OPTIMIZATION OF PUMPING SCHEDULE FOR INCREASING THE YIELD OF OPEN WELLS

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PROJECT REPORT

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DECLARATION

We here by declare that this project report entitled **"OPTIMIZATION OF PUMPING SCHEDULE FOR INCREASING THE YIELD OF OPEN WELLS"** is a bonafide record of project work done by us during the course of project and that the report has not previously formed the basis for the award to us of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

Place : Tavanur

Date : 8-6-'98

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CERTIFICATE

Certified that this project report, entitled, **"OPTIMIZATION OF PUMPING SCHEDULE FOR INCREASING THE YIELD OF OPEN WELLS"** is a record of project work done jointly by Bhaskaran, K., Jinu, A., Priya, M. and Sreevidya, M.L. under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to them.

Place: Tavanur
Date: 8-6-'98

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SYMBOLS AND ABBREVIATIONS

ASCE - American Society of Civil Engineers
C. I. A. E - Central Institute of Agricultural Engineers
Co. - Co-operative
C.W.R.D.M. - Centre for Water Resources Development and Management
°C - degree Celsius
div - divergence
Ed. - Edition
et. al - And others
Fig. - Figure(s)
grad - gradient
h - hour (s)
hp - Horse power
I.C.A.R - Indian Council of Agricultural Research
Inc. - Incorporated
KAU - Kerala Agricultural University
K.C.A.E.T - Kelappaji College of Agricultural Engineering and Technology
Ltd - Limited
lps - litres per second
m^3/day - Cubic metres per day
m^3/h - Cubic metres per hour
m^3/minute - Cubic metres per minute
m - metres
m/minute - metres per minute
mm - milli metre (s)
m ha-m - million hectare metre
m^2 - square metre
min - minute (s)
No - Number
ob - Observed

%	-	per cent
pp	-	page
Pvt	-	Private
th	-	Theoretical
viz.	-	namely
W.L	-	Water level

INTRODUCTION

Water is a prime natural resource, a basic human need and a precious national asset. This most precious resource is sometimes scarce, sometimes abundant and always very unevenly distributed both in space and time. Among the different components of the water resources of the nation, ground water is the most widely distributed, dependable and pure water resource. The amount of ground water within 800 m from the ground surface is over 30 times the amount in all fresh water lakes and reservoirs and about 3000 times the amount in stream channel at any one time.

The main source of ground water is from rain. The rain water gets infiltrated after meeting the soil moisture deficiency, percolates downwards and becomes ground water. The subsurface occurence of ground water may be divided into zones of saturation and aeration. In the zone of saturation, all the interstices are filled with water under hydrostatic pressure. In the zone of aeration, the interstices are occupied partially by air and partially by water. The water occuring in the zone of saturation is generally regarded as ground water.

Ground water occurs within the surface depending on the physical properties of the different formations that exist. Aquifers are formations which contain ground water and sufficiently permeable to transmit and yield it in usable quantities. An unconfined aquifer is one in which water table serves as the upper surface of saturation. There is no clay or other restricting materials at the top of the ground water. So the ground water levels are free to rise or fall. Confined aquifer is a layer of water bearing material that is sandwiched between two layers of much less pervious like a sandy layer between two clay layers or sandstones between layers of shale or solid limestone.

Diverse geological formations require different types of wells for tapping ground water for irrigation and water supply. Broadly, water wells may be divided into three categories, namely, dug wells, dug cum bore wells and tube wells.

A major part of Indian Peninsular and a vast number of developing and under developed countries depend on large diameter open dug wells for their domestic and agricultural need. Dug wells comprise of open surface wells of varying dimensions dug or sunk from the ground surface into the water bearing stratum. They may be circular or rectangular in cross section. Usually, two types of wells are constructed: lined wells and unlined wells in hard rock. Lining may be of concrete rings or stone masonary.

Low yield is often a problem in open wells. The yield of open wells can be increased either by deepening of the wells,providing horizontal bores, rescheduling of pumping time into convenient block periods or by increasing the ground water recharge in the vicinity of open wells. Rescheduling of pumping time into convenient block periods is a comparatively easier procedure for increasing the yield of open wells as it percludes the efforts involved in deepening wells and installing horizontal or vertical bores. The regular sequence of fixed periods of pumping followed by fixed periods of rest are called block periods. The block periods for wells are selected based on the drawdown and recuperation pattern of wells.

A proper study of the drawdown and recuperation pattern of wells is necessary for planning and management of wells, its optimal, economical and equitable use. For determining the recuperation time for a given rise of water level in the well and inflow rate into the well during recuperation, it is necessary to find the aquifer parameters affecting the flow to open wells in terms of the measurable well parameters. So a proper mathematiccal representation for ground water flow into the dug well is important. The exact differential equation governing the ground water flow in unconfined aquifer is the Laplace equation. The present study is aimed at verifying the closed form approximate analytical solution for recovery in large diameter wells in various geological formations such as laterites, clay and alluvial deposits. Though the solutions were developed for confined aquifer, they are said to be applicable for unconfined flow under conditions of small drawdown also.

The specific objectives of this study are :

1. To conduct pumping in wells of different formations.
2. To study the drawdown and recuperation pattern of open wells.
3. To suggest an optimum pumping schedule to increase the yield of open wells.
4. To verify the available theoretical time recovery relationship for unconfined flow conditions.

REVIEW OF LITERATURE

A brief review of drawdown and recuperation patterns, rescheduling of pumping time and unsteady radial flow analysis in open wells are presented in this chapter.

Although ground water is a renewable resource, it is not inexhaustible. Pumpage from wells constitute the major artificial discharge of ground water. If ground water supplies are to be maintained perennially, well planned pumping from wells is essential. The yield of the well is probably the most important single item of ultimate interest. Optimum utilisation of yield from a well is dependent on the behaviour of aquifer and ground water conditions of the area. The per annum utilisation of ground water is estimated at 18.58 mha-m in 1996. Efficient management of ground water utilisation is likely to increase this value to 27.87 mha-m by 1998-'99. A knowledge of correct flow patterns is necessary for the reliable interpretation of pumping test data and to determine well parameters.

2.1 Drawdown and recuperation pattern of open wells

Drawdown and recuperation pattern of wells is very much dependent on the aquifer properties. Analysis of drawdown and recuperation pattern of wells is necessary for determining various aquifer parameters as well as for proper management of wells. The level at which water stands in a well before pumping starts is called the static water level. When a well is being pumped, the water level in the well lowers. Initial contribution of water from the well mostly comes from well storage. It is only after sometime that the aquifer starts contributing to the pumpage. The time gap between the onset of pumping and the beginning of an appreciable flow of water from the aquifer to the well depends mainly on the transmissivity of the aquifer. The linear relationship between drawdown and time implies that water is pumped mostly from storage.

Thus time drawdown curves were initially linear, but later with the beginning of the contribution from the aquifer, they gradually becomes non linear.

When the pump is stopped at the end of a pumping test, the water level in the well starts rising. This is referred to as the recovery of ground water level. Recovery rate is high at the beginning of recuperation due to the steep hydraulic gradient. It gradually reduces as the static water level approaches. A knowledge about the recovery pattern of a well is important in scheduling the pumping time into suitable block periods.

2.2 Pumping schedule

The gross yield of open wells in a given time period can be increased substantially by rescheduling the pumping time into suitable block periods. When a well is pumped to its full capacity, the recuperation rate is high at the beginning due to high hydraulic gradient. It gradually decreases as the water level approaches static water table depth. Hence, intermittent pumping would result in a greater rate of recuperation or increase in yield of the well in a given time.

Brown (1963) carried out pumping in a tube well cyclically ie, pumping at a constant rate for a fixed number of hours each day, and then allowing to rest for a certain time interval. It was found that when the recovery period in each cycle was sufficiently long, the water level returned to the prepumping static level and successive cycles of drawdown and recuperation resulted in a net lowering of water level in the well. On the other hand, when the well was pumped cyclically and recovery period was short of the optimum required for full recovery, the water level at the end of each cycle was lower than that at the end of the preceding cycle. By considering the net drawdown in such a well as the resultant of the drawdown effect of the pumped well and a series of imaginary recharge and discharge wells, Brown derived an equation for the drawdown in the pumped well after n cycles of operation.

$$S_n = \frac{2.3Q}{4\pi T}\log_{10}\frac{1.2.3.......................n}{(1-P)(2-P)(3-P)................(n-P)}$$

where,

S_n = Drawdown in metres in the pumped well after n cycles of operation

Q = Discharge of the pumped well in m^3/day

T = Coefficient of transmissivity in m^2/day

n = Number of cycles of operation

p = Fractional part of the cycle during which the well is pumped.

Tavener (1967) found that alternation of relatively long periods of recharge at low rate followed by pumping for short periods at high rate prolonged the useful life of a recharge well.

Michael *et al.,* (1974) conducted pumping test in a well in hard rock area in suitable block periods. The regular sequence of fixed periods of pumping followed by fixed periods of rest are called block periods.

Table 1. presents typical pumping test data for a well in hard rock area, in which pumping was conducted in suitable block periods.

Column 2 in Table 1, shows the block periods adopted for pumping and recuperation. For example, the data at serial number 1 represents a block period of 24 h, in which pumping was carried out for 3 h and the rest of the time (21 h) was allowed for recuperation. Serial no. 2 represents 1- h block period comprising 30 min pumping and 30 min recuperation. Thus,in a day there were 24 pumping periods and an equal number of recuperation periods. This provided for 12 h pumping, or an addition of 9 h in the total pumping time in a day. When the pump discharge did not vary appreciably, the total yield of the well was assumed to increase by three times. From a practical point of view, it was difficult to have pumping periods at such short intervals. However, block periods of 3 - 8 h could easily be adopted. Possible increases in total pumping time by adopting 3, 6 and 8 h block periods were 206.6 %, 133.3 % and 115 %, respectively, as compared to a single pumping in a day. In case of pumps operated by electric motors, the duration of the block period should suit the availability of electric power. Diesel pumps, however, had no such limitation.

Table 1. Pumping test of an open well in a hard rock area adopting intermittent pumping at different block periods.

Sl. No.	No. of block period (h)	Pumping period (min)	Recuperation period (min)	No. of recuperation per day	Total pumping time in a day (h)	Additonal pumping time obtained (h)	% increase in yield
1	24	180	1260	1	3	--	--
2	1	30	30	24	12	9	300
3	2	51	69	12	10.2	7.2	240
4	3	69	111	8	9.2	6.2	206.6
5	4	81	159	6	8.1	5.1	170
6	6	105	255	4	7.0	4.0	133.3
7	8	129	351	3	6.45	3.45	115

Source : Institute of Hydraulics and Hydrology, Poondi(1982)

Aral *et al.,* (1983) investigated the hydraulic aspects of pumping from axisymmetric ponds, or large diameter wells as a means of developing shallow, unconfined aquifers and it was found that pond storage allowed ground water pumping at higher rates during short time periods than for continuous pumping. The numerical results were applied to a design problem of selecting the pond diameter, pumping rate and pumping schedule for the given aquifer properties.

The available drawdown in such an axisymmetric pond was somewhat limited, and so it was imperative that the hydraulics be carefully analysed for accurate prediction of the allowable pumping rate within the constraints of available drawdown and a given pumping time.

Pumping operations were considered to occur on a daily cycle with a single pumping period followed by a recovery period during which pond storage was recovered by seepage into the pond. Even though pumping rate from the pond was held constant during a pumping period, the seepage rate into the pond was unsteady due to the gradual lowering of the pond level. The withdrawal of storage from the pond during pumping contributed to the pumping discharge, along with seepage to the pond. It can be observed that the total daily volume pumped increased slightly with pumping time, but pumping rate decreased as pumping time increased. This effect was the result of the imposed constraints of a daily pumping-recovery cycle.

The results showed that the storage offered by large ponds allowed much higher pumping rates for short time periods than would be indicated by estimates of steady state seepage rates. The principal advantage of the large pond as a means of developing a shallow aquifer system was well realised.

Romani (1984) proposed a method for the evaluation of yields of open wells dug in hard rock by repeating the pumping as soon as 50 percent recuperation took place. The idea was based on the observation that after pumping an open well dry, the first half of the recovery of water level in the well was much faster than the second half. Consequently, he arrived at the conclusion that the well would produce maximum yield, if it is operated again as soon as the water level reached 50 percent of its undisturbed position.

The suggested method was based on the validity of the assumed equation:

$$t_1+n(t_2+t_1/2)=720$$

where,

t_1 = time in minutes to empty for the first time an undisturbed well

t_2 = time in minutes for 50 % recuperation

n = number of times the well can be operated after first emptying

The proposed method was verified by conducting field tests at two locations. The results of the tests seems to support the basic idea advanced by him.

Bhadauria *et al.,* (1985) conducted pumping tests for three discharges 5 lps, 2.5 lps and 1.25 lps and recuperation tests at different depths with the help of necessary instrumentations and replications for each set of observations on two open wells. The pumping test data were analysed to develop empirical equations for drawdown and recovery trends using standard least square technique.

The specific capacity was determined at different depths in the well using above test's data. In the studies, it was found that flow of water to well is dependent on rate of pumping. The uneven variation in specific capacity shows the heterogeneous formations within the well depth. The study of specific capacities was useful in deciding the pumping schedule of a well. For obtaining maximum well yield, 4 h intermittent pumping was recommended for planning an irrigation system in case of unconfined aquifer.

2.3 Unsteady radial flow to wells

Ground water is in constant motion from a point of recharge to a point of discharge, in accordance with laws governing flow of fluids in porous medium. When a well is at rest, the head of water within the well is equal to that in the formation exposed to the well. When it is pumped the water level with in the well and piezometric surface around it are lowered, and a hydraulic gradient is established resulting in a convergent or radial flow towards the well.

The radial flow is said to be unsteady when the flow conditions at any moment are not constant.

ie.,

$$\frac{dv}{dt} \neq 0$$

2.3.1 Wells in confined aquifer

When a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of discharge extent outward with time. The rate of decline of the head times the storage coefficient summed over the area of influence equals the discharge. Since the water must come from a reduction of storage within the aquifer the head will continue to decline as long as the aquifer is effectively infinite. Therefore unsteady flow exists. However, the rate of decline decreases continuously as area of influence expands.

The partial differential equation governing unsteady radial flow to wells in confined aquifer is

$$\frac{S}{T}\frac{\delta h}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(r \cdot \frac{\delta h}{\delta r}\right)$$

where,

S = storage coefficient

T = transmissibility of aquifer

r = radial distance of the piezometer from centre of pumped well

t = elapsed time

The assumptions involved in deriving the governing differential equation are:

1. Law of conservation of mass is valid
2. Darcy's law holds good
3. There is radial symmetry in flow
4. The vertical component of flow is zero
5. Permeability coefficient K is constant in the r direction and does not change with time
6. There is no physical discontinuity in the system

2.3.2 Wells in unconfined aquifer

In unsteady radial flow in an unconfined aquifer, with the declining water table, dewatering of porespace is not instantaneous but continuous for sometime after drawdown. The region above the water table, though unsaturated, keep supplying water to the receding water table. The specific yield increases with a diminishing rate with the time of pumping. Hence the saturated thickness of unconfined aquifer is variable in magnitude. The partial differential equation for flow to a well in an unconfined aquifer is a Laplace equation and is given by

$$\frac{\delta^2 h}{\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} + \frac{k_z}{k_r}\frac{\delta^2 h}{\delta z^2} = \frac{S}{b\,k_r}\left(\frac{\delta h}{\delta t}\right)$$

Where, k_z and k_r are the hydraulic conductivities in the vertical direction and in the 'r' direction respectively.

The equation is usually subject to a set of boundary conditions; the most difficult to handle is the free surface boundary condition. Common approaches to solve this problem include trial and error procedures to approximate the location of free surface, in combination with numerical solutions of the differential equations.

Theis (1935) obtained a solution for a well fully penetrating a fully confined horizontal isotropic aquifer of infinite areal extent.

When this well was pumped at a constant rate, the influence of the hydraulic discharge extended outward with time. The problem was considered as axisymmetric around the well axis. The classical conservation equation for ground water flow assuming isotropic permeability is

$$\text{div(grad h)} = \frac{S}{T} = \frac{\delta h}{\delta t} \quad .$$

where,

h = hydraulic potential (total head)

S = storativity

T = transmissivity

t = time

In polar co-ordinates, the above equation takes the form,

$$\frac{\delta^{2} h}{\delta r^{2}} + \frac{1}{r}\left(\frac{\delta h}{\delta r}\right) = \frac{S}{T}\left[\frac{\delta h}{\delta t}\right]$$

Theis obtained the solution for the following conditions:

a. Horizontal, homogeneous, isotropic, infinite and uniformly thick aquifers whose hydraulic parameters (transmissivity and storativity) are constant.

b. Fully confined aquifers.

c. All water comes from storage in aquifer material and is released instantaneously when pure water pressure drops.

d. The pumping well fully penetrates the aquifer and is of infinitesimal diameter.

e. The well when pumped at a constant discharge flow rate.

f. The flow is laminar and respects Darcey's law.

