BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT WD/90/34

Hydrogeology Series

Technical Report WD/90/34

# Dug Well vs. Collector Well Performance: ODA R & D Project No. 90/11, Development of Horizontal Drilling Rig for Alluvial Aquifers of High Permeability.

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This report was prepared
for the Overseas
Development Administration

Keyworth, Nottinghamshire British Geological Survey 1990

## BRITISH GEOLOGICAL SURVEY

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# 1. INTRODUCTION

BGS are carrying out an R & D programme, funded by the ODA, to develop a drilling technique which will allow cheap and rapid construction of collector wells in the developing world. A collector well consists of a central shaft from which horizontal adits protrude and which tap the surrounding aquifer.

Initially, the work was directed towards the development of low transmissivity, weathered, hard-rock aquifers (Wright et al., 1988). In this early phase of the work it was shown quite clearly that it was important that well levels in these low transmissivity aquifers must 'fully' recover overnight or after a number of days use the well yield would significantly fall-off and the aquifer would be used inefficiently. It was shown that collector wells were far better than dug wells at meeting this requirement and specific criteria were established to make the decision, "when is a collector well better than a dug well at exploiting this low yielding aquifer". A précis of this work is given in Section 2 below.

Recently, research work has been re-directed towards using collector wells in the development of relatively higher transmissivity alluvial aquifers, such as wadi beds and riverside silty-sandy plains. A new drilling technique has had to be developed to cope with these new aquifers because they were formed of collapsing materials. If these collector wells were to be cheap then small diameter adits were necessary. In these aquifers it was likely these adits would run full and in very transmissive aquifers, logic tells us there is a maximum flow possible in each adit and an insufficient number of adits will restrict the collectors yield. Section 3 looks at this possibility and derives a criterion to predict when throttling of collector well yield will occur.

## 1.1 Aims of this Report

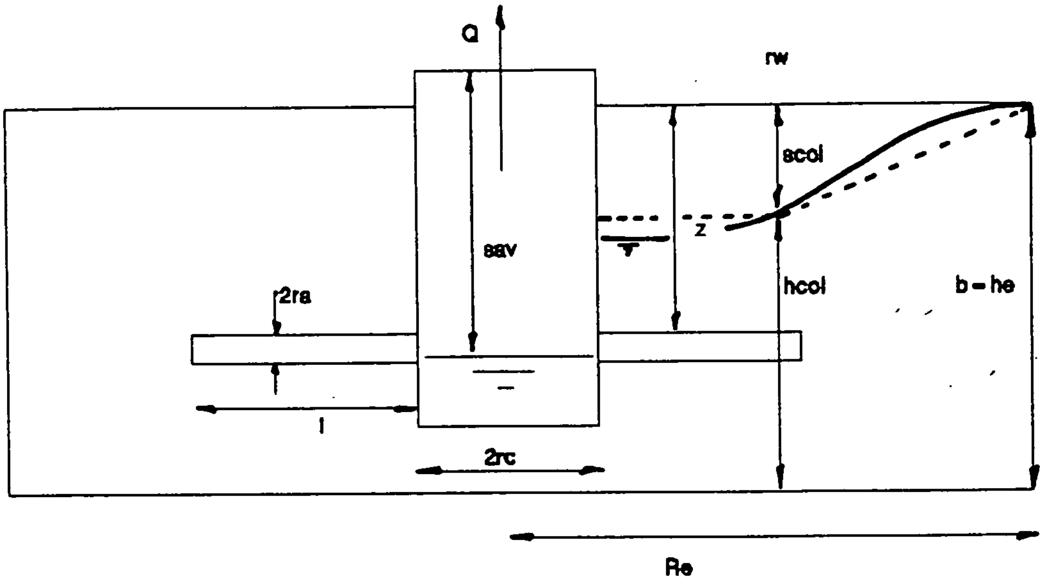
The purpose of this report is to derive criteria which will give rough answers to the questions:

**"When are adits absolutely necessary to ensure overnight recovery of well water levels?"** and
**"When will more than four 1½ inch diameter adits be necessary to avoid throttling of collector well flow?"**

The intention is not to provide an accurate prediction of collector well yields.

