University of Newcastle upon Tyne
Department of Civil Engineering

Report on

SURFACE WATER INFILTRATION SYSTEMS—
HANDBOOK DEVELOPMENT

Prepared by

C.A. Engmann

A Dissertation Submitted in Partial Fulfillment
of the requirements for the Degree of
Msc. in Public Health Engineering

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CHAPTER 1 INTRODUCTION

CHAPTER 2 BIOLOGICAL CHEMICAL ASPECTS OF WATER QUALITY

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LIST OF SYMBOLS

A	Area (m^2)
B	Length of Basin, Gallery (m)
C	Consumption of water per head $(m^3/h.s)$
H	Average saturated aquifer depth (m)
h	Aquifer depth at a distance x from the river (m)
K	Coefficient of permeability (m/day)
L	Length (m)
P	Residual Rainfall (m/s)
p	Porosity (dimensionless), penetration fraction (dimensionless)
q_o	Flow of water per unit aquifer width (m^2/s)
q_a	Flow of surface water per unit aquifer width (m^2/s)
q_n	Flow of natural groundwater per unit aquifer width (m^2/s)
Q_o	Flow of water from a well (m^3/s)
R	A constant
r_o	Radius of well
S_o	Maximum allowable drawdown of water level (m)
ΔS	Additional drawdown in level due to partial penetration of well (m)
S_T	Total drawdown including effect of partial penetration (m)
T_d	Detention time of water underground (s)
V	Velocity (m/s)
W	Width of aquifer (km)
X	Orthogonal co-ordinate
Y	Orthogonal co-ordinate
α	A constant greater than 1

LIST OF SPECIAL SYMBOLS FOR COMPUTER PROGRAMMES

The following symbol changes have been made for the computer programmes:

α = A

p = P

Q_o = Q (Table A2)

q_n = Q1 (Table A2)

q_o = Q (Tables A4, A5)

S_o = S

T_d = T

Vq = entry rate of water into soil (m/s)

CHAPTER 1

INTRODUCTION TO INFILTRATION SYSTEMS

1.1 Prevailing Water Supply Situation in Developing Countries

Surface water is a common source of drinking water for most areas in developing countries, as it is plentiful for much or all of the year, and comparatively easily accessible. The use of surface water, however, has serious disadvantages. Firstly, it is highly polluted, being subject to a great deal of runoff from adjacent land, and thus it is a major source of disease to communities who use it. Furthermore, the water has to be carried, sometimes for long distances, to the place where it is required for use. In addition, small streams may dry up completely during periods of low rainfall or drought, with the result that water has to be obtained from further sources.

The most commonly used methods of providing drinkable water for developing countries are:

(i) Conventional treatment of surface water by chemical and mechanical means;

(ii) The abstraction of naturally occurring groundwater.

However, both these methods have significant drawbacks. The first method is commonly used in developed countries, and is inappropriate for small communities as it requires expensive mechanical plant, which is costly to build and expensive to maintain. It also requires skilled manpower which may be difficult to obtain or train in sufficient numbers. There is, in addition, a

need for consistent supplies of chemicals, which often need to be imported.

The use of groundwater is suitable, particularly for small communities. The water is generally of a higher quality, and does not often require treatment, as the passage of rainwater through the ground upgrades the water quality. However, preliminary investigations for groundwater are often expensive, and it may not be present in sufficient quantity. The water may be very deep and therefore difficult to abstract, or occasionally the water quality may be poor, requiring further treatment, which may not be economically feasible.

1.2 Infiltration of Surface Water as an Alternative Water Treatment Method

This study will evaluate an alternative to the above commonly used methods of obtaining drinkable water. Through the infiltration of sufficient quantities of surface water into the ground, such that during its passage through the soil it undergoes a similar upgrading in quality to that of naturally occurring groundwater, such water on abstraction should be of a quality suitable for drinking water.

There are two main methods of surface water infiltration. The first is by inducing water to flow from a river or lake to a gallery or well, from where it can be abstracted. This can be seen in Fig. 1.1. Initially, when a small amount of water is abstracted from the gallery, there will be a drawdown of the water table. When, for larger abstraction rates, the water level adjacent to the river bank falls below the level in the river, water is induced to enter the aquifer from the river and flow into the gallery. Thus the water that is abstracted consists mostly of river water, with a small proportion of naturally occurring ground water. If the river bed, and the aquifer, are highly permeable,

large amounts of water can be drawn into the gallery without a significant lowering of the adjacent groundwater table.

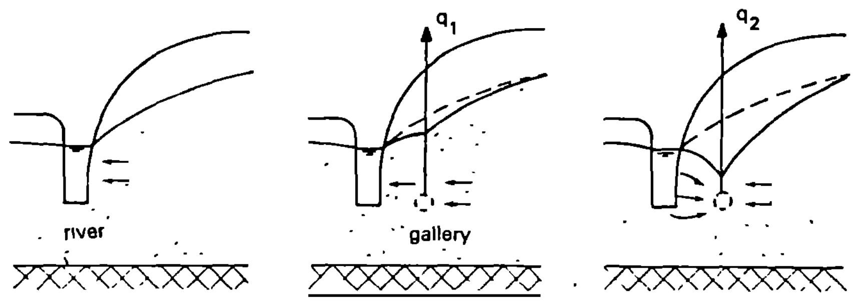

Fig. 1.1 Flow of Water into a Gallery Adjacent to a River

Alternatively, instead of infiltration galleries, wells may be used for abstraction.

A related method of infiltration is where the water, instead of entering the ground directly through the river basin, is transported to a different location, preferably through open channels, where it can be infiltrated through basins, ditches or wells into soil of suitable permeability. Where the distance involved is very long, however, transportation may need to be through pipes and not channels. The water can then be abstracted at a distance, which may be estimated by calculation. Figs. 1.2, 1.3 and 1.4 give an indication of the nature of these systems.

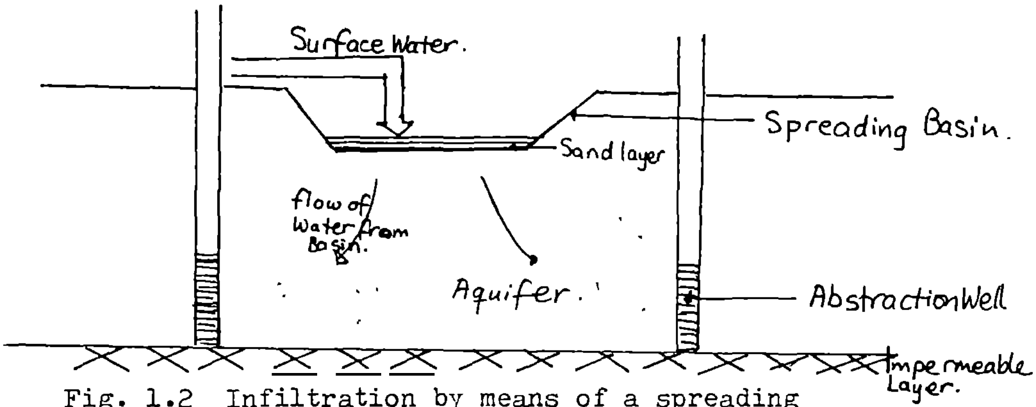

Fig. 1.2 Infiltration by means of a spreading basin to wells (After Huisman, 1983)