The solution given by Theis is as follows:

$$s = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-u}}{u}\,du$$

where,

u = a parameter $= \frac{r^2 S}{4Tt}$

s = drawdown at time t

r = distance from pumping well to the point where drawdown 's' occurs

Q = constant pumping rate

T = transmissivity of the aquifer

S = storativity of the aquifer

Papadopulos *et al.,* (1967) presented a solution for the drawdown in a large diameter well discharging at a constant rate from a homogeneous isotropic artesian aquifer. A set of type curves computed from this solution permitted determination of the transmissibility of the aquifer by analysis of the drawdown observed in the pumped well.

Neuman *et al.,* (1972) proposed an analytical model for the delayed response process characterising flow to a well in an unconfined aquifer. The result suggested that in the absence of significant infiltration at the ground surface, the compressibility was a much more important factor than unsaturated flow above the water table. The theory showed that such methods are limited in their application to relatively large values of time.

Streltsova (1972) deduced partial differential equations for unsteady radial flow to a well tapping an unconfined aquifer of infinite extent and discharging at a constant rate. The relationship between the average head and the free surface head was assumed to be in the form of a vertical transfer linear equation.

Kumaraswamy (1973) developed a laminar inflow theory to explain the flow characteristics of hard rock open wells and evolved the testing methods to determine the well parameters.

Hard rocks like granite, gneisses, etc. do not possess intergranular porosity by virtue of their mode of origin. Ground water in these rocks circulate through joints, fractures, fissures and similar openings. The conventional methods of determining transmissibility, storage coefficient cannot be applied in hard-rock areas as assumptions made in the development of well theories by Theis and others do not hold good in the case of hard-rock aquifer. These aquifers are not at all isotropic, and flow occurs mostly 'laminarly' through fissure planes or conduits leading into the well. The open wells in hard rocks have appreciable storage capacity, low inflows, and no cone of depression forming around them during pumping. Following were the assumptions made for developing the theory:

1. Flow into the well is only through very minute fractures - conduits or fissure planes opening through the inner surface of the well. These planes of very small cross-sections are stacked horizontally over one another and no cross flow is assumed in between these fissure planes.

2. The piezometric line is at the static water level at the beginning of the fissure plane and drops along the conduit to the pumping level inside the well, obeying Darcey's law of laminar flow.

3. The flow in the plane is laminar considering the Reynold's numbers and temperatures involved.

4. No flow is assumed to enter through the bottom of the well, since most hard rock wells are dug to inpermeable hard rock level, completely penetrating the fissured region.

Based on the above assumptions, Kumaraswamy developed inflow equation, recuperation equation and draw down equation.

Inflow equation for hard rock wells:

$$q = W\left(D^{2} - d^{2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where,

W = Hard rock well permeability
D = Static water depth in the well
d = Water depth in the well

Recuperation equation:

Time of recuperation, t_R from depth d_1 to d_2 was given by the equation.

$$t_R = \frac{V}{WD^2}(\phi_2 - \phi_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where,

V = *a.D is the volume of water available in the well* below static water level.
a = Area of cross section of the well.

$$= \ln\left[\frac{1 + \frac{d_1}{D}}{1 - \frac{d_1}{D}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

$$_2 = \ln \left[\frac{1+\frac{d_2}{D}}{1-\frac{d_2}{D}} \right] \text{...} 4$$

where,

D = Static water depth in the well

W = Hard rock well permeability

Drawdown equation:

Maximum inflow rate in the well was

q_{max} = WD^2, obtained by substituting the value of d=0 in the equation(1). P be the constant discharge rate of pump installed in the well.

Taking m = P/WD^2 m may be less than 1 or greater than 1

Case when m>1

$$t_D = \frac{V}{WD^2}\theta \text{...} 5$$

where,

t_D = time for drawdown through x from static water level.

$$= \frac{1}{\sqrt{m-1}} \tan^{-1} \frac{x/d}{(1-x/d)+\sqrt{m-1}} \text{..........} 6$$

Case when m<1

$$t_D = \frac{V}{WD^2}.\theta^1 \text{...} 7$$

where,

t_D = time for draw down through x from static water level, when m<1

$$\theta^1 = \frac{1}{2\sqrt{1-m}} \ln \left[\frac{1+\frac{1+m^1}{1-m^1}\sqrt{1-m}}{1+\sqrt{1-m}} \right] \text{........} 8$$

$$m^1 = \frac{x}{hs} \text{..} 9$$

If m<1, ie, $P<WD^2$, the water level in the well will stabilise at a drawdown hs which is less than D.

A field pumping test was conducted in a hard rock well. A complete recuperation curve was computed based on this theory. It was observed that the test points tally very well with the theoretical curve.

Kipp(1973) developed a theoretical solution to the problem of unsteady flow to a single partially penetrating well of finite radius in an unconfined aquifer. The aquifer was asumed to be homogeneous, isotropic and infinite both in thickness and lateral extent. Perturbation expansion techniques were used to linearise the free surface boundary condition provided that the drawdown remains small and that a time limit is imposed. The solution could be used to model pumped well behaviour for the initial period after the start of pumping.

Streltsova(1973) conducted an experimental verification and proposed a model design by considering the problem of unsteady radial flow in an unconfined aquifer as boundary value problem with discontinuous initial conditions at the surface of the well. The discontinuity of head occured at the surface of the well as pumping commenced, it dies down in time exponentially and thus represented the delay of the transitional process of re-establishing equilibrium in time. The downward variable movement of water in the vicinity of the well resulted from this discontinuity was proportional to the difference between the gradually falling water table and the average head and was a cause of a slow draining of unconfined aquifer.

Cooley *et al.,* (1979) developed a coupled numerical solution for the unsteady flow in single or multiple confined or semi confined aquifers and the well penetrating the system. Analysis of the hypothetical problems indicated that, because of friction losses and non uniform flow in well bore a significant region of non radial flow in the aquifer resulted. when ever aquifer hydraulic conductivity was greater than about 0.015 m/minute and pumping rate is greater than about $1.2 m^3$/minute.

Basak, (1983) proposed a closed form approximate analytical solution for recovery in fully penetrating large diameter well tapping a confined aquifer. The solutions were also applicable for unconfined flow and for conditions of small drawdown. The analysis predicted exponential decreases of inflow rate, a transient logarithmic recovery response and an asymptotic increase of cumulative recovery with time. The solution was verified against the field recovery response in a wide range of geological aquifer formations like fissured rock, lateritic, as well as sandy alluvial deposits.

The governing differential equation for confined aquifer was given by,

$$\frac{S}{\tau}\frac{\delta h}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(r\,\frac{\delta h}{\delta r}\right) \text{..................} 1$$

in which S and τ are storage coefficient and transmissibility of the aquifer respectively. The assumptions involved in deriving the governing differential equations were as follows:

1. Law of conservation of mass is valid
2. Darcy's Law holds good
3. There is radial symmetry in flow, and vertical component of flow is zero
4. Permeability coefficient k is constant in the 'r' direction and does not change with time.
5. There is no physical discontinuity in the system.
6. Dupit's assumptions are valid.

Equation (1) can also be applied for unconfined flow conditions when drawdowns are comparatively smaller.

Initial conditions (IC)

$$h(r_w,o) = \quad hi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Boundary condition (BC)

$$h(r_e,t) = D, t \geq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

$$\frac{\delta h}{\delta r}\left(r_{e,}t\right) = 0 , t \geq 0 \ \ldots\ldots\ldots\ldots\ldots\ldots 4$$

Analytical solutions for equation(1) is sought under conditions (2), (3) and (4). The initial condition of the problem is unknown in the domain, re>r > rw is only known at the boundaries were either they are visible or easily measurable. Equation (1) to (4) can be rewritten in the non dimensional form

$$\frac{\delta y}{\delta T} = \frac{1}{x}\frac{\delta}{\delta x}\left(x\frac{\delta y}{\delta x}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

$$y(1,0) = \lambda \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

$$y(\alpha, T) = 1, \ T \geq 0, \ \alpha > 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

and

$$\frac{\delta y}{\delta x}(\alpha, T) = 0, T \geq 0 \alpha > 1 \ldots\ldots\ldots\ldots\ldots\ldots 8$$

in which,

$$y = \frac{h}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

$$x = \frac{r}{r_w} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

$$T = \frac{\tau}{Sr_{w^2}} t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

$$\lambda = \frac{h_i}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

and

$$= \frac{r_e}{r_w} \text{...} 13$$

equation (5) was solved under equations (6),(7) and (8)

The approximate analytical solution of the governing differential equation (5) was given by

$$y = 1 - \left[(1-\lambda)\exp(-T/\phi) \left[\frac{\left[1/2(\alpha^2 - x^2) - \alpha^2 \log \alpha / x \right]}{1/2(\alpha^2 - 1) - \alpha^2 \log \alpha} \right] \right] \text{.......} 14$$

$$\frac{T}{\phi} = \text{non dimensional time parameter}$$

where,

$$\phi = \frac{\alpha^2}{4} \phi^1$$

in which,

$$\phi^1 = \int_{\frac{1}{\alpha}}^{1} \frac{(1 - Z^2 + \log Z^2)dZ}{1 - \frac{1}{\alpha}} \text{........................} 15$$

Z is the dummy variable equal to x/α or r/r_e

From equation 11,

$$\frac{T}{\phi} = \frac{\tau}{Sr_w^2 \phi} t = \frac{Kb}{Sr_w^2 \phi} t \text{ ....} 16$$

Multiplying numerator and denominator by 2π

$$\frac{T}{\phi} = \frac{2Pbt}{a} \text{..} 17$$

in which $P = \frac{\pi}{2\phi} \frac{K}{S}$ 18

a = Cross sectional area of the well

b = Area perpendicular to flow of unit width

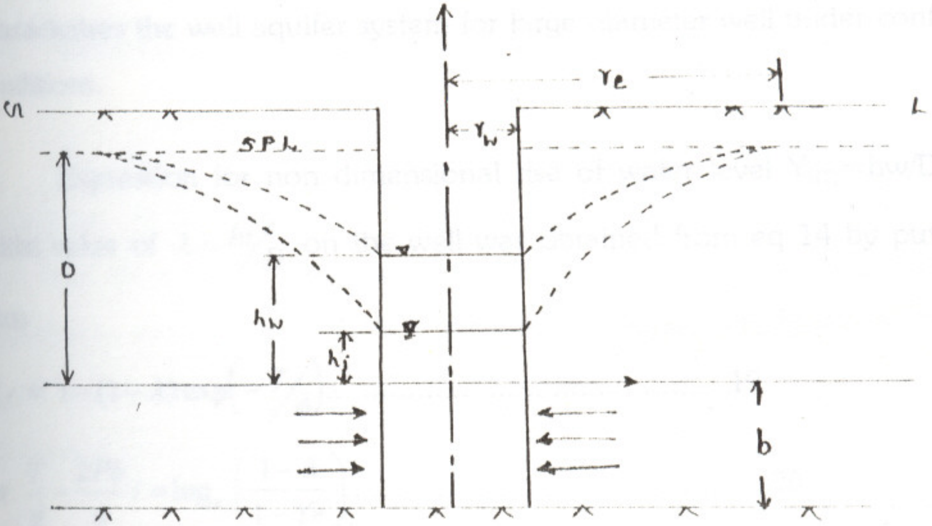

Fig. 1 Definition sketch of the problem

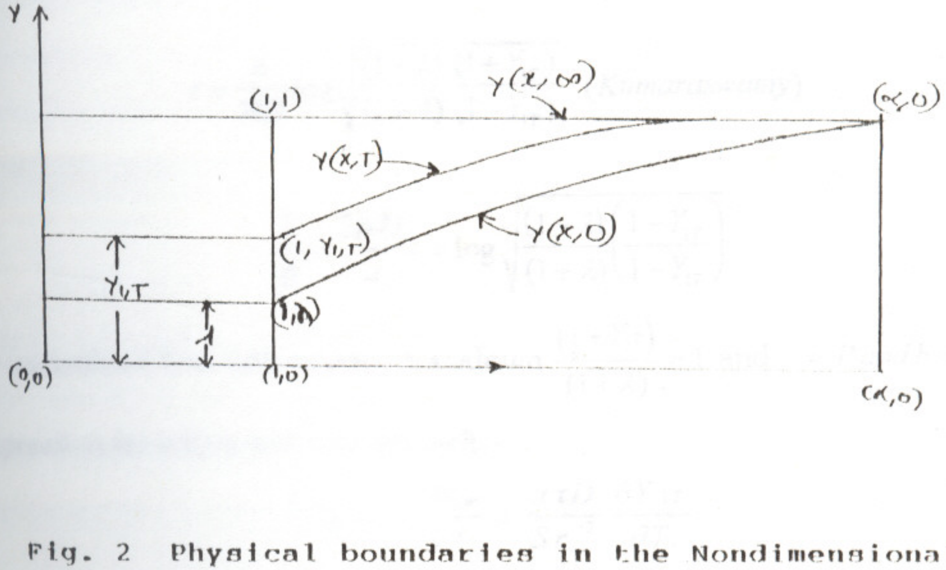

Fig. 2 Physical boundaries in the Nondimensional space

P has a unit of velocity, L/T and is a lumped parameter encompassing both hydgraulic properties of the aquifer (reflected on K/s ratio) and well geometry (reflected in Φ, which is function of re/rw ratio). P = The paratmeter which fully characterises the well aquifer system for large diameter well under confined flow conditions.

Expression for non dimensional rise of water level $Y_{(iT)}$=hw/D from an initial value of $\lambda = {hi}/{D}$ on the well was obtained from eq 14 by putting x=1, thus

$$Y_{iT} = 1-(1-\lambda)\exp\left(-T/\phi\right) \qquad \text{......19}$$

$$\text{or} \quad \frac{T}{\phi} - \frac{2Pb}{a}t = \log_e\left(\frac{1-\lambda}{1-Y_{iT}}\right) \qquad \text{......20}$$

By equation (17) and (19)

$$T = \frac{a}{Pb}\log\sqrt{\frac{(1-\lambda)}{(1-Y_{iT})}} \qquad \text{......21}$$

for unconfined flow conditions

$$t = \frac{a}{WD}\log\sqrt{\frac{(1-\lambda)}{(1+\lambda)}\frac{(1+Y_{1T})}{(1-Y_{1T})}} \quad (Kumaraswamy)$$

$$\frac{T}{\phi} = \frac{2WD}{a}t = \log\sqrt{\frac{(1-\lambda)}{(1+\lambda)}\left(\frac{1+Y_{1T}}{1-Y_{1T}}\right)}$$

for unconfined flow with smaller drawdown $\frac{(1+Y_{iT})}{(1+\lambda)} \approx 1$ and $\approx P \, and \, b \approx D$

Expression for inflow rate into the well :-

$$q = a\,\frac{\partial h_w}{a t} = \frac{a\,\tau D}{S r_w{}^2}\,\frac{\delta Y_{1T}}{\partial T}$$

after some algebraic manipulation, q was given by

$$q = 2PbD(1-\lambda)e^{-\frac{T}{\phi}}$$

q for confined flow condition can also be written as

$$q=2PbD(1-Y_{1T})$$

2.4 Verification of the Proposed Theory

To verify the theory proposed six wells were chosen on various formations. All the wells were under unconfined flow conditions, thus recovery test data from them were expected to match the proposed theory when drawdowns were small. The field recovery response was found to be in very good agreement with the predicted response for all the wells in various geological formations.

Rajagopalan *et al.,* (1985) developed a digital simulation model for the solution of the unsteady state radial flow to a large diameter dug well penetrating the full saturated thickness of an unconfined aquifer. The numerical solution was based on the finite difference approach. The computational algorithm was an iterative version of the alternating direction implicit method. A sensitivity analysis had been carried out on the model parameters of the aquifer namely lateral permeability, anisotropy, specific storage and specific yield. The simulation model has also been applied to a field dug well test data following a parameter adjustment procedure.

Nativ *et al.,* (1988) developed a mathematical model and its numerical solution for a hydraulic system composed of two deep aquifers that are partially separated by an aquiclude. The model was designed to predict aquifer response to pumpage in terms of water pressure and density. Increasing the rate of pumpage was found to enlarge the unconfined area.

Sen (1992) devised to a simple methodology to obtain relevant type curves for extended wells. The basis of the methodology involved the separation of the flow domain into two complimentary parts namely the linear flow between the two ends of the wells and semi radial flow patterns with centers at the fractured ends. The analytical solutions to the problem was obtained by the use of type curves.

Serrano (1995) developed analytical solution of the non linear Boussinesq flow equation and of the exact two dimensional ground water flow equation subject to a non-linear free surface boundary condition using the method of decomposition and were tested with respect to linearised Boussinesq equation. The results indicated that for mild regional gradients, the linearised equation is a reasonable approximation to the non linear equations even if unusually high recharge rates or unusually law hydraulic conductivity values induce high local hydraulic gradients. The linearised equation deviates from the non-linear equations incase of large regional hydraulic gradients and in deep aquifers with shallow boundary conditions.

Szekely(1995) used a quasi, mixed and weighted three dimensional model to approximate the three dimensional unsteady drawdown on vertical pumping and on observation wells, fully or partially penetrating a single, vertically heterogeneous, anisotropic aquifer. Cases of confined, semi confined and unconfined flow conditions were considered. Numerical equations were used to quantify the numerical error of the methods, introduced by the vertical heteroginity of the aquifer. The simulation technique was proved to be appropriate to assess the drawdown in the production and observation wells in aquifers.