## 1.2 Collector Well Notation

Fig. 1 shows a collector well with all the main parameters, which are defined below.



The collector well shown is drawn as though it were in an unconfined aquifer where aquifer thickness, b, and saturated aquifer thickness, $h_e$, are synonymous.

The heavy lines on Fig. 1 show the equivalent simplified flow system, which will be described further in Section 3.

In Fig. 1: $r_c$ is the radius of the dug well casing
l is the length of the adits
$r_a$ is the radius of the adits
z is the depth of the adits below the initial water table (here $z = b$)
Q is the yield of the collector well
S is the storage coefficient of the aquifer
T is the transmissivity of the aquifer
t is the length of time after start of pumping

The equivalent fully penetrating well:

$s_{col}$ is the drawdown at $r_w$
$s_{ad}$ is $(b - s_{col})$
$s_{av}$ is b (for the purpose of this paper)
$r_w$ is $0.7 (r_c + 1)$
$R_e$ is the radius of influence of the equivalent well

## 2. THE LONG TERM YIELDS OF COLLECTOR WELLS AS AFFECTED BY RATES OF WATER LEVEL RECOVERY

Digital models can be constructed to simulate the behaviour of collector well water levels during pumping. Such a model has been constructed and was used to carry out a sensitivity analysis of various parameters affecting flow. This work is described by Herbert et al. (1988). Figs. 2 and 3 show how the recovery of a dug well in a low transmissivity aquifer can be speeded-up by converting it to a collector well.

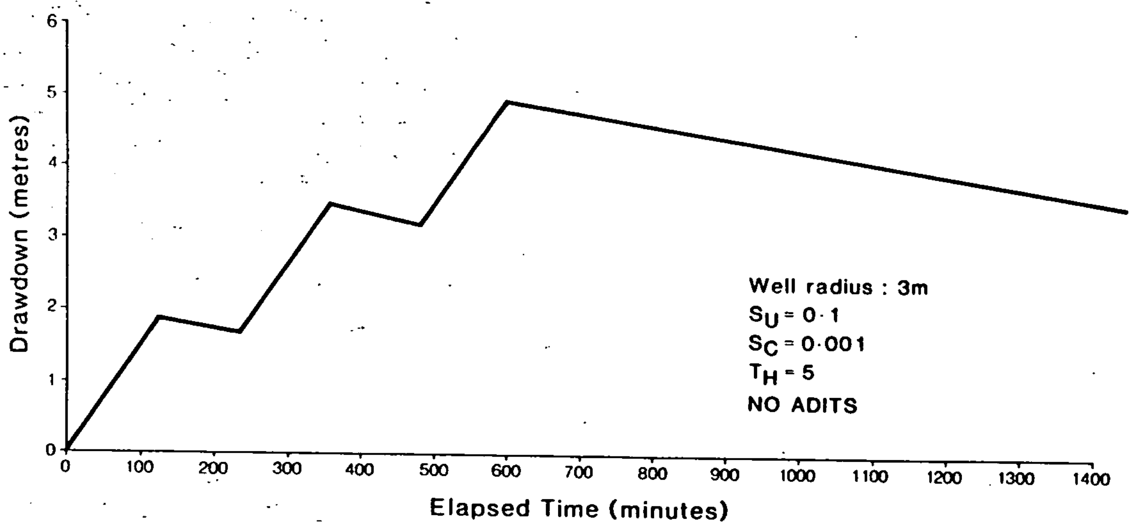


Fig. 2. Modelled response of large-diameter well in aquifer of transmissivity of 5 m$^2$/day and other units as shown. Three periods of pumping with intervals and final recovery period.

Well radius: 1.5 m, S = 0.1, T = 5, NO ADITS.