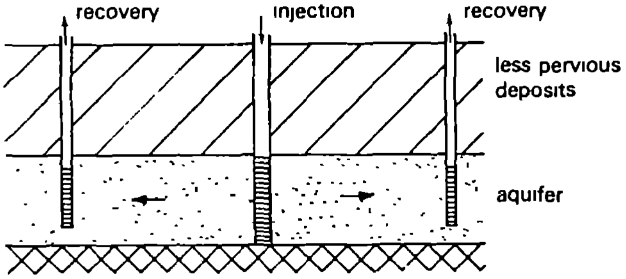

Fig. 1.3 Infiltration through an Injection Well (Huisman, 1983)

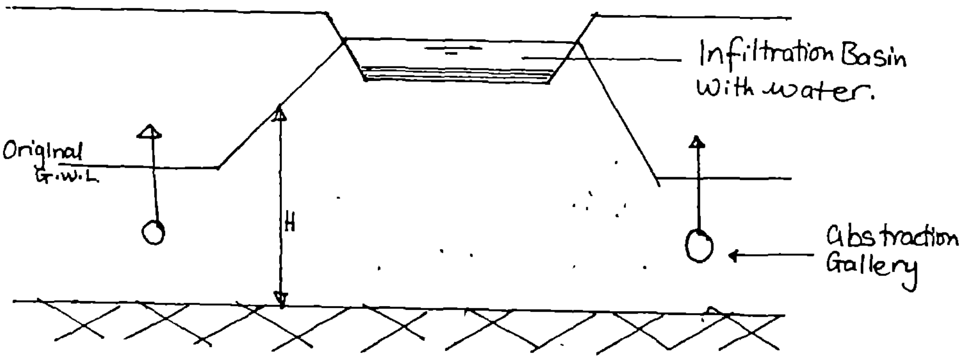

Fig. 1.4 Infiltration by means of a Basin and Parallel Galleries (After Huisman, 1983)

The methods each have their advantages and disadvantages, and these are discussed briefly below:

Induced infiltration is the simplest method, in terms of design, construction and operation, and therefore the cheapest. The main drawback to the method, however, is that it presupposes a relatively permeable layer of rock or soil adjacent to the river, and in some cases this may not be so. Where the water has to be conveyed to basins or ditches for infiltration, the system is rather more flexible in that it will allow an area to be chosen which is more suitable in terms of either permeability or chemical compatibility with the surface water. However, it has several drawbacks for small communities. It is more expensive to construct than induced systems, and the basins, ditches or wells require regular maintenance. Nevertheless, it may be, in some situations, that there is a net benefit to be gained by choosing such methods. The exception is the use of Injection wells. These are particularly costly, require constant maintenance to keep them in working order as they clog easily, and extensive pretreatment of the raw water to remove suspended solids. They are therefore not to be recommended, and for this reason will not be included in this study.

The means of abstraction which will be discussed in this study are infiltration galleries and wells. Infiltration galleries, depending on the nature of the ground, are relatively simple to construct, and do not require very specialised equipment. However, they are not suitable for very great depths, and here, wells may be used instead. In operation, as water generally flows through a smaller total surface area in wells than galleries, wells are more likely to cause maintenance problems.

In subsequent sections, the following approach will be used:

Initially, the quality requirements for surface water will be discussed, in

addition to the effects of using water that fails to meet bacteriological standards. This will be followed by a consideration of the basic theory of infiltration systems. The main biological and chemical changes associated with surface water during infiltration will then be examined, and on the basis of this and previous information, design criteria and tables will be developed. This will be followed by a discussion of the general operation and maintenance of infiltration systems, together with less common maintenance problems that may arise. Finally in Chapter 6, conclusions to be drawn from the study are given, together with recommendations for further work; and a simple handbook for the design and operation of infiltration systems arising from the conclusion is included in the Appendix.

1.3 Water Quality Criteria

The aim in treating surface water should be to produce water which is:

(i) Free from pathogenic micro-organisms;

(ii) Free from chemicals which may be harmful to health;

(iii) Aesthetically pleasing and palatable enough to ensure that consumers will not be inclined to seek other, unsuitable sources of water.

Of these criteria, the first normally is the most critical in developing countries, as most pollution is faecal pollution, which gives rise to the presence of high numbers of pathogenic micro-organisms. There are numerous diseases whose pathogens are associated with water, but these water-related diseases can be classified into four main groups (Feachem et al, 1977). These are:

(i) Faecal-Oral (Water borne or water washed diseases);

(ii) Water Washed diseases;

(iii) Water Based diseases;

(iv) Water Related Insect vectors.

Water borne diseases occur when some pathogenic organisms contaminate domestic water supplies. Such diseases may be prevented by improving the water quality to reduce pathogen concentrations at least below the infective dose, if not to eliminate these entirely. The second group, water-washed diseases, are the result of insufficient water supplies for adequate personal hygeine. These include skin and eye infections, and their prevention depends on the availability of sufficient and easily accessible water for domestic purposes. Water-based infections are caused by parasites in water which, while themselves not infective to man, infect other micro-organisms, such as snails and crustaceans. The larvae of these micro-organisms in turn infect water users. The larvae can be washed off the skin of infected people close to the water source and back into the water. The prevention of water based diseases therefore is by protection of the source of water. Water can also act as a medium for the spread of disease by insect vectors. A common example is the tsetse fly, which acts as a vector for sleeping sickness, and is found near surface water. Thus people using surface water in areas where it is prevalent are liable to catch the disease. Table 1 is a summary of the main groups of water related diseases, with common examples given for each group.

From the above descriptions, therefore, it will be apparent that the main aims in designing infiltration systems will be to ensure a substantial improvement in water quality over that of the original surface water, and to provide adequate water for the use of the community. How much water is adequate is often

TABLE 1

Water-Related Diseases

From 'Water, Wastes and Health in Hot Climates'
(Ed. R. Feachem, M. McGarry, and D. Mara, 1977)

CATEGORY	EXAMPLE
1. Faecal-Oral (Water borne or water washed)	
(a) low infective doses	Cholera
(b) high infective doses	Bacillary Dysentery
2. Water Washed	
(a) skin and eye infections	Trachoma, scabies
(b) other	Louse-borne fever
3. Water Based	
(a) penetrating skin	Schistosomiasis
(b) ingested	Guinea worm
4. Water-Related Insect Vectors	
(a) biting near water	Sleeping Sickness
(b) breeding in water	Malaria

difficult to state specifically, but a figure will be suggested in a later chapter for the purposes of design. It must be noted, however, that any assessment of water demand must include projections for the increase in demand likely to be generated by a more accessible supply of water.

The measurement of improvements or otherwise in water quality is normally by means of faecal coliform bacteria, indicator organisms which are themselves harmless. The WHO International Standards for drinking water (1971) state that there should be no coliform bacteria in a 100ml sample of water under test. For small community water supplies, which is what this study will examine, it allows for up to 10 coliforms per 100ml sample of water.

However, Feachem (1980) has suggested that these criteria are too rigid, and that the emphasis should be on a significant improvement of water quality above the source currently used by the community. It would seem that this is a more realistic approach, as the application of rigid standards may cause a new water supply to be abandoned by water authorities, leaving the community to return to a much more polluted water supply. It is expected that, in surface water infiltration systems, the WHO standard will be met, but it is as well to make the point about aiming for a substantial improvement, rather than aiming for much higher standards and consequently being forced to give up a project. The WHO International Standards also give maximum permissible concentrations of chemicals in domestic water supplies, to ensure that health and aesthetic criteria may be met.