Moench(1996) proposed an alternative Laplace transform solution to the boundary value problem formulated and solved by Neuman to a partially penetrating well in a water table aquifer. It was found that the proposed Laplace transform was simpler than the solutions previously available and generally required much less computation time to invert than other Laplace transform solutions for the same level of accuracy. The results suggested that the alternative solution may prove to be advantageous for automated, least square fitting of theoretical drawdown with measured drawdown.

MATERIALS AND METHODS

The details and methodology of experimentation, data collection and analysis are presented in this chapter.

3.1 Location

The study site is situated in the north eastern side of the KCAET campus, Tavanur in Malappuram District of Kerala situated at 10^{O}53'30" North Latitude and 76^{O} East Longitude. Bharathapuzha river forms the Northern boundary of the study area. Location map of the study area is shown in Appendix IA.

3.2 Geology

The soil profile at the study site is composed of sand, sandy clay, laterite, and weathered rock.

3.3 Climate

Kerala has a humid tropical climate with temperature averaging between 20 and 30^{O} C through out the year. The mean annual precipitation averaging between 2000 and 4000 mm and is distributed over 125 rainy days. Kerala is situated with in the monsoon zone and is exposed to seasonal weather contrasts. One can differentiate between a 'hot weather period' from March to May, a 'South West monsoon period' from June to September, a 'North East monsoon period in November and December. The South West monsoon is the dominant rainy season.

Agroclimatically, the study area falls with in the border line of northern zone, central zone and kole lands of Kerala.

3.4 Description of Wells

The wells selected were numbered as well No.1,well No.2 and well No.3.All three wells are located on the North-Eastern side of the K.C.A.E.T campus.

Well No.1 in hard laterite formation is located in the K.C.A.E.T farm.It has a diameter of 2.4 m and depth of 6m. Well no2 in clayey formation is located near the North eastern boundary of the campus It has a diameter of 2.10m and depth of 5.7m. Both these wells are lined with laterite blocks. Well No.3 in alluvial formation is located on the banks of the Bharathapuzha river. The well has a diameter and depth of 1.93 and 6m respectively. It is lined with prefabricated concrete rings. All the three wells are circular in shape.

3.5 Methodology

The wells were pumped and allowed to recuperate to the maximum and tthe drawdown and recuperation patterns for each well was studied. Pumping was conducted using a 1.5 hp. centrifugal pump of 3.25 lps capacity. Based on this the pumping was scheduled into suitable block periods. Scheduling was done for a period of 8 h in a day. Flow to the open wells were also analysed using the available recovery response theory. Water level measurements where taken during pumping as well as during the recuperation phase. A weighted tape was used to take WL measurements.

3.5.1 Pumping schedule

The depth, diameter and depths to static water level were measured for all the three wells. The wells were pumped till it reached a level when no further water could be drawn. At this stage, the pumping was stopped and the well was allowed to recuperate. Water levels during pumping were measured at one minute interval for the first 15 minutes, at 5 minutes interval for the next 45 minutes and at 60 minutes interval thereafter. Water levels during recuperation were also measured at the same time intervals.

Considering the depth of water in the well and knowing the recuperation rate of the well, three possible schedules of pumping were selected for each of the wells and their feasibility were verified in the field. Pumping schedule was carried out for a period of 8 hours.

For well 1 the well could be pumped to a maximum of 48 minutes. Three schedules were proposed for this well. First scheduling was done for a block period of 4 hours, with 25 minutes pumping and 215 minutes recuperation. Thus two block periods were available in a day. Second scheduling was done for a block period of 2 hours with 15 minutes pumping and 105 minutes recuperation. The third scheduling comprised of 10 minutes pumping and 50 minutes recuperation.

For well No 2, the total pumping time available was 55 minutes. The first, second and third schedules, proposed for this well comprised of 30 minutes pumping and 210 minutes recuperation, 17 minutes pumping and 103 minutes recuperation and 10 minutes pumping and 50 minutes recuperation respectively.

For well No 3, the total pumping time available was 45 minutes. The proposed schedules for this well were 25 minutes pumping and 215 minutes recuperation, 15 minutes pumping and 105 minutes recuperation and 7 minutes pumping and 53 minutes recuperation.

Water level measurements were recorded just before pumping, after pumping and after recuperation.

3.6 Analysis of data

Data collected as described in section 3.5 were analysed using the following standard procedure.

3.6.1 Drawdown pattern

Time drawdown curves were obtained by plotting, time along X axis and drawdown along the Y axis for each of the wells. Relationships between time and drawdown were developed by regression analysis using the package "MSTAT".

3.6.2 Recuperation pattern

Time recovery curves were obtained by plotting time along X axis and recovery along Y axis. Time recovery relationships were also developed by regression analysis using "MSTAT".

3.6.3 Development of rational formulae for drawdown during cyclic pumping

Drawdown in the pumped well after 'n' cycles of operation was taken as a function of two variables, namely, number of cycles of operation, n, and fractional part of the cycle during which the well is pumped, P.

$$S_n = f\,(n,p)$$

ie., $S_n = K\,(p^a \,.\, n^b)$

where,

S_n = draw down in meters in the pumped well after 'n' cycles of operation and K, a and b are constants.

Multiple linear regression technique was used to find out the values of the above constants. This is done with a computer programme written in BASIC, which is presented in Appendix I.

3.6.4 Verification of the recovery response theory

The theory proposed by Basak.P, gives the expressions for transient recovery response and inflow rate into the well. Even though the theory was developed for confined flow conditions, it was also found to be true under unconfined flow conditions for small drawdowns.

Expressions for transient recovery response in the well are :

$$Y_{(1T)} = 1-(1-\lambda)e^{-T/\phi} \text{ ....(1)}$$

$$\frac{T}{\phi} = \frac{2Pbt}{a} = \frac{\log(1-\lambda)}{(1-Y_{(1,T)})} \text{ ....(2)}$$

$$t = \frac{a}{Pb} \log\sqrt{\frac{(1-\lambda)}{(1-Y_{(1,T)})}} \text{ ....(3)}$$

where,

$Y_{(1,T)}$ = nondimensional rise of water level = h_w / D

h_w = height of water surface at any instant from the bottom of the well during recuperation.

D = depth of static water level from the well bottom.

λ = hi/D

hi = initial height of the water surface from the well bottom during recuperation.

T/ϕ = nondimensional time parameter

P = lumped well parameter

t = time in hours

a = cross sectional area of the well in m^2

b = thickness of the aquifer. In unconfined aquifer b=D

The above theory was verified in 3 wells, in different geological formations under unconfined flow conditions. Firstly the lumped well parameter 'p' for each of the wells at different stages of recovery were calculated using equation(3). The arithmetic averages, P_{av}, for the 3 wells were also calculated. T/ϕ for each time is obtained from equation (2) by substituting P_{av} for P. Theoretical non dimensional rise of water level $Y_{(1,T)}$ (theoretical) was obtained by substituting T/ϕ in equation (1). Observed $Y_{(1,T)}$ is given by,

$$Y_{(1,T)} = \frac{h_w}{D}$$

Recovery data was prepared from the above observations and calculations for each of the wells. $Y_{(1,T)}$. observed and theoretical were compared by plotting graph with respect to $\frac{T}{\phi}$

The general condition for the validity of the theory is that

$$\frac{1+Y_{(1,T)}}{1+\lambda} \approx 1$$

RESULTS AND DISCUSSION

Scheduling of pumping time into suitable block periods is necessary for the optimum utilization of the well yield. The results of the so scheduled pumping conducted in three wells in different formations, mathematical relationships developed between time and drawdown and time and recovery, rational formulae evolved for net drawdown during cyclic pumping and field verification of the available recovery response theory are presented in this chapter.

4.1 Drawdown and recovery response

The water level measurements taken during drawdown and recovery phases for the three open wells as described in section 3.5.1 are presented in tables 2 to 4. From the tables, it is seen that the drawdown pattern is almost similar for all the three wells. Comparing the recuperation pattern of the three wells, recovery rate is found to be less for well 3. This is because of the sealing effect of the concrete rings. The contribution of water to this well is only from the bottom. For well 1 and well 2 in the initial stages of recuperations, the latter shows a higher recuperation rate while towards the end of the recuperation phases it is almost the same for the two wells. This is contradictory to the characteristics of clayey formations. This may be due to the presence of some permeable formation which stores water and supplies it to the well when the hydraulic gradient become steep.

4.1.1 Drawdown curves

The drawdown observations were used to plot the time drawdown curves for the three wells. Figures 3, 4 and 5 show the curves for well 1, well 2 and well 3 respectively. It is seen that during the initial phases of pumping a linear

Table 2. **Drawdown and recovery response of Well 1**

Diameter - 2.4m
Depth - 6.00m

Time (min)	Drawdown (m)	Recuperation(m)
0.0	0.00	0.00
1.0	0.12	0.01
2.0	0.23	0.03
3.0	0.31	0.04
4.0	0.39	0.05
5.0	0.45	0.06
6.0	0.51	0.07
7.0	0.59	0.08
8.0	0.70	0.08
9.0	0.77	0.09
10.0	0.82	0.10
11.0	0.87	0.11
12.0	0.92	0.11
13.0	0.97	0.12
14.0	1.05	0.13
15.0	1.09	0.14
20.0	1.40	0.19
25.0	1.67	0.24
30.0	1.197	0.29
35.0	2.21	0.33
40.0	2.39	0.37
45.0	2.69	0.40
50.0	2.61	0.46
55.0		0.51
60.0		0.53
120.0		0.99
180.0		1.38
240.0		1.71
300.0		2.01
360.0		2.19
420.0		2.30
480.0		2.41
540.0		2.49
1020.0		2.58

Table 3. Drawdown and Recovery Response of Well 2

Diameter - 2.13 m
Depth - 6.00m

Time (min)	Drawdown (m)	Recuperation (m)
0	0	0
1.0	0.10	0.05
2.0	0.20	0.09
3.0	0.29	0.16
4.0	0.38	0.21
5.0	0.47	0.26
6.0	0.56	0.30
7.0	0.66	0.36
8.0	0.75	0.40
9.0	0.82	0.43
10.0	0.90	0.49
11.0	1.00	0.54
12.0	1.10	0.60
13.0	1.15	0.62
14.0	1.23	0.65
15.0	1.31	0.68
20.0	1.70	0.80
25.0	2.00	0.92
30.0	2.25	1.09
35.0	2.45	1.15
40.0	2.60	1.26
45.0	2.72	1.30
50.0	2.80	1.37
55.0	2.85	1.42
60.0	2.95	1.50
120.0		1.95
180.0		2.13
240.0		2.20
300.0		2.24
360.0		2.27
420.0		2.28

Table 4. Drawdown and Recovery Response of Well 3

Diameter - 1.93 m
Depth - 6.00 m

Time (min)	Drawdown (m)	Recuperation (m)
0	0	0
1	0.06	5x10-3
2	0.12	0.01
3	0.18	0.015
4	0.24	0.02
5	0.30	0.025
6	0.35	0.03
7	0.41	0.035
8	0.47	0.04
9	0.54	0.045
10	0.61	0.05
11	0.66	0.055
12	0.72	0.06
13	0.79	0.06
14	0.85	0.065
15	0.91	0.065
20	1.17	0.07
25	1.41	0.08
30	1.70	0.095
35	1.93	0.1
40	2.16	0.125
45	2.39	0.15
50	2.61	0.16
55	2.84	0.17
60	3.08	0.18
120	3.24	0.45
180		0.60
240		0.74
300		0.85
360		0.93
1440		2.02