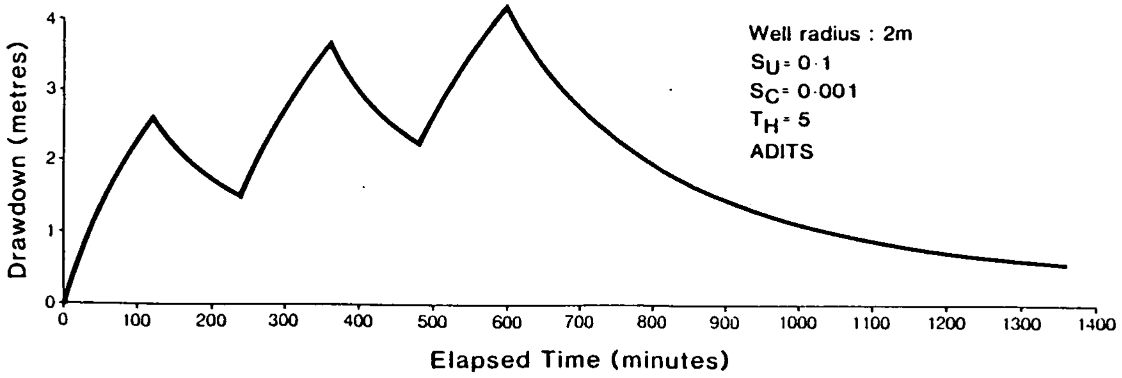


Fig. 3. Modelled response of a collector well in same aquifer of smaller diameter but otherwise same aquifer parameters.

Well radius: 1.5 m, S = 0.1, T = 5, ADITS.

In general, the long-term yields of collector or dug wells will depend on how quickly water-levels recover after pumping. The recovery behaviour can be better understood by a study of the behaviour of dug wells as described by Papadopulos and Cooper (1967). Fig. 4 describes the change in dimensionless drawdown, $s/(Q/4\pi T)$, with dimensionless time, $4Tt/r_w^2S$, as would occur for an ordinary well. In the case of a collector well $r_w$ must be thought of as the radius of an equivalent fully-penetrating well having the same hydraulic performance as a collector well with adits, l, long. This is discussed further in Section 3.

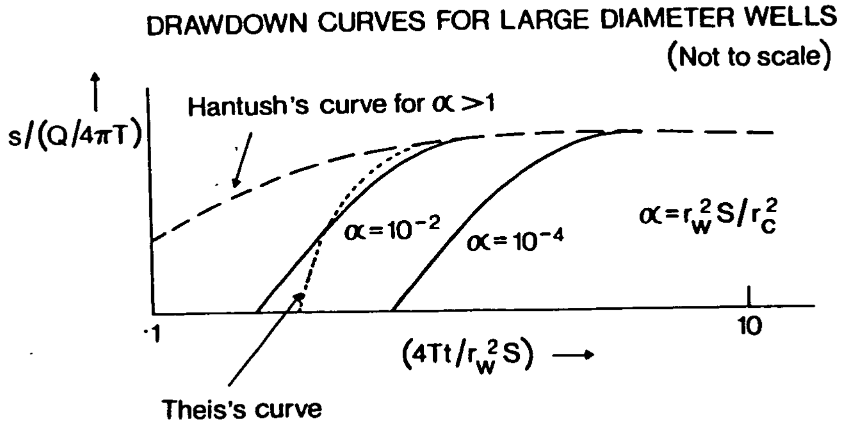


Fig. 4. The dependence of drawdown, s vs. time, t on $r_w^2S/r_c^2$.

The type of drawdown curve changes with a factor, $\alpha = r_w^2S/r_c^2$, in which suffixes c and w refer to casing and well respectively. The characteristics of the recovery can be deduced using the principle of super-position.

Curve (1) in Fig. 5 shows a typical drawdown curve of a large diameter well, for which $\alpha$ is small. It is in two parts. The early part is of length of time, $t_0$, roughly equal to $25r_c^2/T$, and the rate of drawdown is approximately linear and represents a reduction of well storage without significant contribution from the aquifer. The late part is adequately described by the Theis non-steady equation and rates of drawdown are much slower. Two different kinds of recovery response can be predicted for the case when $\alpha$ is small.