It will be assumed for the purposes of this study, that surface waters will not normally contain toxic chemicals from industrial and agricultural waste. Thus any chemicals will be naturally occurring chemicals either present in the surface water, or acquired during its passage underground. Table 2 gives

TABLE 2

Water Quality Criteria

From 'International Standards for
Drinking Water' (WHO 1971)

Parameters	Undesirable effect that may be produced	Highest desirable level	Maximum permissible level
A. Physical			
Color (units)	Discoloration	5	50
Odour	Odours	Unobjectionable	Unobjectionable
Tastes	Tastes	Unobjectionable	Unobjectionable
Total Solids (mg/l)	Taste Gastrointestinal irritations	500	1500
Suspended matter (units)	Turbidity Gastrointestinal irritations	5	25
B. Chemical			
pH (unit)	Taste Corrosion	7.0 to 8.5	6.5 to 9.2
Calcium (mg/l)	Excessive scale formation	75	200
Chloride (mg/l)	Taste Corrosion in hot water systems	200	600
Total hardness, as mg/l of $CaCo_3$	Excessive scale formation	100	500
Mineral oil (mg/l)	Taste Odour	0.01	0.30
Phenolic substances (mg/l)	Taste	0.001	0.002
C. Trace Elements			
Arsenic (mg/l)	Toxic	-	0.05
Copper (mg/l)	Astringent taste Discoloration Corrosion of pipes; fittings and utensils	0.05	1.5
Cyanide (mg/l)	Toxic	-	0.05
Iron (mg/l)	Taste, Discoloration Turbidity Growth of iron bacteria	0.1	1.0
Lead (mg/l)	Toxic	-	0.1
Manganese (mg/l)	Taste Discoloration Deposits in pipes Turbidity	0.05	0.5
Zinc (mg/l)	Astringent taste	5.0	15.0
D. Pesticides			
DDT (mg/l)	Toxic	-	0.05
PCB	Toxic	-	Nil

E. Bacteriological

Standards for the bacteriological quality of drinking water are;

1. Throughout any year, 95% of samples should not contain any coliform organisms in 100 ml.
2. No sample should contain E coli in 100 ml
3. No sample should contain more than 10 coliform organisms per 100 ml.
4. Coliform organisms should not be detectable in 100 ml. of any two consecutive samples.

maximum permissible figures of common chemicals found in water and the effects of excesses of such chemicals. Regarding aesthetic criteria, it must be noted that while it is necessary for the water to look and taste good, aiming for WHO International Standards in this respect may not always be practicable.

The foregoing is an outline of the aspects of water quality which should be achieved by a successful infiltration system. However, for any new surface water source for an infiltration system, it will be necessary for comprehensive tests to be made, both before infiltration and after it, to meet either national or internationally accepted standards for drinking water; such testing will need to be maintained, preferably on a weekly basis, to ensure that the water abstracted is fit for consumption.

CHAPTER 2

THEORY OF INFILTRATION SYSTEMS

2.1 Induced Infiltration to Wells

The flow of water from rivers to wells can only occur when certain initial requirements are fulfilled. These include the need for a permeable river bed, such that it does not act as a barrier to river flow into the adjacent ground in which the well is sited. The area for infiltration must also be of reasonable permeability, at least 0.$\overset{5}{1}$m/day. In addition, the slope of the groundwater water table, and position of the well, must be such that pumping will ensure a steady flow of river water towards the well. Although a proportion of the abstracted water will be natural groundwater, the aim is to maximise the proportion of river water. There are three possible directions in which the groundwater table may lie. It may be horizontal, sloping away from the river, or sloping towards the river. Fig. 2.1 and 2.2 are diagrams for the horizontal case, that show the direction of flow before and after pumping begins respectively. In this situation, flow from the river to the well will always take place, provided the other factors of adequate river-bed and soil permeability are present. Similarly, where the water table slopes away from the river or stream, as in Fig. 2.3, it may be assumed that the direction of flow is from the river into the aquifer (Kazmann, 1948).

When, however, the slope of the water table is towards the stream, as in Fig. 2.4, whether or not infiltration does occur will depend upon the amount of water to be abstracted, which in turn affects the drawdown of water in the vicinity of

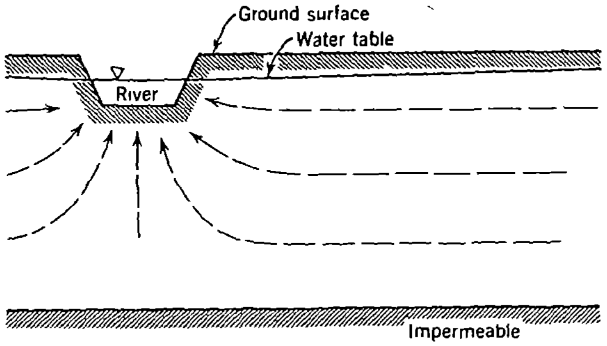

Fig. 2.1 Natural Flow Pattern of Water to a River before Water Abstraction (Todd, 1980)

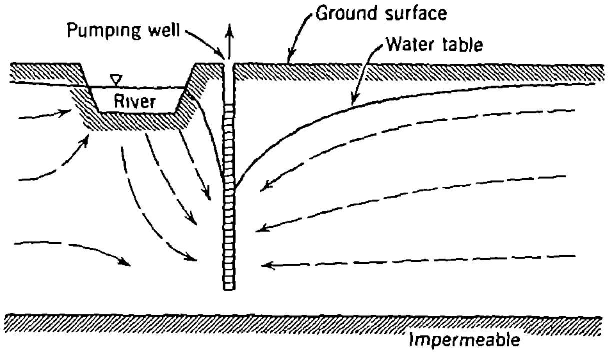

Fig. 2.2 Flow Pattern of Water after Abstraction from a nearby Well (Todd, 1980)

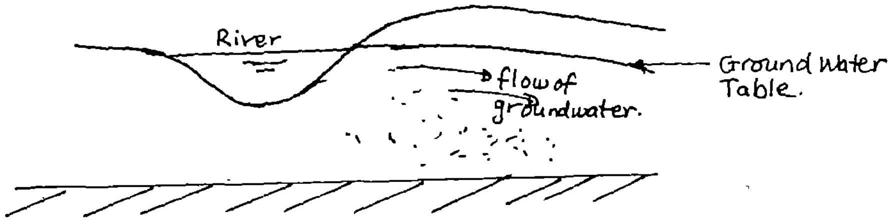

Fig. 2.3 Induced Infiltration with Water Table Sloping Away from the River

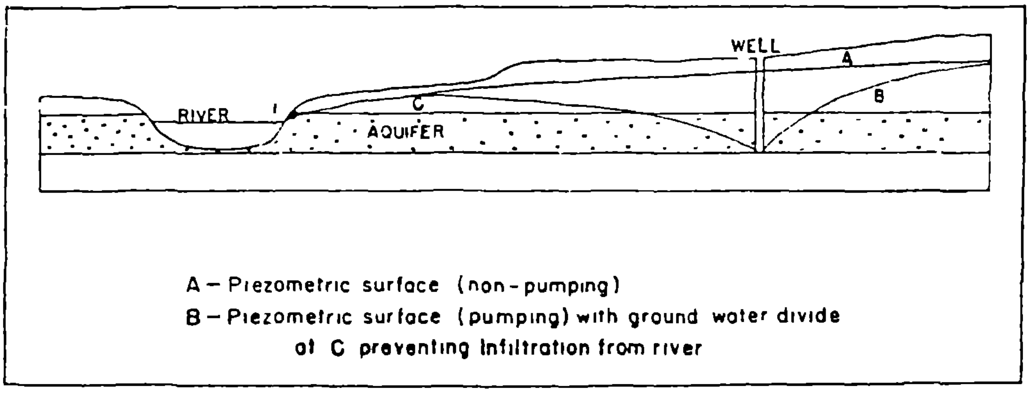

Fig. 2.4 Possible Effect of Pumping on Water Table Sloping Towards a River (Anderson, 1948)

the well, and the position of the well. Provided the base level of the river is above that of the aquifer, the direction of water flowing into the river will be reversed when pumping begins. Thus river water and a proportion of natural groundwater will flow into the abstraction well (Kazmann, 1948). However, where there is not much difference between the base levels of the aquifer and river, the siting of the well is important, particularly where there is a low abstraction rate and therefore minimum drawdown. If the cone of depression that forms around the well is not steep enough, the complete reversal of slope required does not take place (Anderson, 1948). The result of this is illustrated in Fig. 2.4. Under these conditions, flow of river water to the well cannot occur. However, were the well to be placed closer to the river, such that the water table sloped downwards right from the edge of the river-bed, river water could then flow into the well.