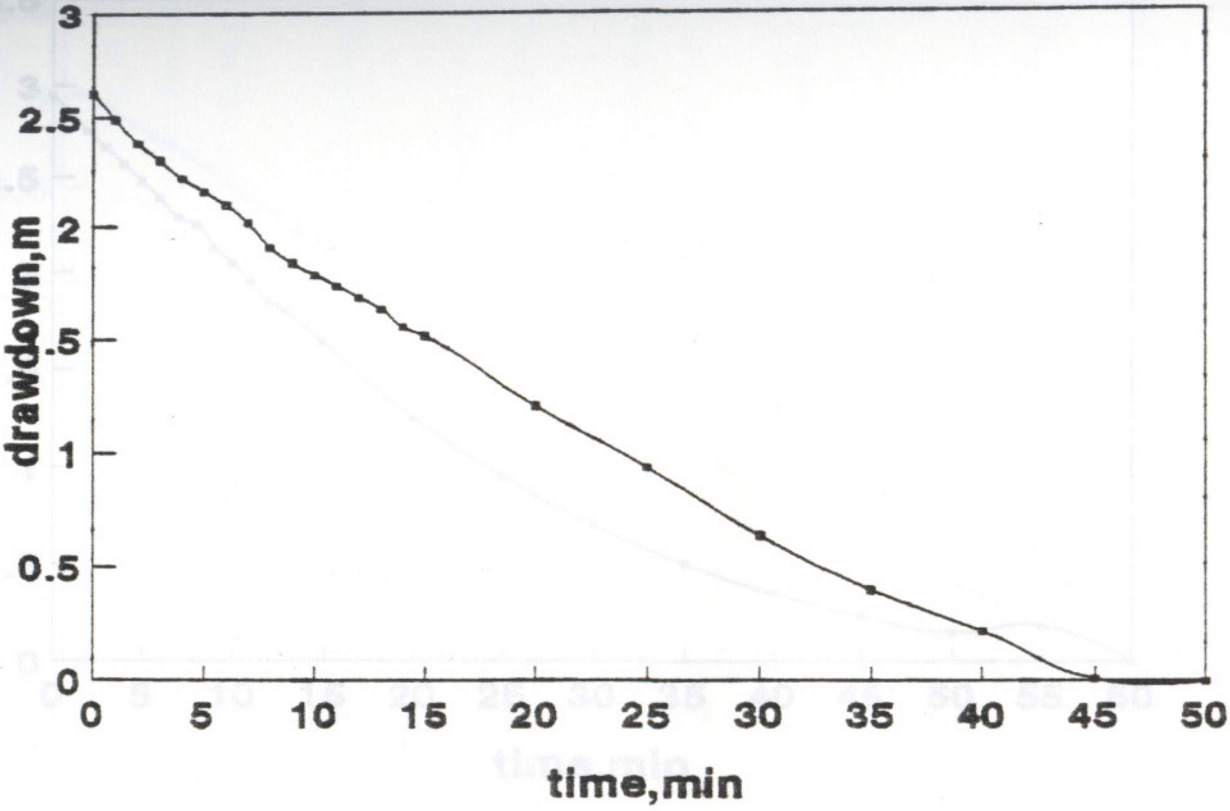

Fig.3 Drawdown curve for well 1

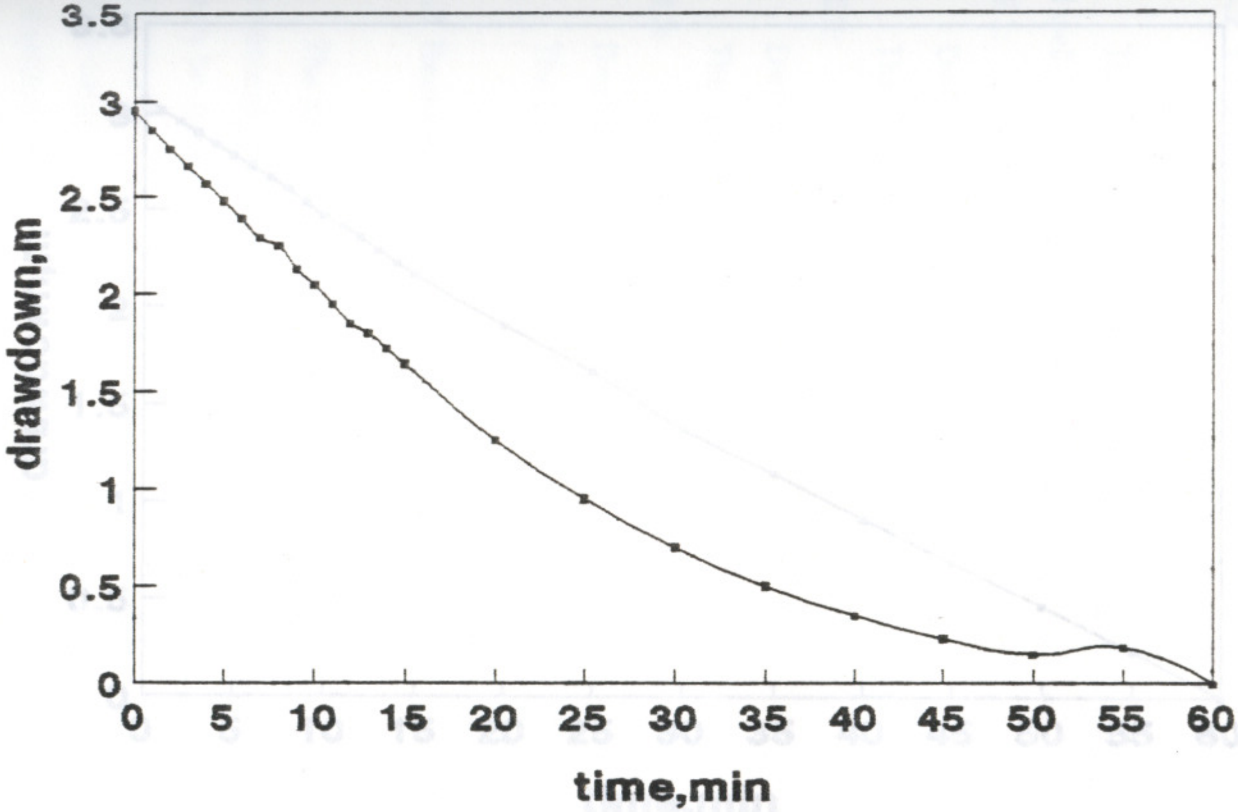

Fig.4 Drawdown curve for well 2

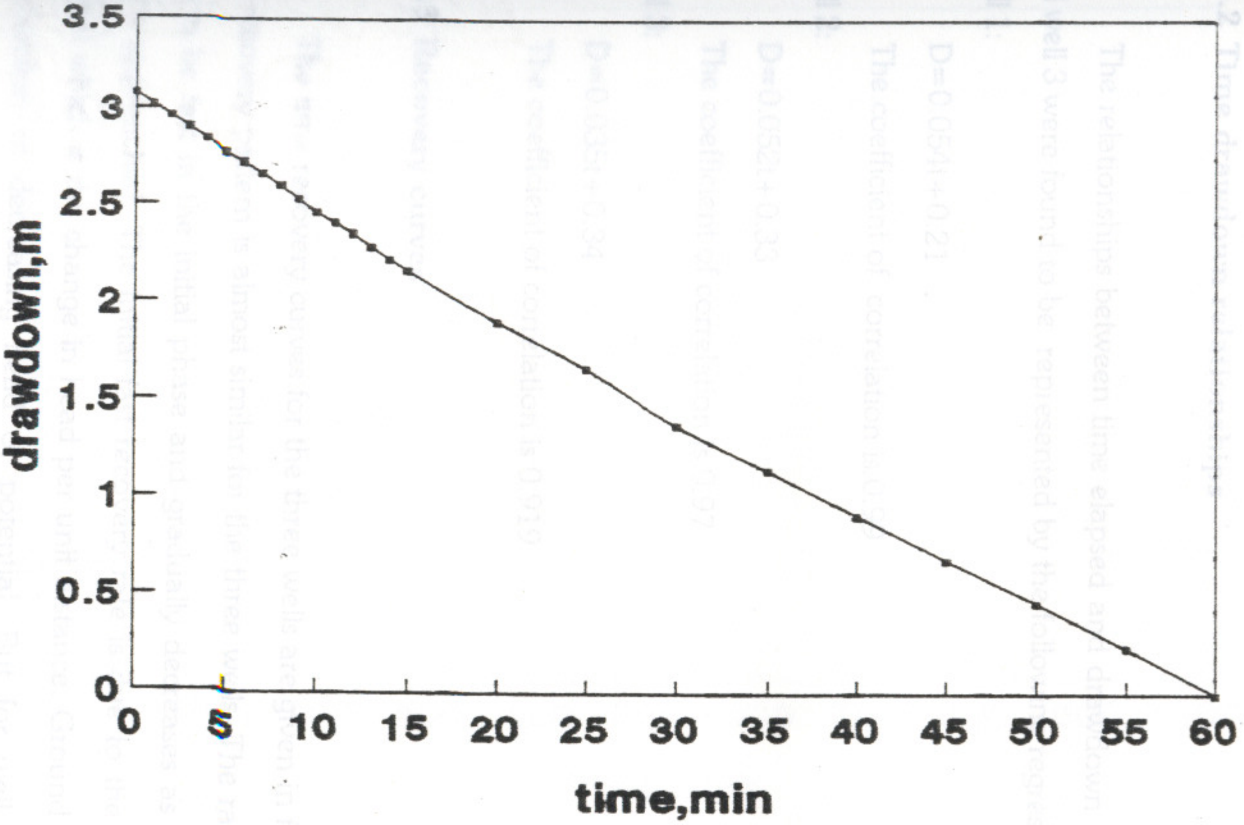

Fig.5 Drawdown curve for well 3

relationship exists between time and drawdown and gradually it becomes non-linear. This indicates that during the initial phases, water is drawn from the well storage and as the hydraulic gradient increases aquifer contribution increases. For well 3 the linear portion extends farther than for the other two wells. This must be because of the very low rate of aquifer contribution.

4.1.2 Time drawdown relationships

The relationships between time elapsed and drawdown for well 1, well 2 and well 3 were found to be represented by the following regression equations.

Well 1:

$D=0.054t+0.21$

The coefficient of correlation is 0.99

Well 2:

$D=0.052t+0.33$

The coefficient of correlation is 0.97

Well 3:

$D=0.035t+0.34$

The coefficient of correlation is 0.919

4.1.3 Recovery curves

The time recovery curves for the three wells are given in figures 6,7and 8. The recovery pattern is almost similar for the three wells. The rate of recovery is seen to be fast in the initial phase and gradually decreases as the static water level is approached. The initial fast recovery rate is due to the steep hydraulic gradient which is the change in head per unit distance. Ground water moves in the direction of decreasing head or potential. But for well 3, the rate of recuperation is found to be less than the other two wells. This can be attributed

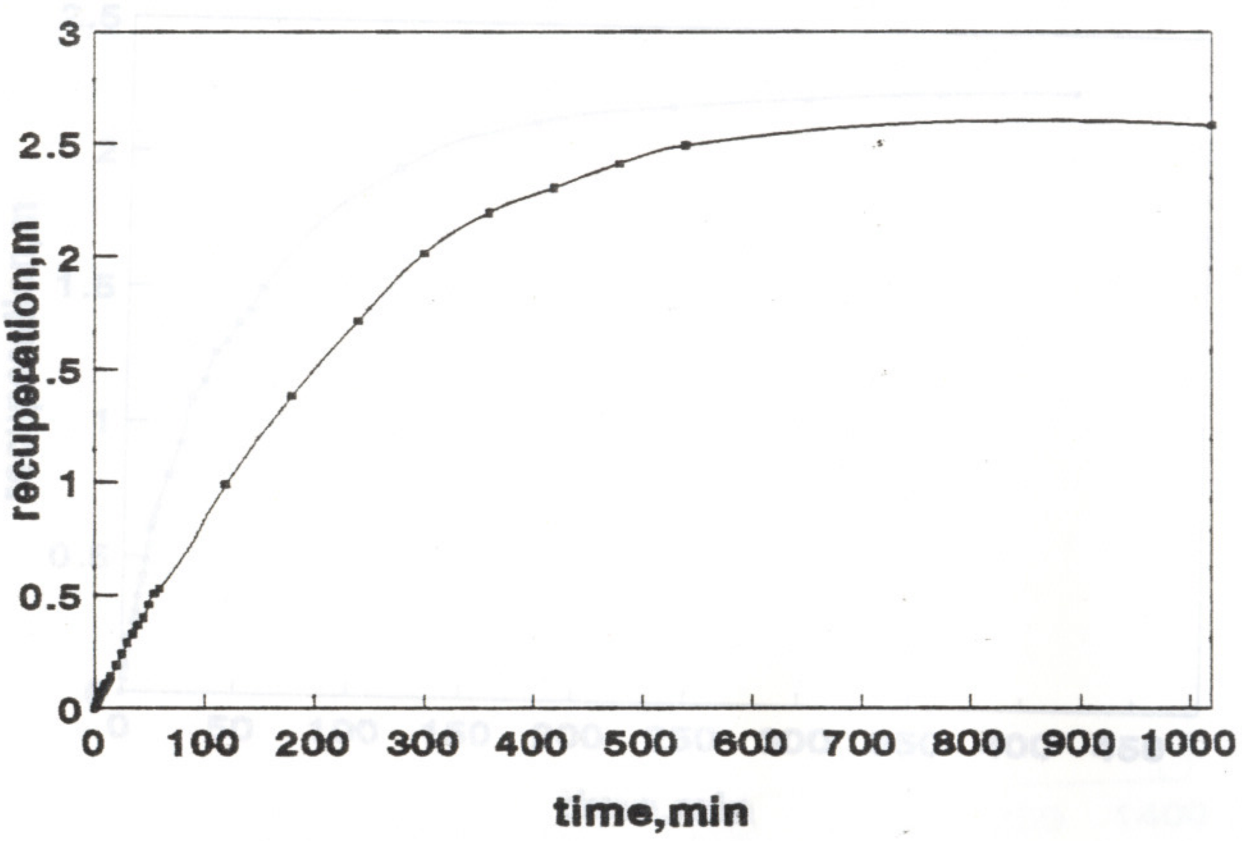

Fig.6 Recovery curve for well 1

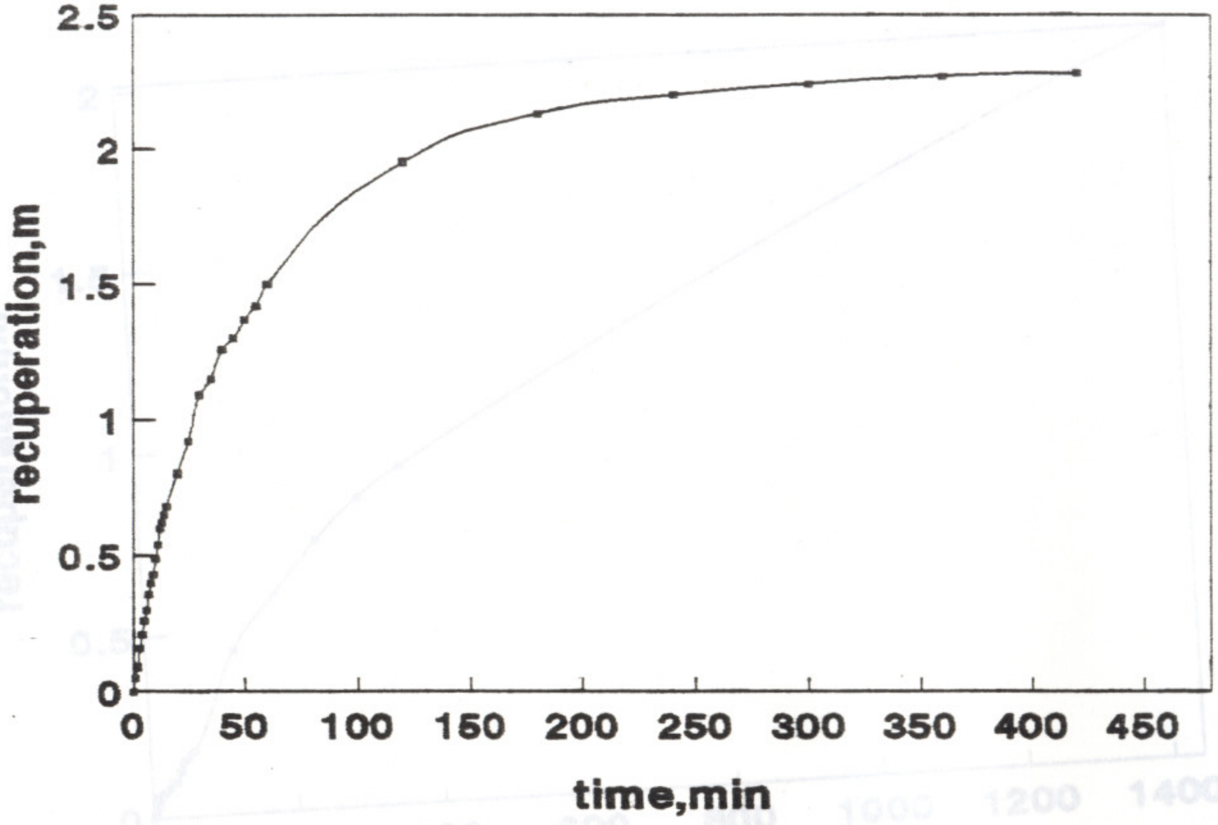

Fig.7 Recovery curve for well 2

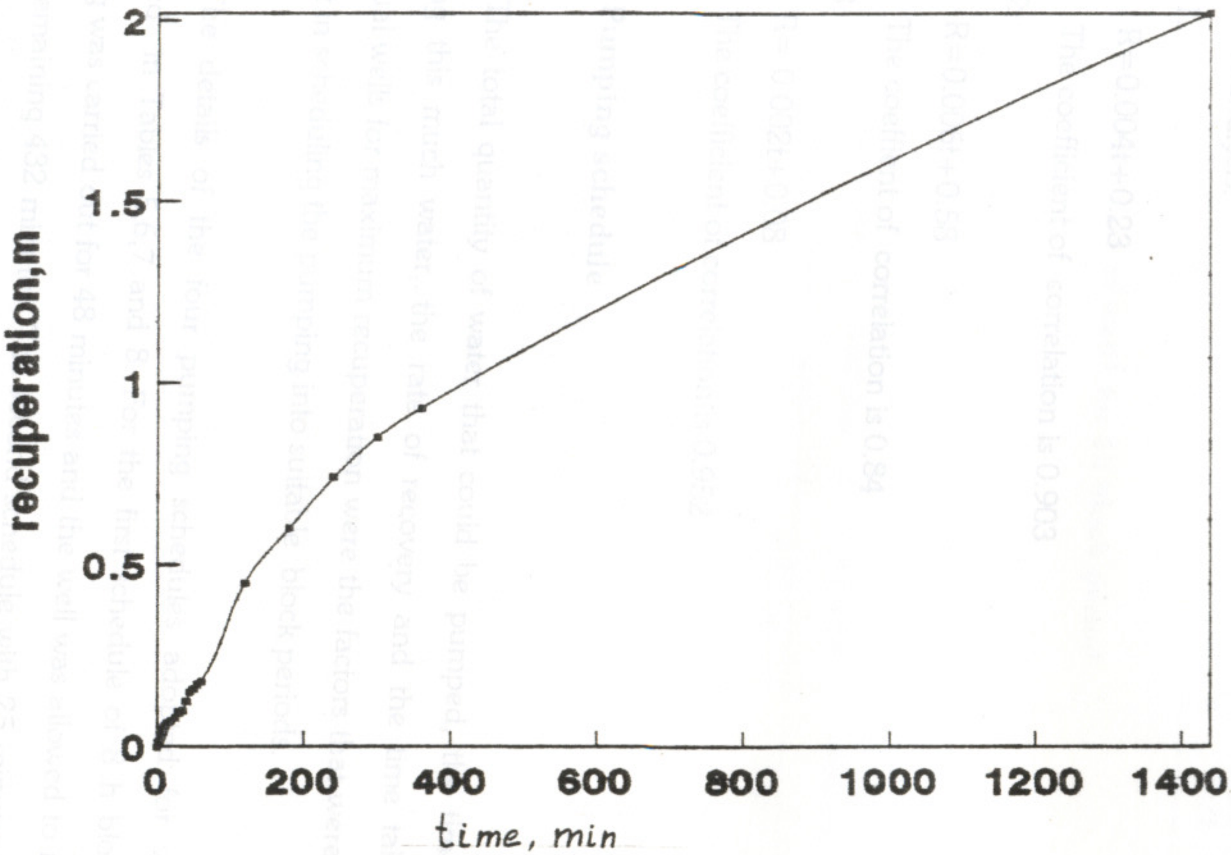

Fig.8 Recovery curve for well 3

to the fact that the well is lined with precast concrete rings and the flow occurs only through the bottom of the well.

4.1.4 Time recovery relationships

Time recovery relationships were developed for the three wells using the regression analysis.

Well 1:

$R=0.004t+0.23$

The coefficient of correlation is 0.903

Well 2:

$R=0.006t+0.58$

The coeffient of correlation is 0.84

Well 3:

$R= 0.002t+0.08$

The coefficient of correlation is 0.952

4.2 Pumping schedule

The total quantity of water that could be pumped, the time taken for pumping this much water, the rate of recovery and the time taken by the individual wells for maximum recuperation were the factors that were taken into account in scheduling the pumping into suitable block periods.