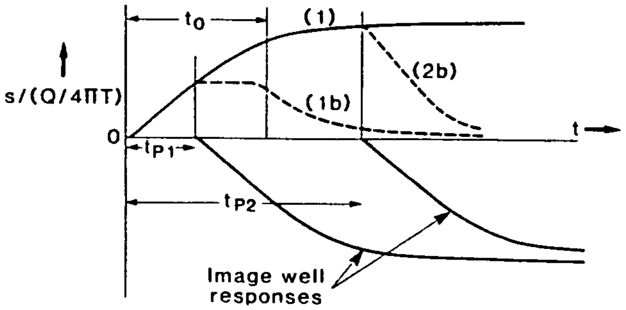


Fig. 5. The recovery of dug wells.

Fig. 5 shows the development of recovery curves for two different assumed times of pumping, $t_{p1}$ and $t_{p2}$. The curves are deduced by assuming an image well starts pumping at an equal and negative rate at time $t_p$. The drawdown of both wells are summed to achieve the recovery response. If the time of pumping is short, $t_{p1} < t_0$, recovery will be like curve 1b. If the time of pumping is long, $t_{p2}$, recovery will be like curve 2b. Hence we can deduce that when $\alpha$ is small the rate of recovery will be slow until total time passed is greater than $25r_c^2/T$.

On the other hand, if $\alpha$ is large, the drawdown curve will tend towards that described by Hantush (1964a) on Fig. 4, and recovery will be relatively rapid. A collector well is qualitatively like this latter case having $r_w >> r_c$ and it can be assumed that recovery will be quick providing $r_w^2S/r_c^2 > 0.1$.

Application of the above criteria will ensure that recovery rates will be relatively rapid. The question remains, can it be rapid enough?

In earlier studies, Herbert et al. (1988) it has been assumed a dug well will be pumped intermittently throughout the day until it is nearly dry, and will then be allowed to recover overnight. There will be a gradual fall of background levels of groundwater through the pumping season due to the extraction of water, however, what is required is that the temporarily large drawdowns arising from the intermittent pumping are almost fully recovered overnight and the residual drawdowns from this intermittent pumping do not therefore accumulate and cause premature drying-up of the well. The requirement described above will depend on aquifer thickness, aquifer hydraulic properties and length of dry season amongst others. No detailed study has been made of these parameters but for all the cases studied to date in hard rock aquifers, which are 5-20 m thick and have transmissivities in the range 1-100 $m^2/d$ a collector well having radials 30 m long will ensure recovery is rapid enough.

To summarise, if $25r_c^2/T$ is large (> 0.1 day) and $r_w^2S/r_c^2 < 0.1$, recovery will be slow and long-term yields will be severely reduced. For weathered hard rock aquifers collector wells having adits 30 m long will ensure long-term yields are not affected by rates of recovery.

## 3. THE YIELDS OF COLLECTOR WELLS AS AFFECTED BY THROTTLING OF FLOW IN THE ADITS

### 3.1 Previous Analytical and Modelling Work

#### 3.1.1 Modelling work.

The flow to a collector well is extremely complex. However, modelling studies have shown that the steady state flows can be predicted very well by replacing the collector well with an equivalent fully penetrating one having an equivalent well radius $r_w$, the collector well drawdown in an unconfined aquifer being given by:

$$(h_e^2 - h_{col}^2) = Q.\ln(R_e/r_w)/(\pi k) \qquad ..... (1)$$

In Eq. 1 $R_e$ is the radius of influence of the collector well and k is the hydraulic conductivity of the aquifer. $R_e$ could be determined by hydrogeological boundaries, rivers, faults, etc. or it could be calculated from consideration of quasi-steady state theory discussed below.

With regard to $r_w$, Huisman (1972) states "Many investigators have determined the value of $r_w$ by model tests, and this parameter has also been measured in the field for a number of existing wells. Much larger values of $r_w$ are now found, on average around 0.7 (1 + $r_c$)".

### 3.1.1.1 *Estimating the radius of influence in a time variant situation*

In practice, flow to all wells is transient. The general transient problem of flow to wells is far more complex than the steady state problem and only approximate solutions embodying certain simplifying assumptions are possible. Hantush has produced one such solution that is considered below. Another approach, which reduces time variant flow to a quasi-steady state, has been described by Barker and Herbert (1989).