There are two main aspects of design where wells are concerned. The first is, as mentioned earlier, the distance between the well and river. The second is to estimate the lowering of the water table at the well face due to pumping. This information is needed primarily to establish the depth to which the well

should be sunk, ensuring that the permeable length of the screen remains below the lowered water table. To develop the necessary equations of flow, a number of assumptions must first be made. These are as follows:

(i) The flow of water is laminar;

(ii) That there are no great variations in aquifer permeability over short distances.

Laminar flow may be assumed because groundwater flow is normally slow, with the exception of flow through rocks of chemical origin, such as limestone, where large tunnels may have formed, giving rise to turbulent flow underground. Such cases are not considered here. The second assumption is necessary because large variations in permeability may give rise to steep gradients in the water table (Rombaugh, 1948). This will in turn make an accurate assessment of the saturated depth, H, difficult.

During induced infiltration the flow of water into the abstraction well cannot be stopped, and as such a situation of steady flow prevails. The first step is to develop an expression for the change in aquifer depth with distance, $\partial h/\partial x$ and thereby obtain expressions for the distance, L, between the river and well. This may be done by considering the combined effects of natural groundwater flow per unit aquifer width, q_n, and the quantity of water abstracted, Q_o.

(i) <u>Influence of natural groundwater flow</u>

Using Dupuit's equation, $q = Kh \; dh/dx$ —— ①

where q is the discharge per unit width, h the saturated aquifer depth at any point along the distance x, and k is the permeability of the aquifer.

Using the expression $dq/dx = q_n$ —— ②

neglecting the influence of rainfall, as this is insignificant compared to the total storage of water in the ground. The variables described are marked in Fig. 2.5 below. Combining equations ① and ②,

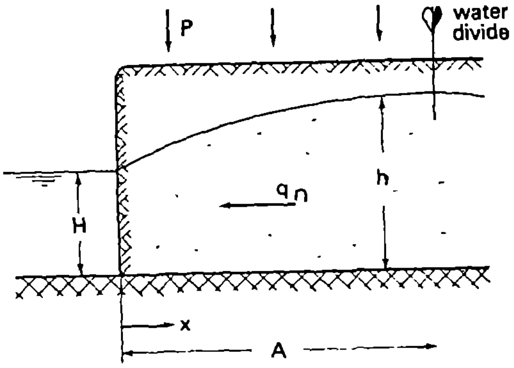

Fig. 2.5 Influence of Natural Groundwater Flow on Water Table Height (Huisman 1983)

$$q_n = Kh\frac{dh}{dx}$$

$$\int \frac{q_n}{K}\, dx = \frac{1}{2}\int_h^H 2h\, dh$$

$$\therefore \frac{2\,q_n\,X}{K} = \Big[h^2\Big]_h^H$$

$$\Rightarrow \frac{2\,q_n\,X}{K} = H^2 - h^2$$

$$\Leftrightarrow H^2 - h^2 = \frac{2\,q_n\,X}{K}$$ —— ③

(ii) Influence of Abstraction

The abstraction rate $Q = A\nu$, where A is the surface area through which water flows into the well.

$A = 2\pi r h'$, where r is a radial distance from the centre of the well, and h' the permeable length of the well.

$V = K \frac{dh}{dr}$, using Dupuit's assumption that flow velocity is proportional to the tangent of the hydraulic gradient.

$$\text{Thus } Q = 2\pi K h' r \frac{dh'}{dr} \qquad \text{——} ④$$

From the concept of continuity, $\frac{dQ}{dr} = Q = Q_o$ —— ⑤

where Q_o is the abstraction rate of water from the well, as shown in Fig. 2.6.

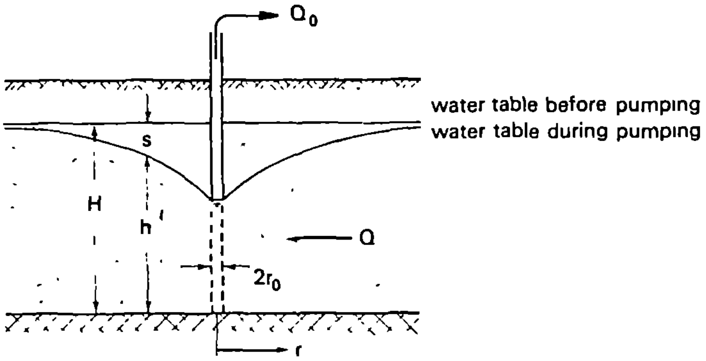

Fig. 2.6 Influence of Abstraction on Water Table (Huisman 1983)

Combining equations ④ and ⑤,

$$\int \frac{Q_o}{2\pi K} \frac{dr}{r} = \int_{h'}^{H} h'\, dh$$

$$\Rightarrow \frac{Q_o}{\pi K} \ln r = \left[h'^{2} \right]_{h}^{H}$$

This may be written as:

$$H^2 - h'^2 = (Q_o/_{\pi}K)\ \ln\ {}^R/r \quad \text{(Huisman, 1983)} \quad \text{———} ⑥$$

Where R is a constant, from which the following equations are developed.

For well abstraction, $R = r'$, and

$$\left({}^{r'}/_{r}\right) = \frac{\sqrt{(L + x)^2 + y^2}}{\sqrt{(L - x)^2 + y^2}} \quad \text{———} ⑦$$

in orthogonal co-ordinates

$$\therefore \quad H^2 - h'^2 = (Q_o/_{\pi}K)\ln \frac{\sqrt{(L + x) + y^2}}{\sqrt{(L - x)^2 + y^2}} \quad \text{———} ⑧$$

Combining the influence of the flow of water to the well and the water abstracted from the well,

$$(H^2 - h^2) - (H^2 - h'^2) = \frac{q_n x}{K} - \left(\frac{Q_o}{\pi K}\right)\ln \frac{\sqrt{(L + x)^2 + y^2}}{\sqrt{(L - x)^2 + y^2}} \quad \text{———} ⑨$$

From equations ③ and ⑧:

$$\text{Thus} \quad \frac{\partial h}{\partial x} = \frac{q_n}{Kh} - \frac{Q_o}{2\pi Kh}\left[\frac{L + x}{(L+x)^2+y^2} + \frac{L - x}{(L-x^2)+y^2}\right] \quad \text{———} ⑩$$

When $x = 0$, and $h = H$, the flow from the river to the well is quickest in a straight line, where $y = 0$, as in Fig. 2.7.