The details of the four pumping schedules adopted for well 1 are presented in Tables 5,6,7 and 8. For the first schedule of 8 h block period, pumping was carried out for 48 minutes and the well was allowed to recuperate for the remaining 432 minutes. The second schedule with 25 minutes pumping and 215 minutes recuperation had 2 cycles of pumping and recuperation. In the third schedule with altogether 4 cycles, pumping for 15 minutes was carried out

Table 5. Pumping data of well 1 for 8 h block period

Pumping time - 48 Minutes
Recuperation - 432 Minutes
No. of Block periods in a day - 1

Sl.no.	Time at start of pupmping	Water level at the start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	2 pm	3.75	2.48 pm	6.36	4.03

Table 6. Pumping data of well1 for 4h block period

Pumping time - 25 minutes
Recuperation time - 215 minutes
No. Of block periods in a day - 2

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at end of block period (m)
1	8.10 am	3.75	8.35 am	5.42	4.29
2	12.10 am	4.29	12.35 pm	5.75	4.42

Table 7 Pumping data of well 1 for 2 h block period

Pumping time - 15 Minutes
Recuperation time- 105 Minutes
No. Of block periods in a day - 4

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	7.50 am	4.00	8.05 am	4.32	4.31
2	9.50 am	4.31	10.05 am	5.08	4.00
3	11.50 am	4.50	12.05 am	5.35	4.75
4	1.50 pm	4.75	14.05 pm	5.55	4.95

Table 8. Pumping data of Well 1 for 1h block period

Pumping time - 10 Minutes
Recuperation time- 50 Minutes
No. Of block periods in a day - 8

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	7.55 AM	3.80	8.05 AM	4.38	4.19
2	8.55 AM	4.19	9.05 AM	4.75	4.45
3	9.55 AM	4.45	10.05 AM	5.03	4.61
4	10.55 AM	4.61	11.05 AM	5.12	4.75
5	11.55 AM	4.75	12.05 PM	5.24	4.86
6	12.55 PM	4.86	1.05 PM	5.40	5.04
7	1.55 PM	5.04	2.05 PM	5.56	5.26
8	2.55 PM	5.26	3.05 PM	5.76	5.40

Table 9. Overall View of Pumping Schedule for Well I

Sl. No.	Duration of Block Period(h)	Pumping Period (Minutes)	Recuperation Period (minutes)	Number of Recuperation per day (8h)	Total pumping time obtained (minutes)	Percentage increase in yield
1	8	48	432	1	48	
2	4	25	215	2	50	4
3	2	15	105	4	60	25
4	1	10	50	8	80	66.67

every 2 h. For the fourth schedule with consecutive 10 minutes pumping and 50 minutes recuperation there were 8 cycles.

The overall view of pumping scheduling adopted for well1 is given in Table 9. For 1h block period comprising of 10 minutes pumping and 50 minutes recuperation an additional pumping time of 32 minutes is obtained for 8h. Assuming that the pump discharge is constant the increase in yield with respect to the block period with 1 pumping in 8 h is 66.67% for this case. From a practical point of view, it may be difficult to have pumping periods at such short intervals. Also the net drawdown in the well is much larger compared to the other cases. Hence a 2 h block period with 15 minutes pumping and 105 minutes recuperation with 25% increase in yield can be adopted for this well.

The pumping schedules adopted for well 2 are depicted in Tables 10,11,12,13 and 14. Though the fourth schedule with 10 minutes pumping and 50 minutes recuperation gives maximum increase in yield of 45.45%, the third schedule with 17 minutes pumping and 103 minutes recuperation and having 23.63% increase in yield is practically adoptable.

The details of the four pumping schedules adopted in well3 are given in Tables 15,16,17,18 and 19. The third schedule comprising of 15minutes pumping and 105 minutes recuperation has maximum increase in yield of 133.33%. This 2h block period can be adopted.

The diagrammatic representation of the various pumping schedules adopted for the 3 wells are shown in figures 9,10 and 11.

Table 10. Pumping data of well 2 for 8h block period

Pumping time - 55 Minutes
Recuperation time- 425 Minutes
No. Of block periods in a day - 1

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	9.25 am	3.25	10.25 am	6.20	3.93

Table 11. Pumping data of Well 2 for 4 h block period

Pumping time - 30 Minutes
Recuperation period- 210 Minutes
No. Of block periods in a day - 2

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	10.25 am	3.90	10.55 am	5.83	4.24
2	2.25 pm	4.24	2.55 pm	6.14	4.17

Table 12. Pumping data of well 2 for 2h Block period

Pumping time - 17 Minutes
Recuperation time- 103 Minutes
No. Of block periods in a day - 4

	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	9.55 am	4.10	10.10 am	5.31	4.64
2	11.55 am	4.64	12.10 pm	5.85	4.86
3	1.55 pm	4.86	2.10 pm	5.92	4.81
4	3.55 pm	4.81	4.10 pm	5.86	4.87

Table 13. Pumping data of well 2 for 1h block period

Pumping time - 10 Minutes
Recuperation time- 50 Minutes
No. Of block periods in a day - 8

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	9.15 am	4.33	9.25 am	5.12	4.78
2	10.15 am	4.78	10.25 am	5.50	5.10
3	11.15 am	5.10	11.25 am	5.82	5.30
4	12.15 pm	5.30	12.25 pm	5.93	5.42
5	1.15 pm	5.42	1.25 pm	6.06	5.41
6	2.15 pm	5.41	2.25 pm	6.04	5.32
7	3.15 pm	5.32	3.25 pm	6.05	5.389
8	4.15 pm	5.39	4.25 pm	6.04	5.44

Table 14. Overall view of Pumping Schedule for Well 2

Sl. No.	Duration of Block Period(h)	Pumping Period (Minutes)	Recuperation Period (minutes)	Number of Recuperation per day (8h)	Total pumping time obtained (minutes)	Percentage increase in yield
1	8	55	425	1	55	
2	4	30	210	2	60	9.1
3	2	17	103	4	68	23.6
4	1	10	50	8	80	45.45

Table 15. Pumping data of well 3 for 8h block period

Pumping time - 45 Minutes
Recuperation time- 435 Minutes
No. Of block periods in a day - 1

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	10.14 pm	3.11	10.59 am	5.35	4.71

Table 16. Pumping data of well 3 for 4h block period

Pumping time - 25 Minutes
Recuperation time- 215 Minutes
No. Of block periods in a day - 2

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	8.00 am	3.82	8.25 am	5.04	4.68
2	12.00 noon	4.68	12.25 pm	5.82	5.38

Table 17. Pumping data of well 3 for 2h block period

Pumping time - 15 Minutes
Recuperation time- 105 Minutes
No. Of block periods in a day - 4

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	8.20 am	3.34	8.35 am	3.85	3.75
2	10.20 am	3.75	10.35 am	4.50	4.37
3	12.20 pm	4.37	12.35 pm	5.02	4.81
4	2.20 pm	4.81	2.35 pm	5.60	5.32

Table 18. Pumping data of well 3 for 1h block period

Pumping time - 7 Minutes
Recuperation time- 53 Minutes
No. Of block periods in a day - 8

Sl.no.	Time at start of pumping	Water level at start (m)	Time at stop of pumping	Water level at stop (m)	Water level at the end of block period (m)
1	8.20 am	3.75	8.27 am	3.96	3.94
2	9.20 am	3.94	9.27 am	4.29	4.25
3	10.20 am	4.25	10.27 am	4.63	4.55
4	11.20 am	4.55	11.27 am	4.84	4.74
5	12.20 pm	4.74	12.27 pm	5.14	5.05
6	1.20 pm	5.05	1.27 pm	5.38	5.31
7	2.20 pm	5.31	2.27 pm	5.61	5.51
8	3.20 pm	5.51	3.27 pm	5.76	5.65

Table 19. Overall View of Pumping Schedule for well 3

Sl. No.	Duration of Block Period(h)	Pumping Period (Minutes)	Recuperation Period (minutes)	Number of Recuperation per day (8h)	Total pumping time obtained (minutes)	Percentage increase in yield
1	8	45	435	1	45	
2	4	25	215	2	50	11.11
3	2	15	105	4	60	33.33
4	1	7	53	8	56	24.44