Quasi Steady State Flow and Selection of $R_e$: Consider transient flow in the immediate neighbourhood of a well. When pumping begins the heads at points close to the well decline rapidly relative to heads at distant points. However, after some period of steady pumping, all of the heads within this neighbourhood begin to decline at similar rates, so the differences between them are near constant. The flow is then said to be in a quasi-steady-state (q.s.s.), meaning that at any instant the head distribution appears to represent steady flow.

Let $s_0(t)$ be the time-dependent drawdown at the outer boundary of the neighbourhood under consideration, and let $\Delta s$ be the q.s.s. head loss between this boundary and some reference point such as the top of the screen. The average drawdown at the reference point during period $t_1$ to $t_2$ will therefore be:

$$\langle s_p \rangle = \Delta s + \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} s_0(t)\,dt \qquad \ldots\ldots (2)$$

While the quantity $\Delta s$ will depend on the well design, the integral term will not, provided the boundary of the neighbourhood is sufficiently far from the well that the head variation there depends only on the total flow rate.

The problem that remains is that of establishing the conditions under which the q.s.s. assumption is justified. Firstly, consideration is given to how large the neighbourhood of the well should be that the behaviour on its outer boundary would not be affected by the well design. Two extreme cases of well design are those where the screen fully penetrates and where the screen is very short, so the flow has to converge rapidly near the well. The effects of this convergent flow are significant out to a distance equal to a few times the aquifer thickness. Therefore a reasonable choice of q.s.s. neighbourhood size is twice the aquifer thickness.

The next problem to consider is how long it takes for q.s.s. conditions to be established within that neighbourhood. One approach to this problem is to determine how long it takes for the radius of influence of the well to extend beyond the neighbourhood. This gives a characteristic time of about:

$$t_c = \frac{Sb^2}{T} \qquad \ldots\ldots (3)$$

where S is the total storage coefficient, T is the transmissivity, and b is the aquifer thickness. If this characteristic time is significantly larger than the typical period of pumping then the q.s.s. approach is justified.

A particular demonstration of the applicability of the above hypothesis has been presented by Boulton (1965). He shows that the time variant flow to a confined or unconfined well can be accurately represented by steady state theory if it is assumed there is a radius of influence, $R_e$, which is a variable function of time given by Eq. 4:

$$R_e = 1.5\ \sqrt{Tt/S} \qquad \ldots\ldots (4)$$

or

$$t = 0.44\ R_e^2 S/T \qquad \ldots\ldots (5)$$

n.b. Eqs. 5 and 3 are equivalent if $R_e = 1.5b$.

Eq. 4 can be substituted into Eq. 1 as follows. The equivalent fully penetrating well, to the collector well, has a radius $r_w$ of $0.7(l + r_c)$. The radius of influence will expand $R_e$ beyond this after time t, so Eq. 1 becomes:

$$(h_e^2 - h_{col}^2) = (Q/\pi k) \cdot \ln((0.7(l+r_c) + 1.5\sqrt{(Tt/S)})/0.7(l+r_c)) \qquad \ldots\ldots (6)$$

Eq. 6 may be used to estimate discharge to a collector well providing times of pumping are greater than that given by Eq. 3 or $R_e > (1.5b + r_w)$.

### 3.1.2 An analytical solution.

Hantush (1964b) discusses the hydraulics of collector wells and presents analytical solutions to a number of cases. He treats the laterals of the collector well as line sinks with a uniform discharge along their axis.

Using the notation of Fig. 1, if well drawdowns, $s_{av}$, are small in relation to aquifer thickness b and if $r_c \ll l$ and $r_a \ll b$, and the aquifer is assumed to be homogeneous and infinite in extent then for times of pumping $t > 2.5b^2S/T$ and $> 5(r_c^2 + l^2)S/T$ the well drawdown is predicted by Eq. 7, where N is the number of adits and $N \geq 4$.

$$\begin{aligned} s_c = {} & (Q/4\pi KbN)\{W(l^2/4vt) \\ & + [(N-1)/l][l'W(l'^2/4vt) - r_c W(r_c^2/4vt)] \\ & + 2N + (b/2l))\ln[(b/\pi r_a)^2/2(1-\cos\pi(2z_i+r_a)/b)] \\ & + [4b(N-1)/\pi l] \sum_{n=1}^{M'} (1/n)[\pi/2 - L(n\pi r_c/b, 0)] \\ & \cdot \cos(n\pi z_i/b) \cos n\pi(z_i+r_a)/b\} \qquad \ldots\ldots (7) \end{aligned}$$

in which $M'$ is an integer large enough so that $M' > b/2r_c$, $v = T/S$, $l' = l + r_c$ and $W(x)$ is the standard well function for non-leaky aquifers, and $L(u,0) = \int_0^u K_0(y)dy$.