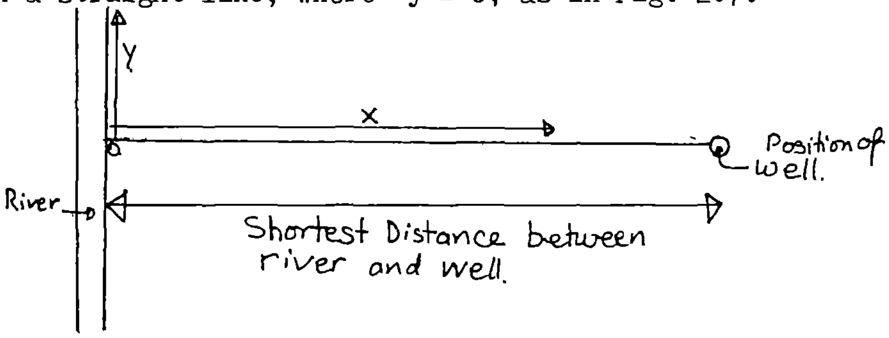

Fig. 2.7 Shortest flowpath between River and Well (After Huisman, 1983)

Under these conditions,

$$\frac{\partial h}{\partial x} = \frac{q_n}{Kh} - \frac{Q_o}{\pi KHL} \qquad \text{———} \ ⑪$$

where $\frac{\partial h}{\partial x}$ is the slope of the water table adjacent to the river. It has already been established that the slope of the groundwater table must be away from the river, i.e. the slope must be negative.

If $\frac{\partial h}{\partial x} < 0$, it follows that

$$\frac{q_n}{KH} < \frac{Q_o}{\pi KHL}$$

$$\therefore \ Q_o > \pi q_n L$$

$$\Rightarrow Q_o = \alpha \pi q_n L, \qquad \text{———} \ ⑫$$

where α is a dimensionless factor greater than 1.

Along the straight route to the well as shown in Fig. 2.7,

$$\frac{\partial h}{\partial x} = \frac{q_n}{Kh} - \frac{Q_o}{2\pi Kh}\left(\frac{1}{(L + x)} + \frac{1}{(L - x)}\right) \qquad \text{———} \ ⑬$$

since $q_n = Q_o/\alpha\pi L$, and assuming $h = H$,

$$\frac{\partial h}{\partial x} = \frac{Q_o}{\alpha\pi Kh} - \frac{Q_o}{2\pi Kh}\left[\frac{1}{L + x} + \frac{1}{L - x}\right] \qquad \text{———} \ ⑭$$

From equation ⑭, and using expressions for velocity and distance, it can be shown that within the boundaries of $x = 0$ to L,

$$T_d = \frac{pH\,L^2}{Q_o}\alpha\pi\left[\frac{\alpha}{\sqrt{(\alpha - 1)}}\left(\tan^{-1}\frac{1}{\sqrt{(\alpha - 1)}}\right) - 1\right] \qquad \text{———} \ ⑮$$

from which,

$$\alpha L^2 \left[\frac{\overline{\alpha}}{\sqrt{\alpha - 1}} \left(\tan^{-1} \frac{1}{\sqrt{(\alpha - 1)}} \right) - 1 \right] = \frac{Q_o \, T_d}{\pi p H} \qquad \text{———} \quad \text{⑯}$$

combining equation ⑯ with ⑫

$$\frac{1}{\alpha} \left[\frac{\alpha}{\sqrt{\alpha - 1}} \left(\tan^{-1} \frac{1}{\sqrt{(\alpha - 1)}} \right) - 1 \right] = \frac{\pi q_n^2 \, T_d}{pH \, Q_o} \qquad \text{———} \quad \text{⑰}$$

The length L, may now be obtained by first solving for α in equation ⑰ for specific values of q_n , T_d, p, H and Q_o , and then, with the value α obtained, equation ⑫ may be solved for L.

2.2 Drawdown associated with Abstraction of Water

The next step is to obtain the drawdown, S, of the well face resulting from abstraction. The total drawdown is given by $S_T = S_o + \Delta S$, where S_o is the drawdown due to a fully penetrating well, and S is the additional correction required if the well is partially penetrating (Todd, 1980). The drawdown, $S_o = h_1 - h_2$, h_1 and h_2 being the saturated aquifer depths at the well face before and after abstraction begins respectively.

$$h_1 = \sqrt{\frac{2 q_n L}{K} + H^2} \qquad \text{———} \quad \text{⑱}$$

$$h_2 = \sqrt{\frac{2 q_n L}{K} - \frac{Q_o}{2\pi K} \ln \left(\frac{2L}{r_o} \right)^2 + H^2} \qquad \text{———} \quad \text{⑲}$$

$$\Delta S = \frac{Q_o (1 - p)}{2\pi KH p} \ln \frac{(1 - p)h}{2r_o} \qquad \text{(after Todd, 1980)} \qquad \text{———} \quad \text{⑳}$$

p is the ratio between the length of the well and the saturated aquifer

depth H. Thus there are several factors that affect the drawdown at the well face, but the most important, from equations ⑱ to ⑳, are that the value of Q_o is particularly important, as is the distance L. Furthermore, where the well is a partially penetrating one, the shorter the permeable length of the well in relation to the depth H, the greater the additional drawdown ΔS.

2.3 Induced Infiltration to Galleries

There are two main components of flow to galleries, as with wells. These are the river water, and groundwater components. These are shown in Fig. 2.8 below.

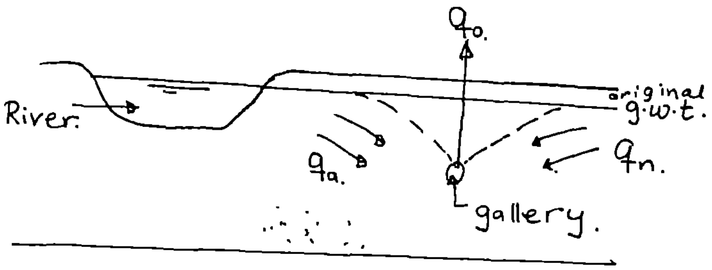

Fig. 2.8 Abstraction of Surface Water by means of a Gallery (Huisman, 1983)

From the information that $T_d = pHL/q_o$, ——— ㉑ (Huisman, 1983)

and $S_o = q_o L / KH$ ——— ㉒ (Huisman, 1983)

$q_o = q_a + q_n = K H S_o / L$, ——— ㉓

$\therefore L^2 = q_a / (q_a + q_n) \; {}^K/_p \; S_o \, T_d$ ——— ㉔

Obtaining q_n in terms of q_a to eliminate it from equation ㉔,

$q_a > q_n$, and assuming that $q_a \simeq 4 q_n$,

$$L^2 \simeq 0.8\ {}^K\!/_p\ S_o\ T_d \quad \text{———} \quad ㉕$$

Hence $L \simeq 0.9\sqrt{{}^K\!/_p\ S_o\ T_d}$ ——— ㉖ (Huisman, 1983)

2.4 Infiltration from Basins to Galleries

In the case of basins, the flow of water need not be divided into two components as for induced infiltration, as the directions for both the surface and natural groundwater are similar, and equal to q_o . Apart from this qualification, the same conditions prevail as for Induced infiltration in Section 2.2. Thus, in equation ㉔, instead of q_a , q_o may be substituted,

$$\therefore\ L^2 = {}^{q_o}\!/_{(q_a + q_n)}\quad {}^K\!/_p\ S_o\ T_d$$

$$\therefore\ L = \sqrt{{}^K\!/_p\ S_o\ T_d}$$

2.5 Drawdown Associated with Abstraction Galleries

The drawdown associated with galleries at any one point is less than for wells, for the same abstraction rate Q_o, as in the case of galleries, the abstraction is spread over a longer distance. For this study, a standard drawdown S_o has been chosen, 1.5m. However, this value, as for wells, must take account of the effect of galleries that do not fully penetrate the aquifer (the general case). In addition, there is an implicit assumption in the equation for L, that S_o is for a gallery of infinite length. This is obviously not the practical case, and a correction must be made for this also, particularly as the gallery lengths for small communities are likely to be very short. The correction

for partial penetration has the effect of increasing the drawdown above S_o, but this depends primarily on the value of q_o , and for the small values of q_o , being considered for small communities, this is not very large. Correction for partial penetration of the gallery however, has the effect of reducing the drawdown to below the initial value. Thus, considered together, the resultant drawdown would remain at approximately 1.5m or less. However, an additional depth of 0.5m may be added as an extra precaution, with the result that the gallery should always be sited at a depth below 2m of the initial water table.