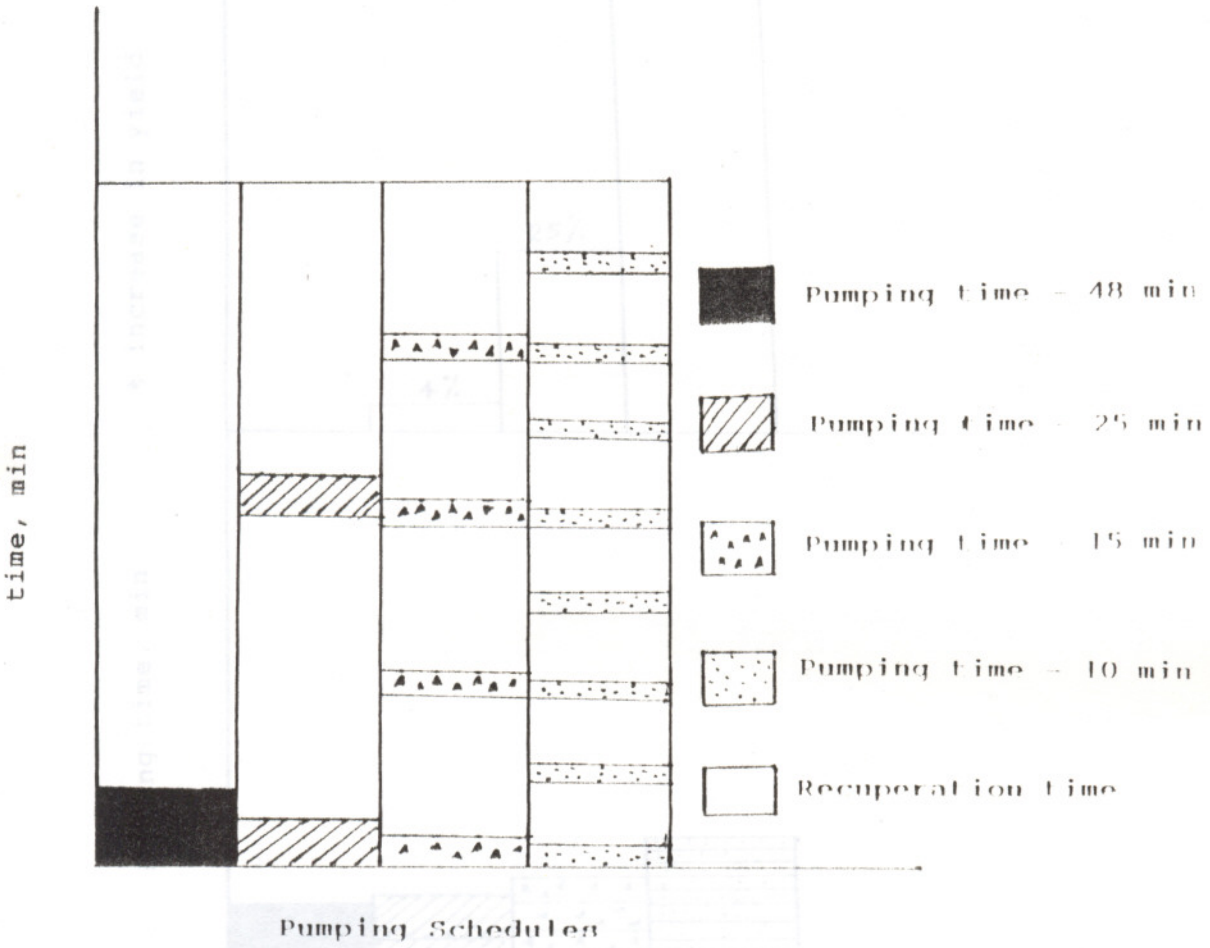

Fig. 9(a) Diagrammatic representation of pumping schedules of well I

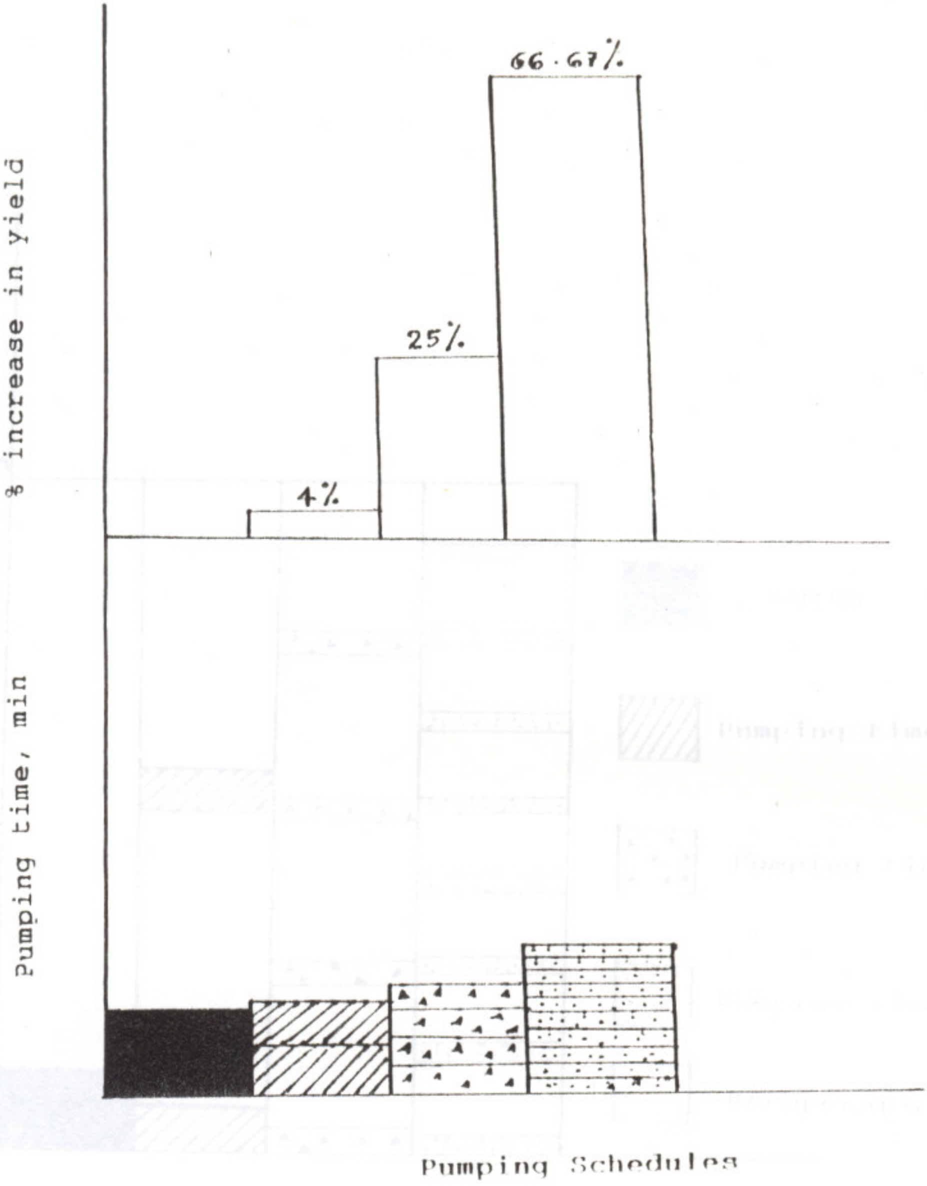

Fig. 9(b) Diagramatic representation of pumping schedules of well I

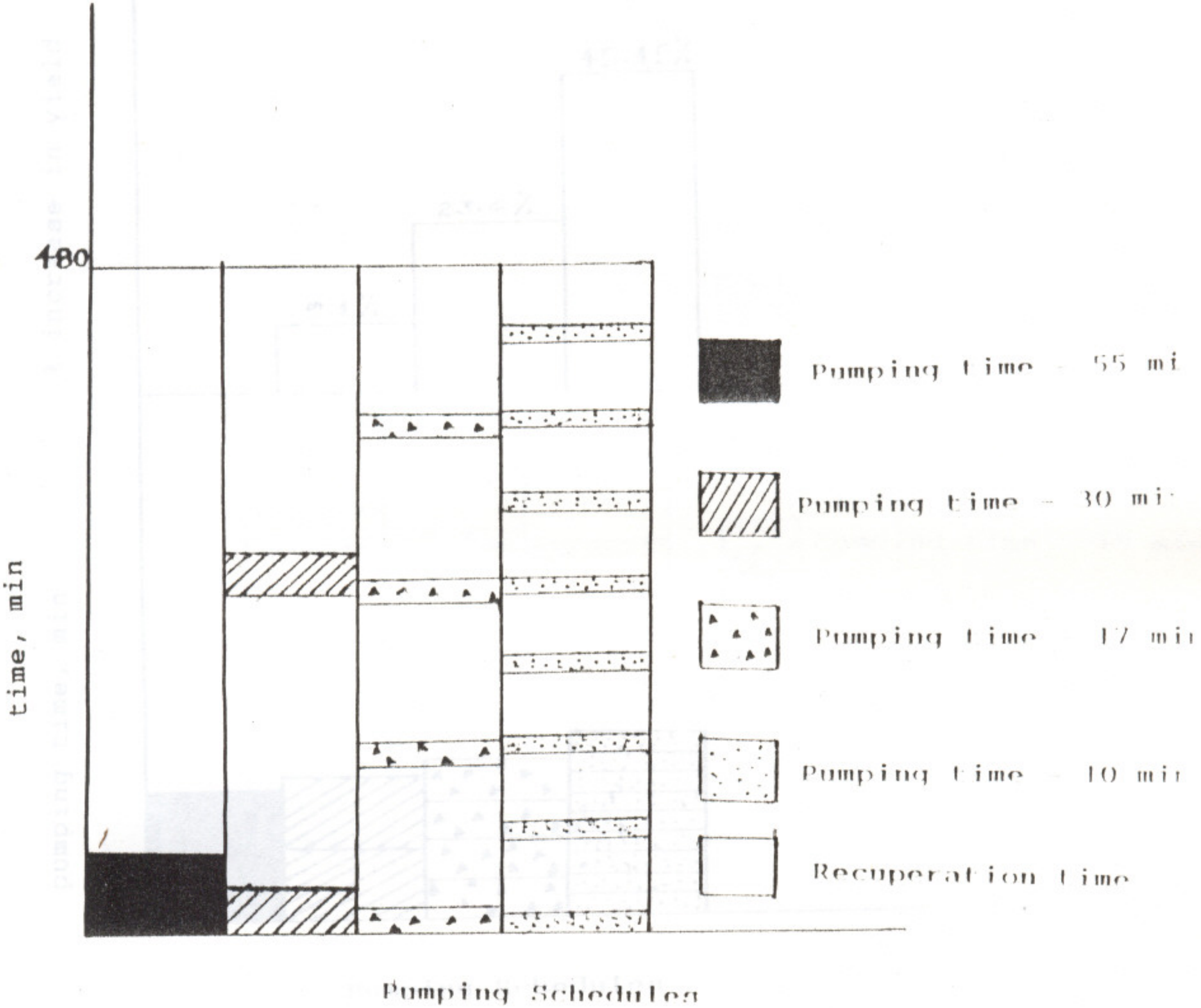

Fig. 10(a) Diagramatic representation of pumping schedules of well 2

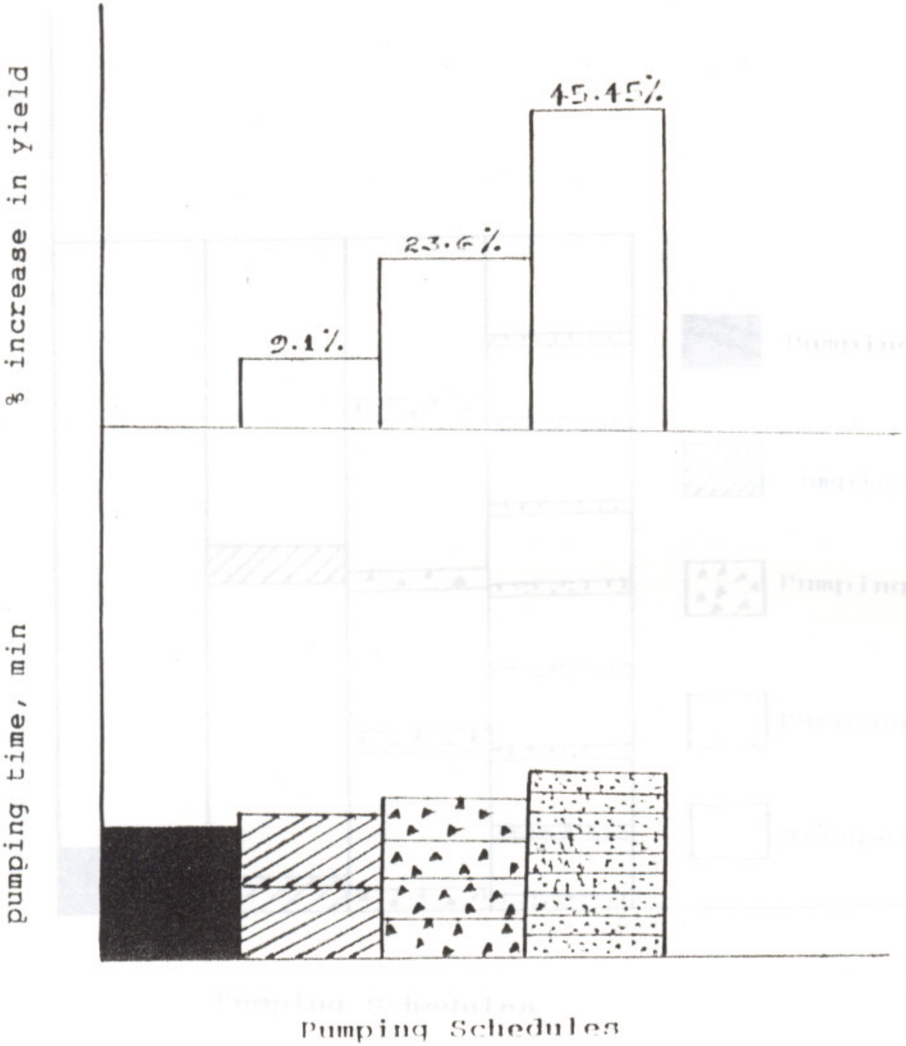

Fig. 10(b) Diagramatic representation of pumping schedules of well 2

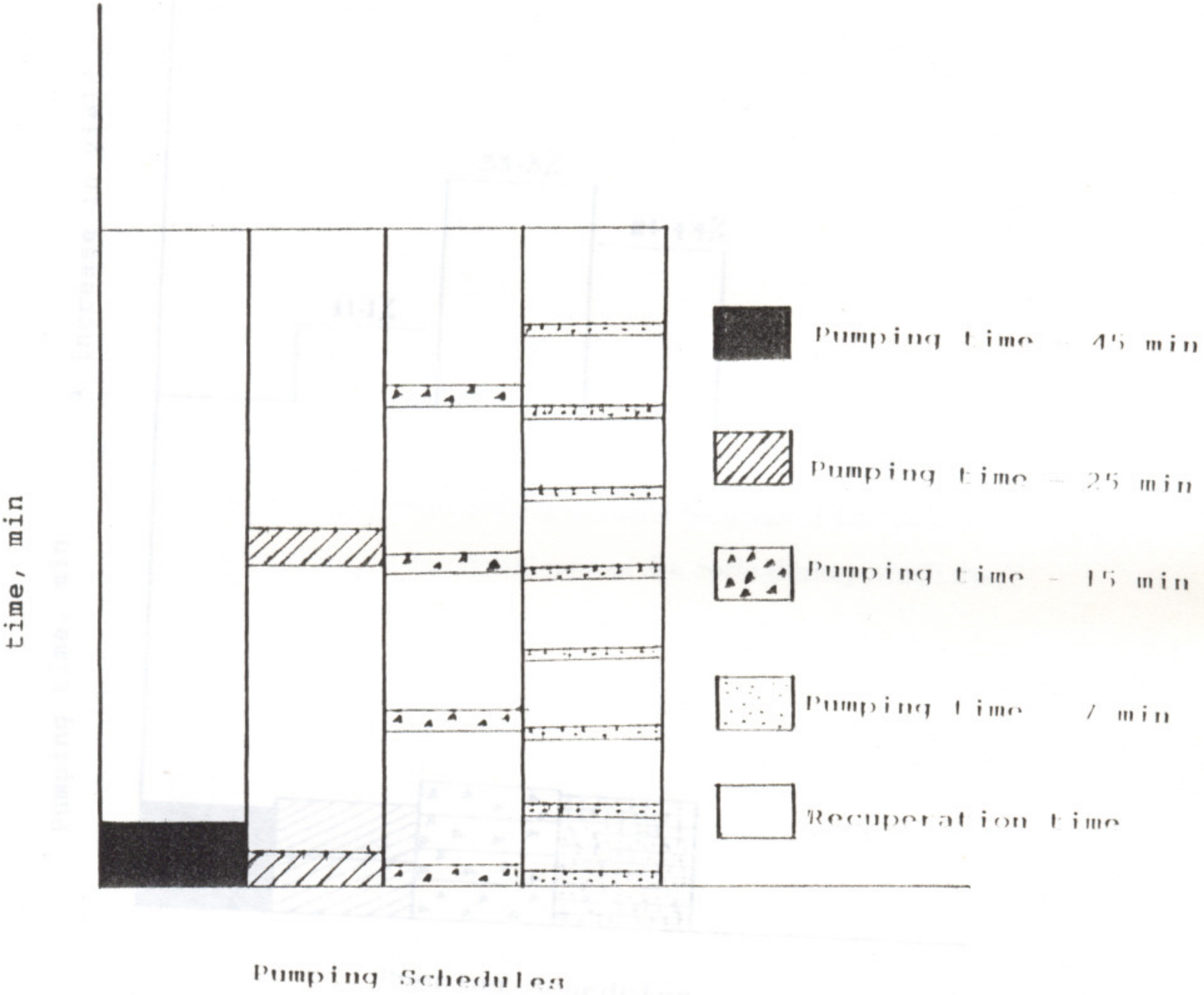

Fig. 11(a) Diagramatic representation of pumping schedules of well 3

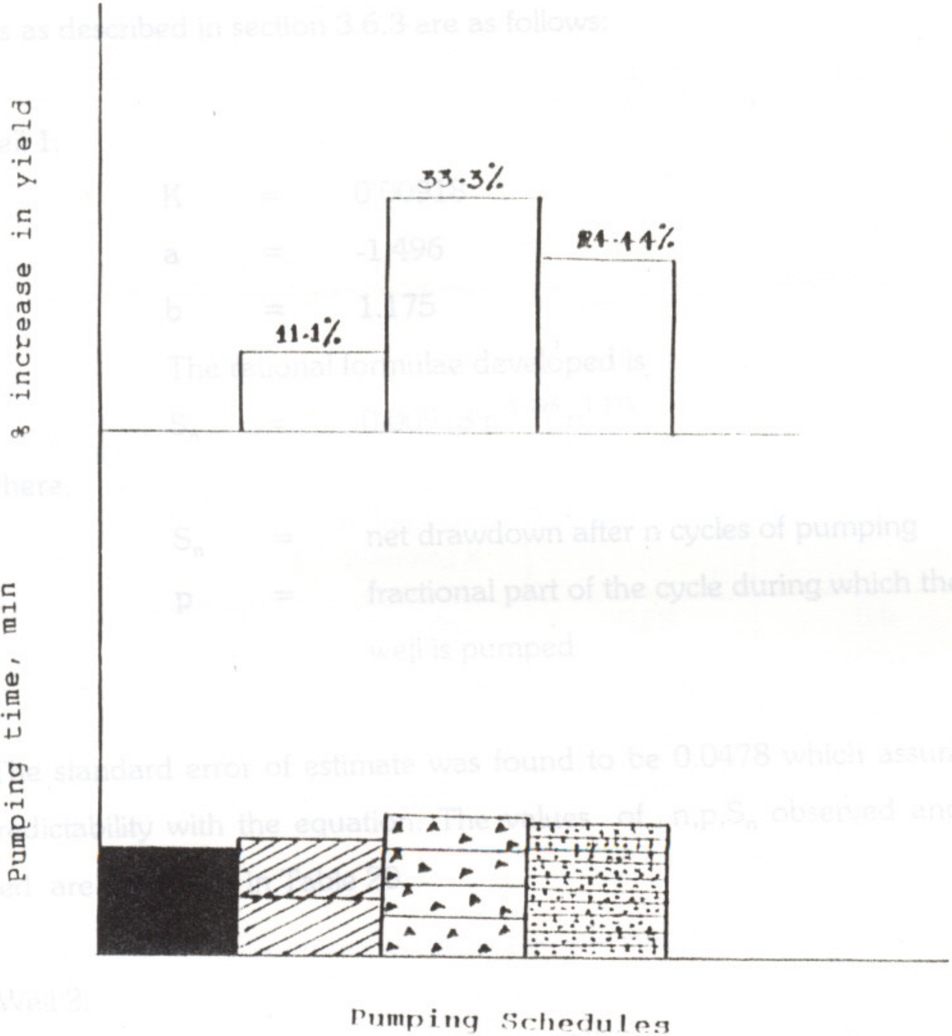

Fig. 11(b) Diagramatic representation of pumping schedules of well 3

4.2.1 Development of rational formulae for drawdown during cyclic pumping

The results of the multiple linear regression analysis done for each of the three wells as described in section 3.6.3 are as follows:

Well 1:

$K = 0.00918$

$a = -1.496$

$b = 1.175$

The rational formulae developed is

$$S_n = 0.00918\, p^{-1.496}\, n^{1.175}$$

where,

S_n = net drawdown after n cycles of pumping

p = fractional part of the cycle during which the well is pumped

The standard error of estimate was found to be 0.0478 which assures a good predictability with the equation. The values of n,p,S_n observed and S_n calculated are presented in Table 20.

Well 2:

$K = 8.891816 \times 10^{15}$

$a = 17.18984$

$b = -2.735581$

The rational formulae developed is

$$S_n = 8.891816 \times 10^{15}\, p^{17.18984}\, n^{-2.735581}$$

Table 20 Observed and calculated net drawdown of well 1

Sl. No.	No. of cycles of pumping (n)	Fractional part of the cycle during which pumping is done (p)	Net drawdown observed (m) S_n (ob)	Net drawdown calculated (m) S_n (th)
1	1	0.1	0.28	0.287
2	2	0.104	0.67	0.613
3	4	0.125	0.95	1
4	8	0.1667	1.6	1.542

Table 21 Observed and calculated net drawdown of well 2

Sl. No.	No. of cycles of pumping (n)	Fractional part of the cycle during which pumping is done (p)	Net drawdown observed (m) S_n (ob)	Net drawdown calculated (m) S_n (th)
1	1	0.1146	0.68	0.6
2	2	0.125	0.27	0.39
3	4	0.14167	0.77	0.52
4	8	0.1667	1.11	1.27

Table 22 Observed and calculated net drawdown of well 3

Sl. No.	No. of cycles of pumping (n)	Fractional part of the cycle during which pumping is done (p)	Net drawdown observed (m) S_n (ob)	Net drawdown calculated (m) S_n (th)
1	1	0.09375	1.6	1.533
2	2	0.104	1.56	1.67
3	4	0.125	1.98	1.902
4	8	0.11667	1.9	1.87

The standard error of estimate is 0.165 which shows a moderate predictability with the equation. The values of n, p, S_n observed and S_n calcuated are given in Table 21.

Well 3:

$$K = 9.046$$

$$a = 0.75$$

$$b = 0.01778$$

$$S_n = 9.046\, p^{0.75}\, n^{0.01778}$$

The standard error of estimate is 0.076 which shows that S_n can be well predicted using the above equation. Table 22 gives the values of n,p,S_n observed and S_n calculated for well 3.

4.3 Field verification of the available recovery response theory

The values of lumped well parameter P and non-dimensional time parameter T/ϕ , theoretical non-dimensional rise in water level $Y_{(1,T)}$th and observed non-dimensional rise in water level $Y_{(1,T)}$ ob calculated as described in section 3.6.4 for all the three wells are given in Appendix II.

The observed and theoretical recovery response for well 1 is shown in Figure 12. Figure 13 is the enlarged view of the initial coinciding portion of Figure 12. Almost all the observed points fall either on the predicted response curve or very close to it. Thus the field recovery response is seen to be in very good agreement with the predicted response for this well in lateritic formation.

The observed and theoretical recovery response for well 2 is given in Figure 14. From the graph it can be observed that the theory holds good up to a T/ϕ value of 0.045. Figure 15 gives the enlarged view of this portion. As the well is in clayey formation, the theory is expected to be valid in this range only.