The accuracy of Eq. 7 depends on the accuracy of the assumptions. In particular there is no guarantee that uniform discharge will occur along the adits, so accuracy of predictions is uncertain.

Most importantly, no well losses are allowed for in Eq. 7. In small diameter adits in transmissive aquifers it is certain these will run full and well/adit losses will not be negligible. Eq. 7 should thus only be used where these conditions do not obtain. Further, it must be remembered that Eq. 7 will be accurate only for unconfined aquifers with small drawdowns or for confined aquifers where the aquifer is not dewatered.

## 3.2 A New Approximate Collector Well Discharge Predictor for Throttled Flow

The limitations put on the accuracy of Eq. 7 have led to the development of the following predictor for collector well discharge having large drawdowns and where adits run full.

Earlier it has been shown how a collector well can behave like an equivalent fully penetrating well having a well drawdown $s_{col}$ given by Eq. 6. When the collector well adits are running full there will be an additional drawdown, $s_{ad}$, due to well/adit losses. In these circumstances the total drawdown $s_{av}$ will be given by Eq. 8:

$$s_{av} = s_{col} + s_{ad} \qquad \ldots\ldots (8)$$

### 3.2.1 Estimating $s_{ad}$, the head losses in the adits.

Recently Barker and Herbert (1989) developed an equation for calculating the losses in vertical tubewells, which occur as a result of momentum change and friction inside the well screen. If it is assumed the inflow to the vertical well is uniform up its length the head loss within the well will be given by Eq. 9:

$$\Delta s = Q_w^2 \left(\alpha' l/4 + \beta/3\right) \qquad \ldots\ldots (9)$$

Where $Q_w$ is the well flow, $\alpha'$ and $\beta$ are constants and l is the length of the well screen.

In Eq. 9 the $\alpha'$ term represents the loss due to friction and the $\beta$ term is the head loss resulting from imparting a vertical momentum to the flow up the well.

Barker and Herbert (1989) relate $\alpha'$ to a dimensionless friction factor, f, which is dependent on details and material of manufacture of screen. Similarly $\beta$ can be expressed in terms of a screen radius, $r_a$, and Eq. 9 can be rewritten as follows:

$$\Delta s \quad = \quad Q_w^2(fl/(16\pi^2 g r_a^5) + 2/(\pi^2 g r_a^4 3)) \qquad \ldots\ldots \ (10)$$

Eq. 10 can be used to calculate the head losses in an adit where $Q_w$ will equal $Q_{ad}$, $r_a$ in Eq. 10 will be adit radius and if there are N adits the discharge in Eq. 10 will be given by:

$$Q_{ad} \quad = \quad Q/N \qquad \ldots\ldots \ (11)$$

Combining Eqs. 6 and 10, the discharge Q of a collector for a given available drawdown $s_{av}$ can be estimated.

Thus, Eq. 6 can be rewritten as:

$$Q \quad = \quad (h_e^2 - h_{col}^2) \text{ Const } 1 \qquad \ldots\ldots \ (12)$$

Eq. 10 can be rewritten as:

$$Q \quad = \quad N \cdot \sqrt{\text{Const } 2} \cdot \sqrt{h_{col}} \qquad \ldots\ldots \ (13)$$

where $h_{col}$ is the max. available drawdown to the adits, i.e. $h_{col} = s_{ad} = \Delta s$.

$$\text{Thus} \quad (h_e^2 - h_{col}^2)C1 \quad = \quad N\sqrt{C2}\ \sqrt{h_{col}} \quad \text{n.b.} \quad Cn = \text{Const } n \qquad \ldots\ldots \ (14)$$

