$$Q = 0.05241 \times \frac{\psi_\infty - \psi_{r\omega}}{k} = 0.05241 \times 2.40 = 0.126 \text{ cfs.}$$

From Table 6A, for a discharge of 0.125 cfs, 17.5 ft. length of 6" diameter strainer is required. Allowing 2 feet for drawdown, 18 feet of strainer will yield the required discharge of 0.126 cfs. Therefore, use 6" dimaeter strainer and 20 feet penetration.

If in the above calculations we again find that we can not obtain the required discharge from the available screen length, we can try still bigger size of strainer i.e. 8" diameter. String strainers of 10" diameter, however, are not recommended. If it is not possible to meet the discharge by 8" diameter strainer also, then we will have to increase the penetration and perform the above calculations again.

(B) DUG WELL:

The procedure of designing a dug well is similar to that of a tubewell. For 15% penetration from figure 6B we get:

$$\dot{Q} = \frac{k \cdot Q}{\psi_\infty - \psi_{r\omega}} = \begin{bmatrix} 0.06456 & \text{for} & 3' \text{ diameter well} \\ 0.06916 & \text{for} & 5' \text{ diameter well} \\ 0.07396 & \text{for} & 8' \text{ diameter well} \end{bmatrix} \qquad (1)$$

and $\dot{\xi} = \frac{\xi}{m} = 0.425$ (2)

From equation 2 we get

$\xi = 0.425 \times 100 = 42.5$ feet.

$k = 2{,}601$ (as calculated for tubewells)

$\psi_\infty = 9{,}611.84$ (as calculated for tubewells)

$\psi_{r\omega} = (\sqrt{\psi_\infty} - \xi)^2 = (98.04 - 42.5)^2 = (55.54)^2 = 3{,}084.69 \text{ ft}^2$