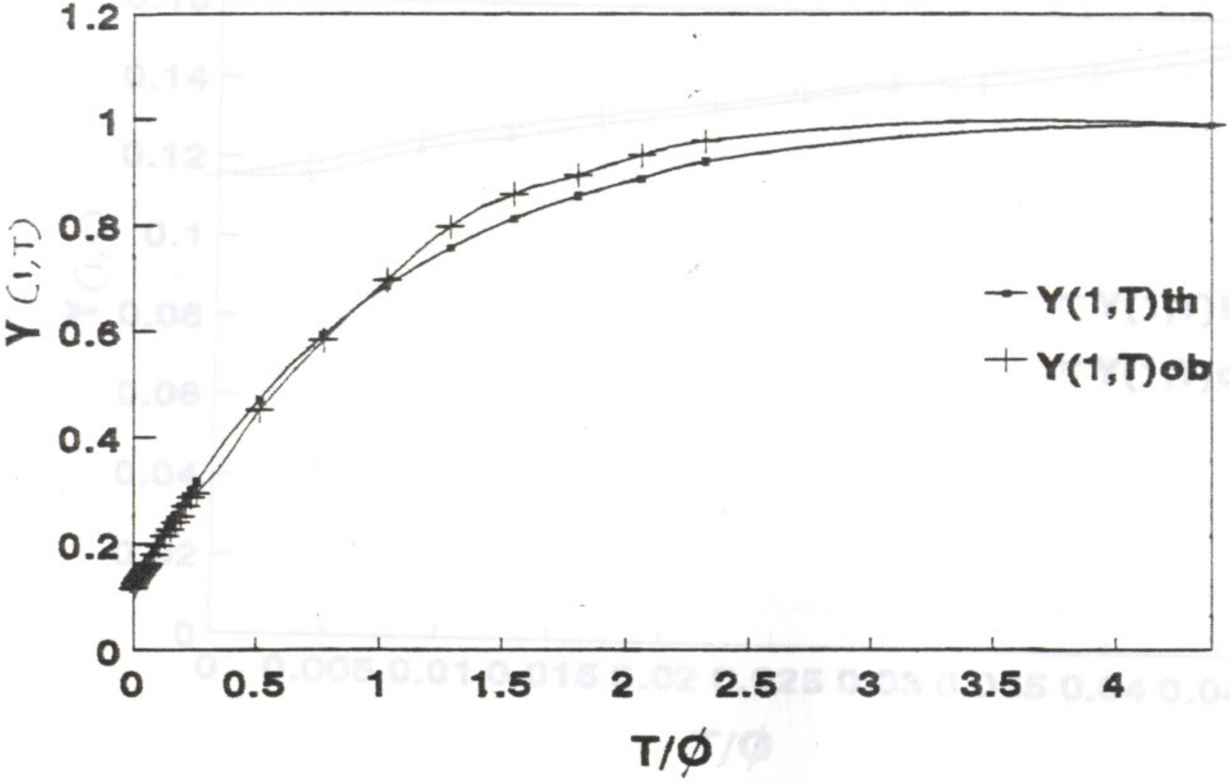

Fig.12 Observed and theoretical recovery response for well 1

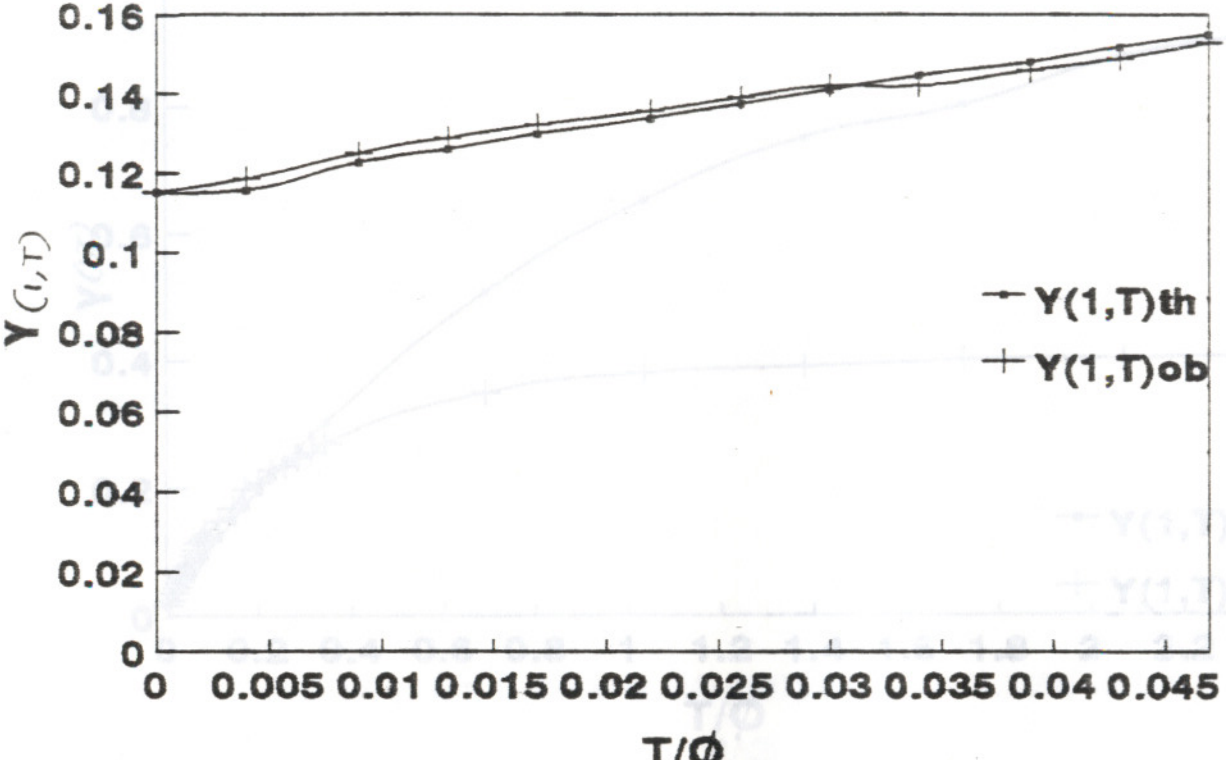

Fig.13 Enlarged view of recovery response for well 1

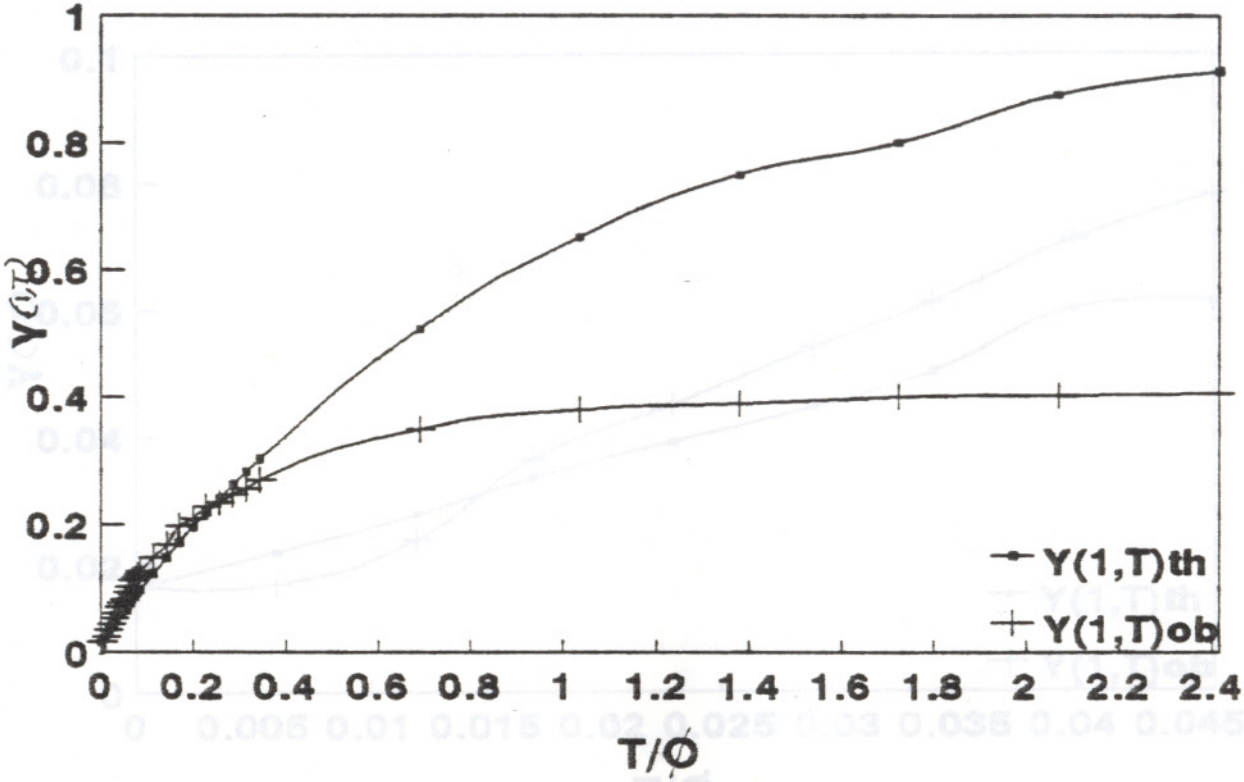

Fig.14 Observed and theoretical recovery response for well 2

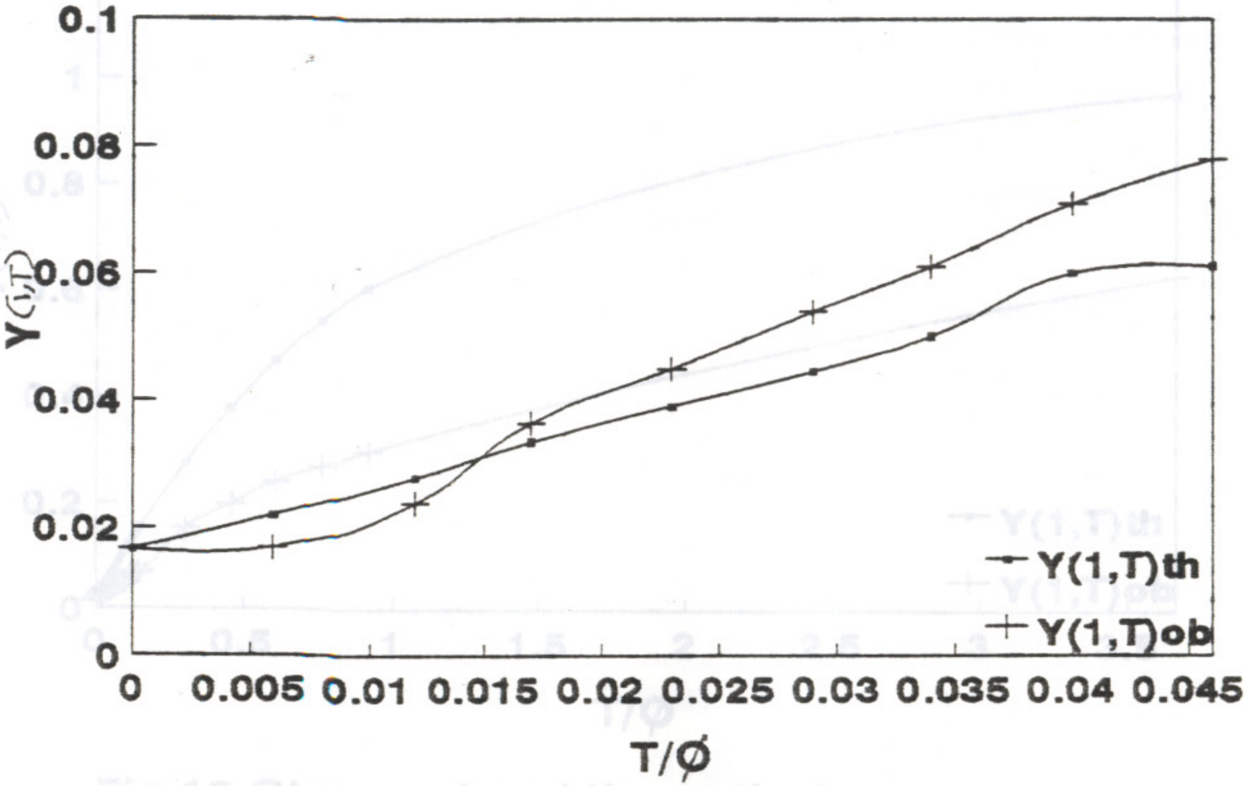

Fig.15 Enlarged view of recovery response for well 2

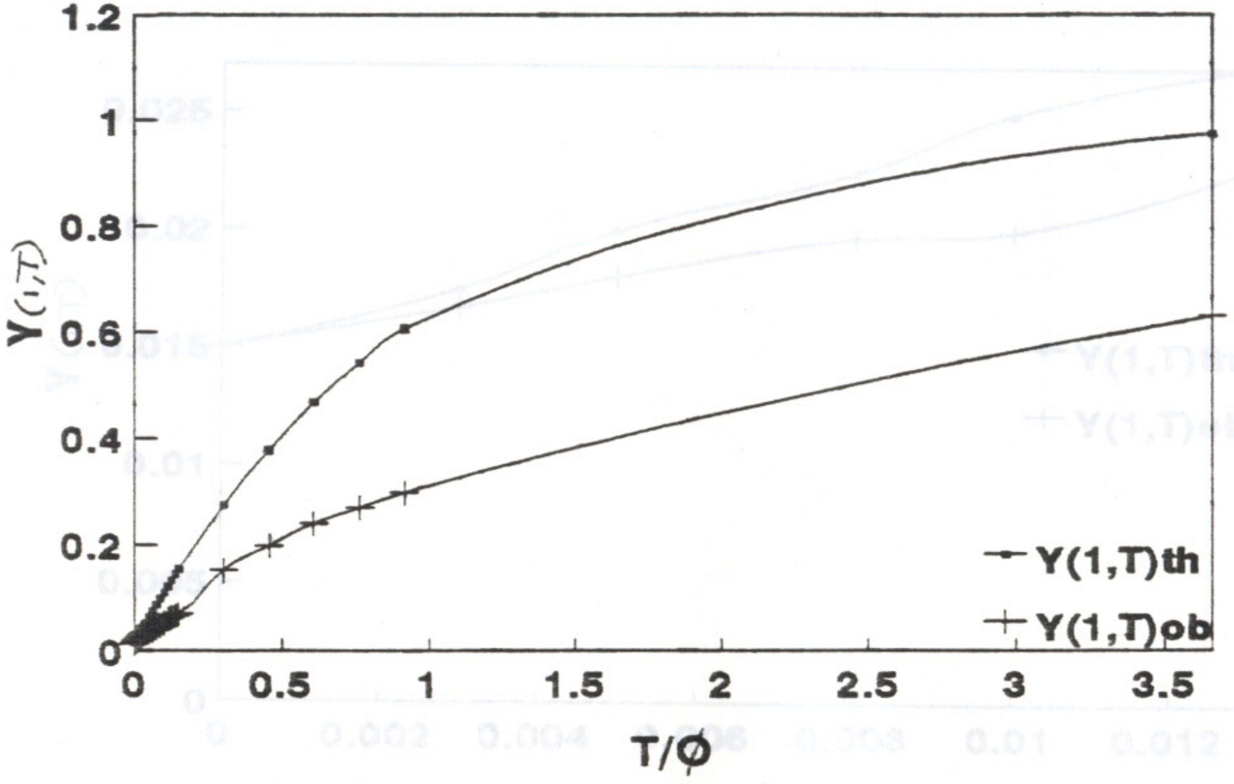

Fig.16 Observed and theoretical recovery response for well 3

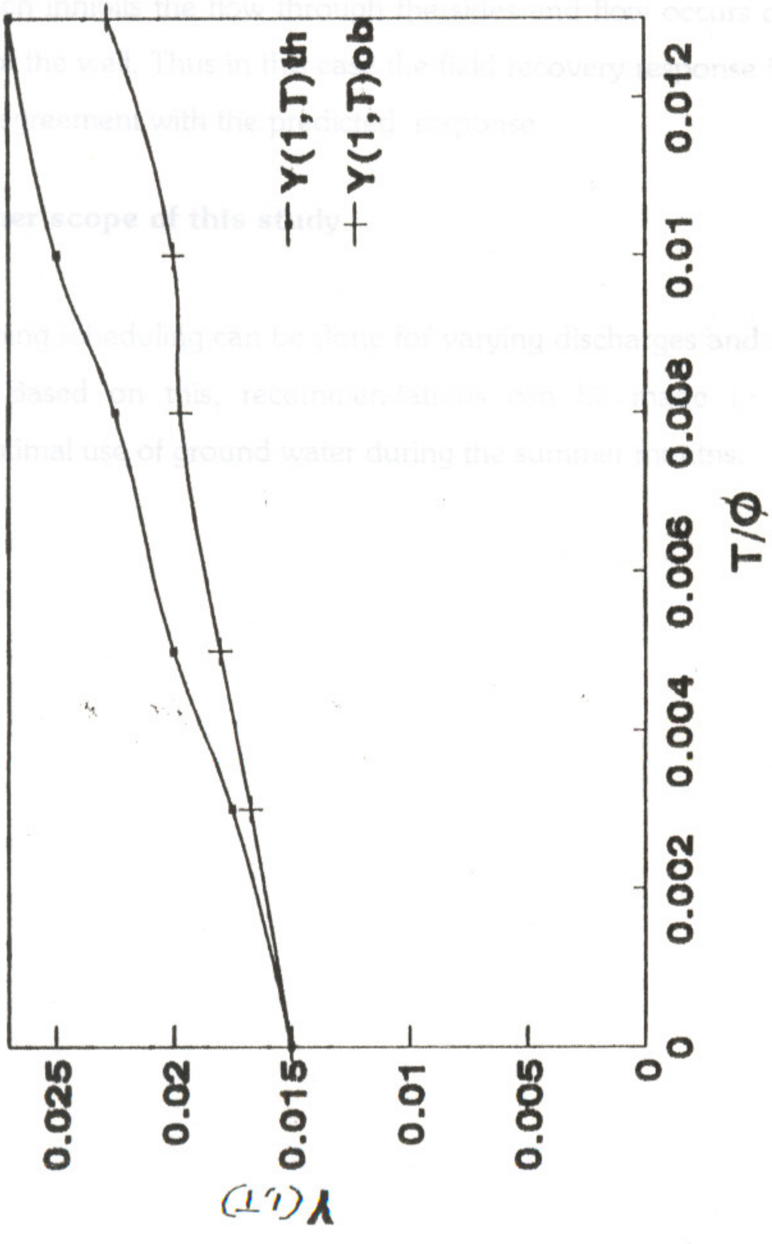

Fig.17 Enlarged view of recovery response for well 3

The graph for observed and theoretical recovery response for well 3 is shown in Figure 16. From the graph it is obvious that there is considerable deviation between observed and theoretical $Y_{(1,T)}$values. Figure 17 shows the enlarged view of the initial portion where the deviation between observed and theoretical $Y_{(1,T)}$ is small. Though the well is in sandy formation, the concrete lining of which inhibits the flow through the sides and flow occurs only through the bottom of the well. Thus in this case the field recovery response is seen to be in very little agreement with the predicted response.

4.4 Further scope of this study

Pumping scheduling can be done for varying discharges and for different formations. Based on this, recommendations can be made to the farmers regarding optimal use of ground water during the summer months.