CHAPTER 3

BACTERIOLOGICAL AND CHEMICAL CHANGES IN SURFACE WATERS DURING INFILTRATION

3.1 Water Quality Changes During Infiltration

The point at which quality changes begin depends on the type of infiltration. For infiltration through basins, the process begins in the basin, with physical processes such as sedimentation, and chemical processes occurring. There is also the die-off of micro-organisms, including bacteria and viruses, associated with the storage of water, even for short periods of time (Huisman, 1983).

For both induced and artificial infiltration, the entry of water into the soil brings about quality changes which can be divided into two stages: changes in the unsaturated zone above the water table, and subsequently, changes in the saturated zone below the groundwater table. These may further be subdivided into biological and chemical changes. Biological changes begin with physical processes to remove pollutants from the water onto soil particles, followed by the action of bacteria on these pollutants to stabilize them to harmless end products (Pincine and McKee, 1968). Chemical changes include oxidation-reduction, solution precipitation, and ion-exchange reactions.

3.2 Flow of Water in the Unsaturated Zone

The flow of water in the unsaturated zone is much slower than below the water table. This is because in the unsaturated zone, water only passes through the

finer pores of the soil. Thus the water has a much longer contact time with the soil than in the unsaturated zone (Lewis et al, 1980). As the degree of change in water quality is mainly proportional to the detention time in the soil, this implies that the unsaturated zone is the more important in the improvement of water quality, and as such most of the upgrading of water quality takes place here.

At the surface of the river bed or basin, solids, including bacteria, larger than the pore diameter of the soil are retained on the surface. Under aerobic conditions, bacteria will break down organic matter to form carbon dioxide, ammonia, and other compounds (Metcalf and Eddy, 1979). Particles smaller than the pore size of the soil, however, process further downward, where they may be subject to settling on individual soil grains. As the total surface area of the particles is extremely large, there is substantial scope for the removal of micro-organisms, particularly bacteria, from the water (Huisman and Wood, 1974). Those particles not removed by filtration or sedimentation may be removed by absorption. This is particularly true for viruses, which are only a fraction of the size of bacteria, and are therefore not easily removed by filtration. Adsorption appears to be the main removal mechanism for viruses (Lewis et al, 1980). It occurs either by electrostatic attraction or physical attraction to slimes on the surface of soil grains (Huisman and Wood, 1974).

In the case of viruses, their adsorption has been shown to be related to the pH of the virus and soil, the presence of positively charged ions, and the charge of the viruses (Stum and Morgan, 1981). Organic matter, including bacteria and viruses, usually have negative charges, and they are attracted to positively charged soil particles. This process continues until the soil grains are covered with the negatively charged organic matter, whereupon the soil grains, due to their reversed charge, begin to attract positively charged particles such

as Iron and Manganese ions. In this way, the reversal of charge continues, each time removing more constituents of the water. Thus adsorption is a very useful process for the removal of pollutants in surface waters (Huisman and Wood, 1974).

Bacteria in addition to decomposing organic matter, are themselves progressively decreased in number. This occurs because, with increasing distance into the soil, the supply of organic matter for use as food by bacteria decreases. Thus the bacteria are forced into a state of endogenous respiration, where they consume their own cell tissue to survive, and after a while die off altogether (Metcalf and Eddy, 1979).

The oxidation of organic matter by bacteria produces several end products, but of these, the major ones include carbon dioxide, bicarbonates, sulphates, phosphates and nitrates. Nitrates are an end product of the oxidation of ammonia. Both nitrates and ammonia however, in high concentrations, can be harmful, and the balance between ammonia and nitrate concentrations in abstracted water will depend upon whether aerobic or anaerobic conditions have been prevalent.

For inorganic compounds, the most important processes are oxidation processes, leading to precipitation within the aquifer, and ion exchange processes. Under oxidation processes, important processes include the oxidation of soluble ferrous and manganous ions to insoluble Ferric and Manganese oxides. These precipitate within the aquifer (Sneigocki, 1963). Other reactions include the precipitation of Magnesium and Barium as insoluble carbonates and sulphates (Selm and Hulse, 1960).

The effect of precipitation may be either to reduce permeability within the

aquifer due to the accummulation of solid deposits, or to cause clogging around abstraction well or gallery (Warner and Doty, 1967). However, Bernard (1957) observed no permeability reduction in an aquifer where water reacted with natural groundwater containing a high concentration of iron (1000 mg/L) during recharge.

Of the precipitation reactions likely to take place, it can be said that Calcium and Ferric compounds are normally the most common (Huisman, 1983).

In practice, it will probably be the case that as the surface waters in tropical countries have been assumed to be non-industrial, the probability of serious chemical problems occurring within the aquifer is somewhat reduced.

A change that may occur in both the unsaturated and saturated zones is the ion exchange reaction of clay minerals with sodium ions present in the surface water. Clays occur very commonly in most aquifers. They form over 50% by volume of sedimentary rocks (Weaver, 1958). In surface waters with a higher sodium content than natural groundwater, clay minerals may adsorb the sodium minerals, and either become swollen with water or form a suspension. In either case, the swelling will have the effect of reducing permeability within the aquifer (Sneigocki, 1963). The greater the clay content of the soil, the more severe the effect will be, thus the effects of such a reaction should be considered when the results of the initial borehole tests and chemical analyses of water are known (Section 4.2). However, it may be true to say that an aquifer with such a clay content as to cause serious difficulties in this respect is not likely to be very suitable as for infiltration from the point of view of initial permeability alone.

3.3 Flow of Water in the Saturated Zone

In the saturated zone, the main characteristic is that there is a much lower

oxygen concentration than before, due to the greater level of stabilization of organic matter in the unsaturated layer. Furthermore, adsorption of particles from the water is much less, as the state of saturation allows less contact between these particles and the aquifer grains. While oxygen is still present, the breakdown of substances continues as for the unsaturated zone. If the oxygen supply becomes exhausted, however, anaerobic reactions begin to occur. Among the more important of these are: the conversion of nitrates and nitrites to ammonia, and, at a much slower rate, carbonaceous material to carbon dioxide and methane. Bicarbonates are also converted to carbonates, and the precipitation of calcium carbonate, for example, means the water becomes less hard. However, accompanying anaerobic changes mean the process is, overall, a disadvantage, resulting in the deterioration of water quality. The aim should therefore be to ensure that there is enough oxygen to last the detention time of the water underground.