If we let $\sqrt{h_{col}} = y$, Eq. 14 can be rewritten:

$$y^4 + ay - b \quad = \quad 0 \qquad \ldots\ldots \ (15)$$

where a and b are new, easily determined constants. The four possible solutions to Eq. 15 were obtained using readily available software entitled "Derive". The solutions are long and tedious to express so a spreadsheet file has been written incorporating the solutions called $Q_{COLUNC}$, which will predict Q for any chosen different sets of parameters of Fig. 1 and using the solutions to Eq. 15. This spreadsheet is suitable for running on the

Supercalc5 spreadsheet and is held by the author. A typical 'screen' and solution of this spreadsheet file is presented in Appendix A.

In the solution shown in the Appendix, it is assumed there are four 30 m long adits of 1½" diameter placed at the bottom of any aquifer 2.5 m thick having a transmissivity of 500 m$^2$/d. The discharge of the collector with adits is assessed to be 987 m$^3$/d whilst the yield of a dug well of radius 1 m would be 767 m$^3$/d. The spreadsheet also calculates the yield of the collector, qcol (no throttling), as if there were no losses from the adits, the discharge would be 1812 m$^3$/d. It is clear that the adits are throttling the flow of this collector. Either many more adits should be drilled than four or their diameter increased.

## 4. RESULTS FROM VARIOUS ANALYSES

Table 1 shows the results of solutions obtained using the spreadsheet file mentioned earlier. The object of these runs was to determine criteria for determining when throttling might occur when only four adits were used in a collector well.

For every solution of Table 1, the following parameters were kept constant.

| | |
|---|---|
| t (time of pumping) | 0.5 days |
| S (storage coefficient) | 0.02 |
| $r_c$ (radius of dug well) | 1.0 m |
| $h_e = b = s_{av}$ (aquifer thickness or available drawdown) | 2.5 m |
| f (coefficient of roughness of adit screen) | 0.02 |

In Table 1, Q is the calculated value of the collector well, $Q_{COL}$ is the flow assuming no adit head loss and $Q_{dw}$ is the yield of a fully penetrating, fully screened dug well of radius 1 m. The starred results are where little throttling of flow occurs or $Q/Q_{COL} \approx 1$. These results and many others suggest that if four 1½" diameter adits are used where l = 15 and 30 m, then for T less than 300 and 200 respectively, no significant throttling of flow will occur.

For completeness the discharge predicted by Hantush's equation is given in Table 1. It should be remembered that Hantush's solution is only correct for small drawdowns or for confined aquifers. The yield in a confined aquifer should be approximately double that of an unconfined aquifer for the maximum drawdown case, $h_w = 0$ so the fact that the Hantush yields are about 1.6 times those for the spreadsheet solution is not surprising.

## 5. CRITERION TO ASSIST DESIGN OF COLLECTOR WELLS

Using the notation of Fig. 1 it is shown that:

(a) Overnight recovery of water levels will not be achieved if $25r_c^2/T > 0.1$ day and $r_w^2S/r_c^2 < 0.1$. Experience shows that (i) weathered hard rock aquifers have $T \approx 1$ to $100\ m^2/d$, $b = 5$ to $20$ m and $S = 0.01$ to $0.1$, (ii) dug wells having $r_c > 1$ m will not recover fully overnight after intermittent pumping, (iii) collectors having adits 30 m long, $r_w \approx 0.7\ (30+1)$ m, have all recovered sufficiently overnight so as not to affect long-term yields.

(b) Four 1½" diameter adits 15 m long will not cause significant throttling of possible collector well flow providing $T < 300\ m^2/d$. If the adits are 30 m long, $T < 200\ m^2/d$.