$\psi_\infty - \psi_{r\omega} = 9{,}611.84 - 3{,}084.69 = 6{,}527.15$

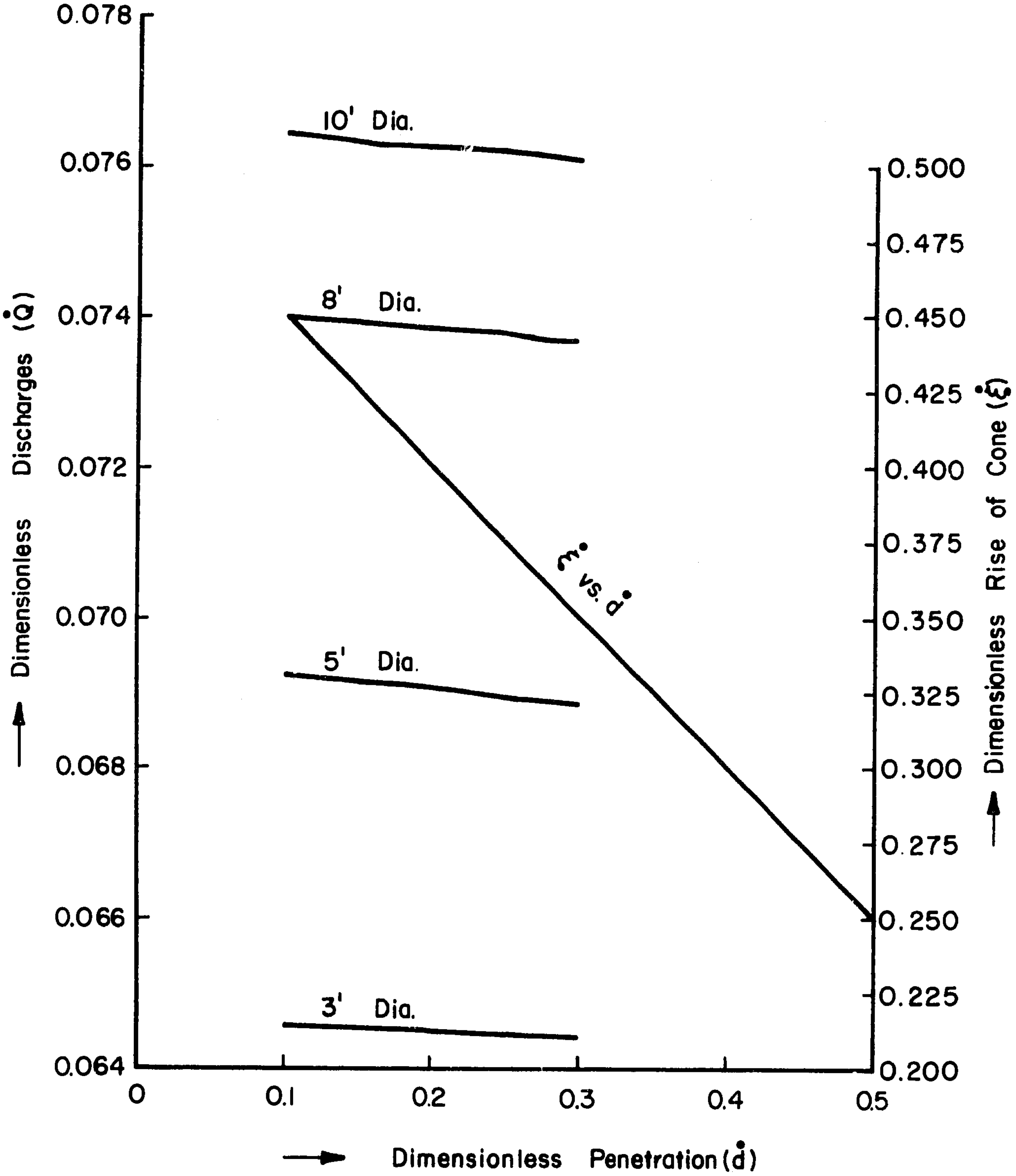

0.078
0.076
0.074
0.072
0.070
0.068
0.066
0.064
→ Dimensionless Discharges ($\dot{Q}$)
10' Dia.
8' Dia.
5' Dia.
3' Dia.
$\dot{\epsilon}$ vs. $\dot{d}$
0.500
0.475
0.450
0.425
0.400
0.375
0.350
0.325
0.300
0.275
0.250
0.225
0.200
→ Dimensionless Rise of Cone ($\dot{\epsilon}$)
0
0.1
0.2
0.3
0.4
0.5
→ Dimensionless Penetration ($\dot{d}$)

Figure 6B.

$$\frac{\psi_\infty - \psi_{r\omega}}{k} = \frac{6527.15}{2601} = 2.51$$

For a 3' diameter well:

$$Q = 0.06456 \times \frac{\psi_\infty - \psi_{r\omega}}{k} = 0.06456 \times 2.51 = 0.162 \text{ cfs}$$

Allowing 2.5 feet for drawdown and assuming that 1% area of the lining allows the entry of water to the well:

Area of Water Entry $= \frac{1}{100} \times 12.5 \times \pi \times 3 = 1.18$ sft.

Therefore,

Velocity of entering water $= \frac{0.162}{1.18} = 0.138$ ft/sec .

Max^{m} permitted velocity for $K_f = 0.003$ is 0.1 ft/sec.

Therefore, increase penetration of the well.

For 20% penetration:

$$\dot{Q} = \frac{k \cdot Q}{\psi_\infty - \psi_{r\omega}} = \left[\begin{array}{lll} 0.06452 & \text{for} & 3' \text{ diameter well} \\ 0.06911 & \text{for} & 5' \text{ diameter well} \\ 0.07386 & \text{for} & 8' \text{ diameter well} \end{array}\right.$$

and $\dot{\xi} = \frac{\xi}{m} = 0.4$

Therefore, $\xi = 0.4 \times 100 = 40$ feet

For 20% penetration:

$$\frac{\psi_\infty - \psi_{r\omega}}{k} = 2.40 \text{ (as for a tubewell)}$$

Now, for a 3' diameter well:

$$Q = 0.06452 \times \frac{\psi_\infty - \psi_{r\omega}}{k} = 0.06452 \times 2.40 = 0.155 \text{ cfs}$$

Again allowing 2.5 feet for drawdown and assuming 1% area of the lining allows the entry of water to the well:

$$\text{Area of Water Entry} = \frac{1}{100} \times 17.5 \times \pi \times 3 = 1.65 \text{ sft}$$

Therefore,

$$\text{Velocity of entering water} = \frac{0.155}{1.65} = 0.094 \text{ ft/sec} \quad .$$

As this is nearly equal to the max^{m} permissible velocity of 0.1 ft/sec the design is adopted.

Another method could be to keep penetration the same, i.e. 15% , and increase the diameter of the well.

For a 5' diameter well:

$$Q = 0.06916 \times \frac{\psi_{\infty}-\psi_{r\omega}}{k} = 0.06916 \times 2.51 = 0.174 \text{ cfs}$$

Allowing 2.5 feet for drawdown and assuming that 1% of the area of the lining allows the entry of water to the well:

$$\text{Area of Water Entry} = \frac{1}{100} \times 12.5 \times \pi \times 5 = 1.96 \text{ sft}$$

Therefore,

$$\text{Velocity of entering water} = \frac{0.174}{1.96} = 0.089 \text{ ft/sec}$$

As this is less than 0.1 ft/sec design is safe.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