SUMMARY AND CONCLUSIONS

Scheduling of pumping time is essential for the optimal use of yield of open wells particularly during the summer months. Hence a field study to suggest an optimum pumping schedule for wells in three different formations viz. laterite, clay and alluvial formation lined with precast concrete rings was conducted.

The main features of the experimental procedures are as follows:

1. The three wells were pumped and were allowed to recuperate to the maximum level . The water level measurements were taken during the drawdown and recovery phases.

2. Time drawdown and time recovery curves were plotted for each well using the drawdown and recuperation observations.

3. Time drawdown and time recovery mathematical relationships were formulated for the three wells.

4. Based on the total quantity of water that could be pumped , time taken for pumping this much water , recovery rate and time taken by each well for maximum recuperation, three possible pumping schedules for 1h, 2h and 4h block periods were selected and their feasibility tested in the field

5. The net drawdown during cyclic pumping was taken as a function of two independent variables viz. fractional part of the cycle during which the well is pumped and the no. of cycles of pumping. Multiple linear regression technique was used for the analyses of the data.

6 The available recovery response theory was verified in the three wells. The observed and theoretical recovery response viz. $Y_{(1,T)}$ ob and $Y_{(1,T)}$ th were determined and they were compared by plotting graphs with respect to the non-dimensional time parameter T/φ.

The following results were obtained from the analyses of the data collected:

1. The drawdown curves for all the three wells show a linear relationship during the initial phases of pumping indicating that the water is drawn mostly from well storage initially.

2. The mathematical relationships between the drawdown (D) and time (t) for the three wells are as follows:

Well 1

$$D = 0.054t + 0.21$$

Well 2

$$D = 0.052t + 0.33$$

Well 3

$$D = 0.035t + 0.34$$

3. The recovery curves for all the three wells were found to be almost similar with initial fast recovery rate which can be attributed to the steep hydraulic gradient at the beginning.

4. The mathematical relationships between the recovery (R) and time (t) for the three wells are as follows:

Well 1.

$$R = .004t + .23$$

Well 2

$$R = .006t + .58$$

Well 3.

$$R = .002t + .08$$

5. The optimum pumping schedule that can be adopted for well 1 is a 2 h block period with 15minutes pumping and 105 minutes recuperation with 25% increase in yield. For well 2 the optimum pumping schedule is a 2 h block period comprising of 17 minutes pumping and 103 minutes recuperation with 23.63% increase in yield and that for well 3 is a 2 h block period with 15 minutes pumping and 105 minutes recuperation and having 33.33% increase in yield.

6. The following rational formulae for net drawdown during cyclic pumping were evolved for the three wells by multiple linear regression analysis.

Well 1

$$S_n = 0.0918\, p^{-1.496}\, n^{1.175}$$

Well 2

$$S_n = 8.891816 \times 10^{15}\, p^{17.18984}\, n^{-2.735581}$$

Well 3

$$S_n = 9.046\, p^{.75}\, n^{.01778}$$

where,

S_n = net drawdown after n cycles of pumping

p = fractional part of the cycle during which the well is pumped

7. The field recovery response is seen to be in very good agreement with the theoretical recovery response predicted according to the available recovery response theory for well 1 in lateritic formation. For well 2 in clayey formation the theory was found to be valid only upto a T/φ value of .045. For well 3 in alluvial formation lined with concrete rings the theory does not hold good.

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* Originals not seen.

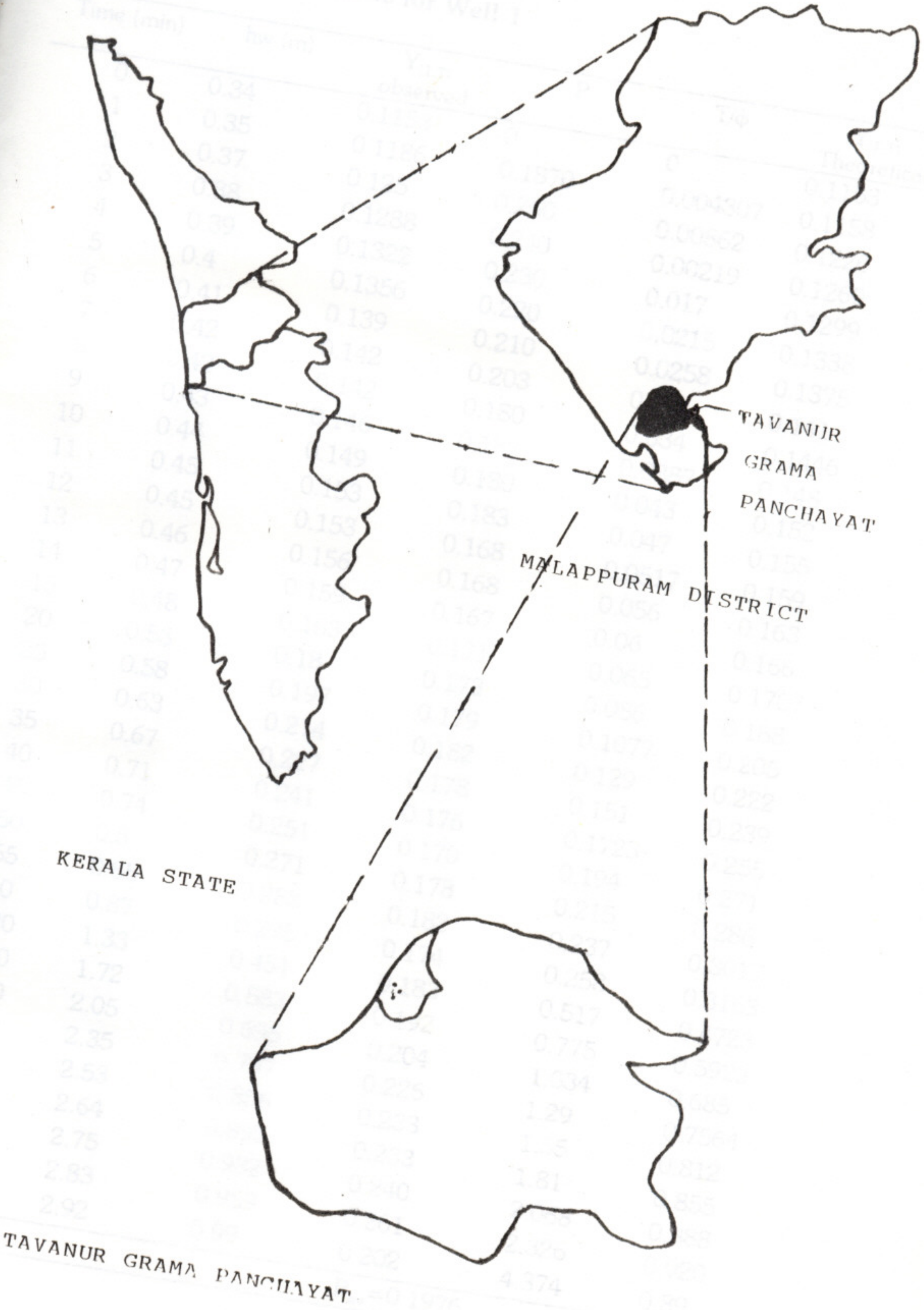
APPENDIX I

Computer program used for multiple regression analysis

```
10  REM MULTIPLE REGRESSION
20  DIM S(11),P(11),N(11),C(3),Y(11),VS(11),VP(11),VN(11)
30  DIM A(3,3),B(3,3)
40  INPUT M
50  FOR I = 1 TO M
60  INPUT VS(I),VP(I),VN(I)
70  S(I)= LOG (VS(I))
80  P(I)= LOG (VP(I))
90  N(I)= LOG (VN(I))
100 NEXT I
110 SA=0
120 PA=0
130 NA=0
140 PS=0
150 NS=0
160 PP=0
170 NN=0
180 PN=0
190 FOR I =1 TO M
200 SA=SA+S(I)
210 PA=PA+P(I)
220 NA=NA+N(I)
230 PS=PS+P(I)*S(I)
240 NS=NS+N(I)*S(I)
250 PP=PP+P(I)*P(I)
260 NN=NN+N(I)*N(I)
270 PN=PN+P(I)*N(I)
280 NEXT I
290 A(1,1)=PP*NN-PN*PN
300 A(1,2)=(-1)*(PA*NN-PN*NA)
310 A(1,3)=PA*PN-PP*NA
320 A(2,1)=(-1)*(PA*NN-NA*PN)
330 A(2,2)=M*NN-NA*NA
340 A(2,3)=(-1)*(M*PN-PA*NA)
350 A(3,1)=PA*PN-PP*NA
360 A(3,2)=(-1)*(M*PN-NA*PA)
370 A(3,3)=M*PP-PA*PA
380 D=M*A(1,1)+PA*A(1,2)+NA*A(1,3)
390 FOR I = 1 TO 3
400 FOR J = 1 TO 3
410 B(I,J)=A(I,J)/D
420 NEXT J
430 NEXT I
440 FOR I = 1 TO 3
450 C(I)=B(I,1)*SA+B(I,2)*PS+B(I,3)*NS
460 NEXT I
470 SST=0
480 SSR=0
490 SSE=0
500 FOR I = 1 TO M
510 Y(I)=C(1)+C(2)*P(I)+C(3)*N(I)
520 ST=(S(I)-(SA/M))^2
530 SR=(Y(I)-(SA/M))^2
540 SSR=SSR+SR
550 SE=(S(I)-Y(I))^2
560 SSE=SSE+SE
570 NEXT I
580 COD=SSR/SST
590 R=(COD)^(1/2)
600 K=EXP(C(1))
610 A=C(2)
620 B=C(3)
630 PRINT K,A,B
640 END
```

APPENDIX IA

Location Map of the study area



APPENDIX II

1.Recovery response table for Well 1

Time (min)	hw (m)	$Y_{(1.T)}$ observed	P	T/ϕ	$Y_{(1.T)}$ Theoretical
0	0.34	0.1153	0	0	0.1153
1	0.35	0.1186	0.1870	0.004307	0.1158
2	0.37	0.125	0.260	0.00862	0.1226
3	0.38	0.1288	0.240	0.00219	0.1260
4	0.39	0.1322	0.230	0.017	0.1299
5	0.4	0.1356	0.220	0.0215	0.1338
6	0.41	0.139	0.210	0.0258	0.1375
7	0.42	0.142	0.203	0.03	0.141
8	0.42	0.142	0.180	0.034	0.1446
9	0.43	0.146	0.182	0.0387	0.148
10	0.44	0.149	0.180	0.043	0.152
11	0.45	0.153	0.183	0.047	0.155
12	0.45	0.153	0.168	0.0517	0.159
13	0.46	0.156	0.168	0.056	0.163
14	0.47	0.159	0.167	0.06	0.166
15	0.48	0.163	0.171	0.065	0.1707
20	0.53	0.18	0.173	0.086	0.188
25	0.58	0.197	0.179	0.1077	0.205
30	0.63	0.214	0.182	0.129	0.222
35	0.67	0.227	0.178	0.151	0.239
40	0.71	0.241	0.176	0.1723	0.255
45	0.74	0.251	0.170	0.194	0.271
50	0.8	0.271	0.178	0.215	0.286
55	0.85	0.288	0.182	0.237	0.3017
60	0.87	0.295	0.174	0.258	0.3163
120	1.33	0.451	0.183	0.517	0.4723
180	1.72	0.583	0.192	0.775	0.5923
240	2.05	0.695	0.204	1.034	0.685
300	2.35	0.797	0.226	1.29	0.7564
360	2.53	0.858	0.233	1.55	0.812
420	2.64	0.895	0.233	1.81	0.855
480	2.75	0.932	0.240	2.068	0.888
540	2.83	0.959	0.261	2.326	0.920
1020	2.92	0.99	0.202	4.374	0.89
			$P_{av}=0.1976$		

2. Recovery response table for Well 2

Time (min)	hw (m)	$Y_{(1.T)}$ observed	P	T/φ	$Y_{(1.T)}$ Theoretical
0	0.050	0.0167	0	0	0.0167
1	0.100	0.017	0.0106	0.00575	0.022
2	0.140	0.024	0.124	0.0115	0.0279
3	0.210	0.0365	0.236	0.0173	0.0336
4	0.260	0.045	0.252	0.6173	0.0391
5	0.310	0.054	0.267	0.023	0.0446
6	0.350	0.061	0.266	0.0288	0.0500
7	0.410	0.071	0.281	0.0345	0.0600
8	0.450	0.078	0.278	0.0403	0.061
9	0.480	0.083	0.2680	0.046	0.0665
10	0.540	0.094	0.283	0.052	0.0716
11	0.590	0.103	0.289	0.0575	0.077
12	0.650	0.113	0.297	0.0633	0.0823
13	0.670	0.1165	0.285	0.069	0.0876
14	0.700	0.1220	0.279	0.0748	0.09275
15	0.730	0.1270	0.274	0.0805	0.0980
20	0.850	0.148	0.247	0.0863	0.1230
25	0.970	0.169	0.232	0.115	0.1484
30	1.140	0.198	0.235	0.1438	0.1725
35	1.200	0.280	0.215	0.1725	0.196
40	1.310	0.228	0.209	0.2013	0.2187
45	1.350	0.235	0.193	0.230	0.214
50	1.420	0.247	0.184	0.2588	0.2625
55	1.470	0.256	0.175	0.2876	0.2830
60	1.550	0.270	0.170	0.3163	0.3030
120	2.010	0.350	0.119	0.345	0.5070
180	2.180	0.380	0.0887	1.035	0.6510
240	2.25	0.390	0.0688	1.380	0.750
300	2.29	0.400	0.057	1.725	0.820
360	2.32	0.403	0.048	2.0705	0.8760
420	2.33	0.405	0.040	2.4156	0.912
			$P_{av}=0.199$		

3. Recovery response table for Well 3

Time (min)	hw (m)	$Y_{(1.T)}$ observed	P	T/ϕ	$Y_{(1.T)}$ Theoretical
0	0.50	0.015	0	0	0.015
1	0.055	0.0167	0.046	0.0255	0.0175
2	0.060	0.018	0.0407	0.00509	0.0200
3	0.065	0.0197	0.0426	0.007635	0.0225
4	0.070	0.0200	0.0340	0.0100	0.0250
5	0.075	0.0228	0.0425	0.0127	0.0270
6	0.080	0.0240	0.0409	0.0153	0.0299
7	0.085	0.0260	0.0429	0.0178	0.0320
8	0.089	0.0270	0.0409	0.0204	0.0350
9	0.095	0.0290	0.0425	0.023	0.0374
10	0.100	0.030	0.0410	0.0255	0.039
11	0.105	0.032	0.0423	0.0280	0.042
12	0.110	0.033	0.0411	0.0305	0.044
13	0.110	0.033	0.038	0.0331	0.071
14	0.115	0.0350	0.039	0.0356	0.049
15	0.115	0.0350	0.3365	0.0382	0.0520
20	0.120	0.036	0.0288	0.0651	0.0640
25	0.130	0.0395	0.0270	0.0636	0.0757
30	0.145	0.044	0.0266	0.07635	0.0874
35	0.160	0.0489	0.0260	0.06890	0.0988
40	0.175	0.053	0.0263	0.1020	0.1105
45	0.200	0.061	0.0284	0.1145	0.1216
50	0.210	0.064	0.0273	0.1273	0.1330
55	0.220	0.067	0.0263	0.1400	0.1330
60	0.230	0.070	0.0256	0.1527	0.1545
120	0.500	0.152	0.0333	0.3050	0.2740
180	0.650	0.198	0.0305	0.458	0.3770
240	0.790	0.240	0.0289	0.6110	0.4670
300	0.900	0.270	0.0267	0.7635	0.5410
360	0.980	0.298	0.0250	0.9163	0.6060
1440	2.070	0.630	0.0820	3.6650	0.9750

$P_{av}=0.0340$

OPTIMIZATION OF PUMPING SCHEDULE FOR INCREASING THE YIELD OF OPEN WELLS

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ABSTRACT OF THE PROJECT REPORT

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BACHELOR OF TECHNOLOGY
IN
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ABSTRACT

The field study was conducted in three open wells tapping, lateritic, clayey and alluvial formations to suggest an optimum pumping schedule for each of them. Drawdown and recuperation curves for the three wells were plotted to draw conclusions on the effect of well storage and aquifer contribution on well yield during various phases of pumping and recuperation. Time-drawdown and time-recovery mathematical relationships were established using the regression analysis for each well. Based on the total amount of water that could be pumped and rate of recuperation, three possible pumping schedules for 1h, 2h and 4h block periods were selected. Even though a 1h block period, gave maximum percentage increase in yield in the case of well 1 and well 2,a 2h block period with 15 and 17 minutes pumping respectively can be suggested considering the practical feasibility. For well 3, a 2h block period with 15 minutes pumping gave maximum percentage increase in yield. So it can easily be adopted. The rational formulae for net drawdown during cyclic pumping was developed for each of the wells using multiple linear regression analysis. Available recovery response theory was verified in the wells. In the case of well 1 in lateritic formation, predicted response and actual field response was found to match extremely well. In clayey formation, the theory was found to be valid under very small conditions of drawdown. The theory does not hold good in the case of well lined with precast concrete rings.