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Table 1

## PREDICTIONS OF DISCHARGE RATES

(Constants: $t = 0.5$ days, $S = 0.02$, $r_c = 1$ m, $B = h_e = s_{av} = 2.5$ m)

| Hantush Q | Q | $Q_{dw}$ | $Q_{col}$*** | N | T ($m^2/d$) | l (m) | D "(m) | Cases where little throttling |
|---|---|---|---|---|---|---|---|---|
| <- - - - - - - | - $m^3/d$ | - - - - - - | - -> | | | | | |
| 4187 | 1275 | 1436 | 2534 | 4 | 1000 | 15 | 1½ (.019) | |
| 4366 | 2459 | 1436 | 2534 | 15.6 | 1000 | 15 | 1½ (.019) | ✓ |
| 2310 | 1069 | 767 | 1417 | 4 | 500 | 15 | 1½ (.019) | |
| 1280 | 753 | 411 | 801 | 4 | 250 | 15 | 1½ (.019) | ✓ |
| 602 | 383 | 182 | 385 | 4 | 100 | 15 | 1½ (.019) | ✓ |
| 811** | 509 | 182 | 526 | 4 | 100 | 30 | 1½ (.019) | ✓ |
| 1659 | 822 | 411 | 1052 | 4 | 250 | 30 | 1½ (.019) | |
| 2902 | 987 | 767 | 1813 | 4 | 500 | 30 | 1½ (.019) | |
| 2920 | 1799 | 767 | 1812 | 4 | 500 | 30 | 3 (.038) | ✓ |

** Hantush time criterion not met

*** Collector yield with no throttling

# APPENDIX 1

## Print-out of Spreadsheet Solution to Calculate Q, $Q_{COL}$ and $Q_{dw}$

```
DUG OR COLLECTORS?                            N.B.UNITS ARE M.DAYS
__________________
Radius of influence          T m^2/dv  t days   S         Re=
                              500       .5       .02       167.7051
Col weil radii               l m       rc m     B=        C1=
                              30        1        2.5       290.0053
Adit params                  f                  D ins     C4=
                              .02                1.5       36135.81
Available drawdown he        savl
                              2.5
Number adits                 No
                              4
a=        b=        p=       q=        r=       A=        B=
 2.621941 6.25       288.2605 3.952159 .1316903 1.560518ERROR
y=        or        or       hcol=     or       or
 1.298717 -1.82232ERROR       1.666666 3.320845ERROR
_____________________________________________________________
Yield of collector           Q   =     or       or
                              987.5143 -1385.65ERROR
Yield of dugweil             Qdw=
                              766.6599
_____________________________________________________________
N.B.This overestimates adit/collector      TODAY=    12/ 7/90
yield.Also only acc for >4 adits.          R.Herbert
```

```
qcol(no throttling)
 1812.533

d\l=      .05
qcol\qcnt .5448255
```

## KEY PARAMETERS OF COLLECTOR WELL (Fig. 1)

$r_c$ is the radius of the dug well casing
$l$ is the length of the adits
$r_a$ is the radius of the adits or screen of an equivalent vertical well
$z$ is the depth of the adits below the water table (here $z = b$)
$Q$ is the yield of the collector well
$S$ is the storage coefficient of the aquifer
$T$ is the transmissibility of the aquifer
$t$ is the length of time after start of pumping

### The equivalent fully penetrating well

$s_{col}$ is the drawdown at $r_w$
$s_{ad}$ is $(b - s_{col})$
$s_{av}$ is $b$ (for the purpose of this paper)
$r_w$ is $0.7\ (r_c + l)$
$R_e$ is the radius of influence of the equivalent well

### Notation in remainder of text

$Q_w$ is flow in a vertical well
$Q_a$ is flow in an adit of a collector well
$Q_{COL}$ is flow in a collector well with no adit losses
$Q_{dw}$ is flow in a dug well (collector well without adits)
$\alpha = r_w^2 S / r_c^2$
$\alpha'$, $\beta$ are constants in Eq. 9
$t_c$ is characteristic time of a groundwater system
$t_0 = 25 r_c^2 / T$, time before well storage effects ended
$t_{pn}$ is time of pumping
$h_e$ is aquifer thickness $= b = s_{av}$ (for purposes of max. yield)
$h_w$ is head in well $= 0$ (for purposes of max. yield)
$N$ is number of adits
$l' = l + r_c$
$f$ is friction factor of a leaky screen (dimensionless)
Const $n = Cn$, constants simplifying Eqs. 6 and 10
$\Delta s$ is head loss within a vertical well