1. Indiscriminate pumping of water from the aquifers where a relatively thin layer of water overlies the saline water is not proper and can result in ruining the whole aquifer in terms of water quality.
2. Skimming wells, i.e. wells of small discharges and small penetrations, seem to be a solution for obtaining fresh water from such aquifers as the water is pumped by skimming wells with a minimum of mixing either within the well or within the aquifer.
3. The unsteady-state equation developed by McWhorter (6) is adequate for designing such wells. This equation does not require computation with a computer.
4. Various patterns of skimming wells for pumping fresh water were studied in order to select the one which will deliver fresh water at minimum cost. As a result of this study, it was found that although combinations of wells provide greater discharge than a single well, the increase in cost is not proportional to the increase in discharge.
5. Tubewells and Dug Wells of 10-20% penetrations are found to be most economical for the purpose. These wells will have to be designed for any particular area on the basis of the aquifer characteristics, thickness of the fresh water layer and the salinity of the deep saline water.
6. Designs selected for the skimming wells are such that these will require only unskilled or semi-skilled labor in their construction and will, therefore, provide greater opportunities of employment for the rural population.

7. Locally manufactured pumps, motors, pipe, strainers, etc. have been provided in the design of these wells, and therefore, foreign exchange will not be required for their construction. Further this will also increase the employment opportunities as the manufacture of these materials will have to be greatly increased to meet the demands of the farmers.

8. A large number of such wells will be required to provide proper drainage to any area as the discharge obtained from a single well will be quite small, being in the range of 0.1 to 0.2 cubic feet per second.

9. Cost of the water obtained from electricity operated skimming wells is estimated to be Rs. 18 to 21 per AF., while the cost of the water obtained from private tubewells is Rs. 13/= per AF..

10. Electricity operated wells are cheaper than diesel operated wells. Electric wells not only have lower capital and operation cost but are also easier to operate. The cost of providing electric connections for such small capacity wells may prove quite costly and will have to be looked into in greater detail.

11. The installation cost of a diesel operated tubewell is about 33% higher than an electric operated tubewell, and its operation cost is almost double the operation cost of an electricity operated tubewell. As cost figures on the diesel motors were not available, detailed analysis of the same could not be made. Rough estimates show that the cost of the water obtained from diesel operated Private Tubewells, Skimming Tubewells and Skimming Dug Wells will be Rs. 25/= per AF., Rs. 37/= per AF., and Rs. 33/= per AF. respectively.

12. Actual field experiments should be conducted to study the rise of the salt water cone under the actual field conditions in order to verify the presently available solutions.

REFERENCES

1 Bennett, G. D., A. Rehman, I. A. Sheikh and Sabir Ali, (1967), "Analysis of aquifer tests in the Punjab region of West Pakistan". USGS Water Supply Paper No. 1608-G.

2. Bennett, G. D., M. J. Mundorff and S. A. Hussain, (1968), "Electric analog studies of brine coning beneath fresh water wells in the Punjab region of West Pakistan". USGS Water Supply Paper No. 1608-J.

3. Greenman, D. W., W. V. Swarzenski and G. D. Bennett, (1967), "Groundwater Hydrology of the Punjab, West Pakistan, with emphasis on problems caused by canal irrigation". USGS Water Supply Paper No. 1608-H.

4. International Bank for Reconstruction and Development, (1966), "Programme for the development of irrigation and agriculture in West Pakistan". Washington, D. C.

5. Lieftuick, Pieter, ( ), "Water and Power Resources of West Pakistan - A study in sector planning". Published by International Bank of Reconstruction and Development as Administrators of Indus Basin Development Fund.

6. McWhorter, D. B., (1972), "Steady and unsteady flow of fresh water in saline aquifers". CUSUSWASH Water Management Technical Report No. 20, Colorado State University, Fort Collins.

7. Muskat, M., (1946), "The flow of homogenous fluids through porous media". J. W. Edwards, Ann Arbor, Michigan.

8. Sahni, Brij Mohan, (1972), "Salt water coning beneath fresh water wells". CUSUSWASH Water Management Technical Report No. 18, Colorado State University, Fort Collins.

9. Schmorak, S. and A. Mercado, (1969), "Upconing of fresh water - sea water interface below pumping wells - field study". Water Resources Research, Vol. 5, No. 6.

10. Wang, Flura Chu, (1965), "Approximate theory for skimming well formulation in the Indus Plain of West Pakistan". Jour. of Geoph. Res., V. 70, No. 20, pp. 5055-5063.

11. West Pakistan Water and Power Development Authority, (1963), "Programme for water and power development in West Pakistan 1963-75". WAPDA, Lahore.

12. West Pakistan Water and Power Development Authority and Tipton and Kalenbach Inc., (1967), "Regional plan for northern Indus Plain". WAPDA, Lahore.

13. West Pakistan University of Engineering and Technology, Lahore, (1970), "A study of the contribution of private tubewells in the development of water potential in Pakistan". Lahore, Pakistan.

14. Walton, W. C., (1970), "Groundwater resource evaluation". McGraw Hill Book Co..