3.4 Oxygen Supply During Infiltration

The presence or absence of oxygen during infiltration has been shown to determine the nature of reaction products, and therefore the characteristics of abstracted water. Factors that determine whether or not anaerobic conditions will occur are:

(i) The oxygen content of the surface water;
(ii) The oxygen present in the unsaturated zone;
(iii) Concentration of organic matter in the surface water;
(iv) Whether there is any significant organic matter forming part of the aquifer (Huisman, 1983).

For rivers in developing countries, there are a number of problems, in that as the saturation concentration of oxygen in water decreases with increasing temperature (Metcalf and Eddy, 1979), the rivers will have a low dissolved oxygen concentration. In addition, they are likely to be highly polluted, and will therefore have a high organic content, which in turn exerts a high oxygen demand.

There are two approaches to the problem of insufficient oxygen. One is to decrease the oxygen demand of the water, and the other is to increase the oxygen supply. However, neither of these methods is relevant to induced infiltration by its very nature. The solution in the case of induced infiltration is therefore to keep the detention time to the minimum deemed necessary to achieve a satisfactory improvement in the water supply. If this does not work, some simple form of post treatment of the water may be necessary, but only if the problem is serious, and the method of treatment is as simple as the initial induced infiltration process.

Where infiltration is through basins, however, there is more scope for increasing the supply of oxygen. It is necessary to bear in mind, however, that the penetration of oxygen from the atmosphere into the soil is limited to only a couple of metres or so (Pincine and McKee, 1968), and this determines the total distance over which maximum aerobic activity is likely to take place.

Decreasing the organic content of the water may be achieved by screening suspended water from the raw water (Section 4.12). Where the oxygen content of the water is to be increased, there are two main methods. The first is by having basins sited high above the groundwater table, so that in the distance between the basin and groundwater table, a larger amount of oxygen may diffuse into the soil than otherwise (Bize, 1979). However, oxygen uptake by this method can only be a slow process, as diffusion is slow (Huisman, 1983).

Another, more effective method, is by operating basins intermittently, with resting periods where the basin is allowed to dry out. When the basin dries out, oxygen is able to enter the soil from the atmosphere, and this, with the accompanying lowering of the groundwater table due to the cessation of infiltration, results in additional oxygen entering the soil. This is equivalent in volume to the displacement of water under the basin (Huisman, 1983). Intermittent infiltration also allows the aerobic degradation of organic matter on the basin surface by bacteria to take place, and reduces the incidence of clogging of the basin. The lengths of use and resting periods for basins are normally determined by trial and error. However, after a resting period, in subsequent flooding of the basin, a period of time is required for the maximum rate of infiltration to be achieved. It is therefore advisable that the wet and dry cycles for basins should not be too short. The important source of increased oxygen supply in basins is from the photosynthetic activity of algae. Algae grow rapidly under tropical conditions, and during the day, when photosynthesis occurs, large amounts of oxygen may be produced, increasing the concentration of oxygen in the water. This is to some extent offset by the consumption of oxygen by algae during the dark, in respiration, when oxygen production has ceased (Huisman, 1983). However, algae do provide a net benefit in oxygen production.

3.5 Nature and Causes of Clogging in Infiltration Basins

Clogging of infiltration basins leads to a reduction in infiltration rates. Clogging may occur from three main causes. These are: the accumulation of suspended matter at the basin surface, biological solids build-up beneath the basin, and clogging due to the nature of the soil surface (Berend, 1970).

Clogging from suspended solids can be reduced by screening out suspended solids, referred to earlier, and by making sure that additional suspended solids from the basin surface do not enter the water. This can be done by protecting the waterline of the basin with slabs if necessary (Berend, 1970).

Clogging from the nature of the soil may be prevented in the first instance if, during construction of the basin, care is taken not to compact the soil surface.

Biological clogging is rather less simple. Wood and Bassett (1975) have attributed it to the accumulation of anaerobic bacteria just under the basin. They suggest that as anaerobic bacteria are not so efficient at using dead cells and wastes, there is an accumulation of these materials. However, experimental work by Okubo and Masumoto (1983) has revealed that both anaerobic and aerobic bacteria can be responsible for clogging. It would seem that whichever solution is most likely in practice, the most that can be done is to reduce the incidence at least of anaerobic bacteria by preventing anaerobic conditions from developing.

In all cases of clogging, however, as it occurs mostly at or just below the basin surface (Bouwer, 1970), the precaution most commonly used is to include in the basin a removable sand layer within which clogging can occur.

CHAPTER 4

DESIGN OF INFILTRATION SYSTEMS

4.1 Selection of an Infiltration System

The selection of an infiltration system depends largely on the hydrogeological characteristics of the area adjacent to the surface water. The first step in choosing an infiltration system, therefore, is to conduct a geotechnical investigation of the area over which infiltration is to take place. As a rough estimate, this may be taken as 100m x 150m as shown in Fig. 4.1, though the actual area for infiltration is likely to be considerably less.

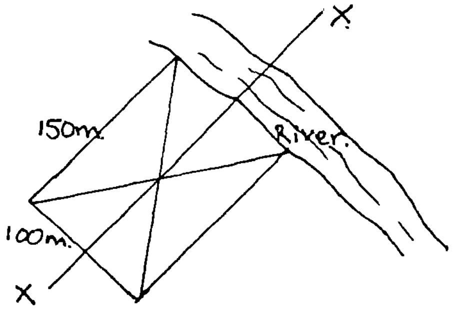

Fig. 4.1 Area for Geotechnical Investigation

The purposes of the investigation are as follows:

(i) To assess the most suitable system of infiltration;

(ii) To obtain a description of the geological profile of the area, and depth of the aquifer;

(iii) To estimate the average saturated depth, H, over the area;

(iv) To acquire samples for laboratory tests for the horizontal permeability, K, of the soil, porosity, p, and the particle size distribution of the soil.

In addition to the geotechnical investigation, it will also be necessary to take measurements of the width of the river, and obtain information on high and low water depths of the river.

During the survey, samples should also be taken of the river water and groundwater, to conduct chemical and bacteriological tests on the surface water, and chemical tests on the groundwater. The purposes of these tests would be to obtain information on the initial characteristics of the surface water, so that it may be compared to the water abstracted at the end of the infiltration process. Also, a comparison of surface water chemical content with groundwater would enable some predictions to be made as to the likelihood of significant precipitation of compounds either within the aquifer, or around the abstraction wells or galleries. It is also necessary to know the oxygen content of the surface water, so that it may be compared to the oxygen demand of organic matter in the surface water and any organic matter in the soil.

From the overall results of the survey, some indication will be obtained of the most suitable method for water treatment, in the light of the advantages and disadvantages of each system as described in Chapter 1.

A discovery of massive clay deposits in the area of the survey, for example, may mean that infiltration within the area would be unsuitable, in which case the surface water may need to be transported elsewhere for infiltration. Whether this will be by pipes or channels will depend on the distance involved; channels would be used for areas nearby, and pipes for long distances. However, pipes should be avoided wherever possible. Alternatively, it may be that if the clay deposits are near the surface of the ground, it may be possible to dig an infiltration basin deep enough to reach a layer of more permeable strata for infiltratio
If there is a possibility of clogging at the point of abstraction, infiltration

galleries may be preferred to abstraction wells; provided, that is, the groundwater table is within 5m of the ground surface. Galleries may also be chosen instead of wells if the aquifer is of a narrow width.

In this way, the results of the survey help to determine the most suitable form of infiltration to be used.

4.2 Geotechnical Investigation

Initial information on the geology of the area may be obtained, in some cases, from geological maps from the Ordnance Survey Department, and this will provide some indication of the general characteristics of the soil, and of suitable spacing of boreholes for the survey. Boreholes should be deep enough to establish the depth of the aquifer. From the boreholes, records may be made of the type and depth of different strata, noting any special features, such as clay lenses, that might have a marked effect on the overall permeability of the soil. Representative samples may also be taken from boreholes to obtain values for horizontal permeability, porosity, and particle size distribution tests as mentioned in Section 4.1.

Particle size distribution analyses will be used in the classification of unconsolidated material. Where infiltration galleries are to be used for abstraction, they are needed to determine the need for a gravel packing, and the size of gravel to be used.

4.3 Basis of Design Calculations

The principal factors to consider in design relate to improving the raw water

quality to a point where it is suitable for use as drinking water, and to maintain a steady flow of water from the surface water source to the point of abstraction.

There are three main parameters that control the dimensions of the infiltration system. The first is the detention time of surface water underground. The length of time that the surface water remains underground before being abstracted will determine the extent to which the water quality is improved, as the upgrading of water quality has been shown, in Chapter 3, to be a function of time. Values used in design are normally empirical, based on experience at similar places elsewhere.

Hasnoot and Leeflang (1970) have given values of 40-80 days for infiltration systems in Holland, and Winquist and Mazehurst (1970) suggest a period of 200 days as a suitable figure. However, the advantage of long detention times must be balanced against the possibility of anaerobic conditions developing within the aquifer. This is particularly so for tropical surface waters, which are characterised by a high level of pollution, and a relatively low concentration of dissolved oxygen. The detention time used for design in this study is taken as 80 days.

To maintain a steady flow of water during infiltration, it is necessary to prevent excessive clogging of the river bed or infiltration basin. In the case of rivers, accumulated material on the river bed may be carried away by the water, particularly during periods of high flow (IRC, 1981). However, for infiltration basins, clogging will lead to a marked reduction in the infiltration rate, requiring cleaning of the basin. To keep the number of times cleaning is required to a minimum, a low infiltration rate is required; however, it must not be so low that a large basin area is required for infiltration. Edworthy

and Downing (1979) report an infiltration rate of 0.36m/d for lagoon recharge, and Berend (1970) suggests 0.2 - 2m/d as the most practical range of infiltration rates. Furthermore, the higher the initial rate of infiltration, the more rapid the rate of clogging. The high level of suspended solids in tropical river water also aggravates the problem of clogging. The design value for infiltration into basins is therefore taken as 0.4m/d. Similarly, abstraction wells and infiltration galleries may be subject to clogging, from chemical deposits or from the accumulation of aquifer material within infiltration pipes. The design of wells and infiltration pipes takes into account these possibilities, and keeps their occurrence to a minimum.

There is also a need to take account of the drawdown associated with the abstraction of water. There may be a legal requirement to keep the lowering of the groundwater table to a specified value. Where this occurs, the value will depend very much on local groundwater levels, and the use to which groundwater may be put. An allowable maximum of 1.5m drawdown has been chosen for the design tables in the Appendix. A lower value would mean shorter distances for infiltration, given that for induced infiltration to galleries, for example,

$$L = 0.9\sqrt{K/p}\, S_o\, T_d$$

Thus, if K, p, and T_d remained constant, L is proportional to S_o, the maximum drawdown. The danger of short distances for infiltration is that there is a possibility that some of the surface water, by taking the shortest path between the surface water source and abstraction point, may not be sufficiently improved in quality.

The drawdown at the point of abstraction also determines the minimum depth at which abstraction galleries and wells must be situated. For this purpose, it

is necessary to correct the maximum drawdown to take into account partial penetration of wells and galleries, and the finite length of galleries as referred to in Chapter 2.

In the following sections, the use of design information in the form of tables and equations will be discussed for induced infiltration and infiltration via basins.

4.4 Choice of Variables for Design Tables

Tables are given in the Appendix for the estimation of distances over which infiltration will take place, and in the case of infiltration basins, also for the width of the basins, W, and the flow of water per unit length of infiltration from basins to galleries, q_o .

In compiling these tables, it has been necessary to make some assumptions about the likely practical values for variables. The range of permeabilities, K, taken as 0.5 - 100 m/d, is an interval covering materials of moderately low permeability such as silt and clay mixtures, to highly permeable material such as sand and gravel mixtures (Todd, 1980). Outside this range, the permeabilities may either be too low to yield appreciable quantities of water, such as massive igneous rocks, or else too high. Moreover, it is unlikely that highly permeable material above 100 m/d would be found uncombined with other, less permeable material.

For the saturated aquifer depth, H, used in the calculation of q_o, a value of 10m has been taken as being the most convenient base from which q_o for other saturated depths may be calculated. This is because the saturated depth may

be as high as 30m or more. For a value of H equal to 15m, for example, the true value of Q_o will be 1.5 times that given in the table.

Values for porosity, P, have been taken as ranging from 0.30 to 0.50, by examining mean values for the porosity of various geological materials (Johnson, 1967). In the calculation the lengths for induced infiltration to wells (Section 4.6), q_n, the flow per unit length of infiltration for natural groundwater to the abstraction well is dependent on the aquifer width, W, and residual rainfall, P. As $qn \triangleq PW/_2$, q_n has been given values for a range of aquifer widths from W = .5km to W = 20 km, and P has an average value of 600 mm/year.

4.5 Induced Infiltration to Galleries

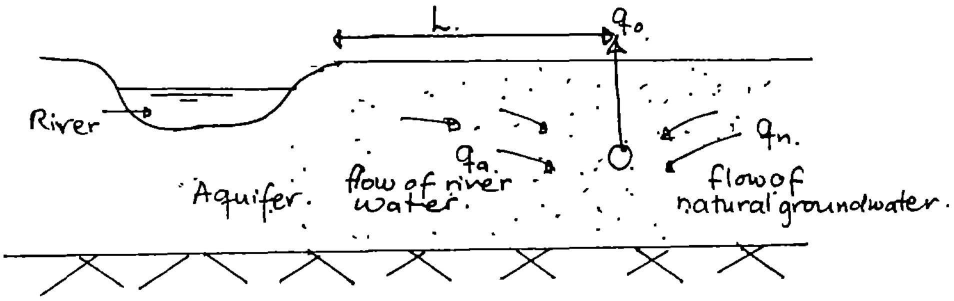

Fig. 4.2 Induced Infiltration to a Gallery
(Huisman, 1983)

Initially, the distance, L, between the river and infiltration gallery must be established. This is given by Table A1 in the Appendix. For values of permeability and porosity obtained from the geotechnical investigation, given a detention time of 80 days and maximum drawdown of 1.5m, the value of L may be read from the table. The required length of the infiltration gallery is given by $B = Qo/_{qo}$, where B is the length of the gallery in metres, Qo is the required abstraction rate of water in m^3/s, and qo the flow per unit aquifer width in m^2/s.

The value of Q_o is C x P_n, where C is the consumption of water per head of population, and P_n is the population for which the system is designed.

To calculate the length B, Q_o must first be estimated from information on water use by the community, and a projection of future water demand. The flow of water per unit length of infiltration, q_o, may be obtained from Table A4 in the Appendix, by using the same values for K and ρ as in the determination of L. As explained in Section 4.4, these are values for H = 10m, and q_o may be adjusted for different values of H, the saturated aquifer depth.

The detailed design of infiltration galleries is given in Section 4.9.

4.6 Induced Infiltration to Wells

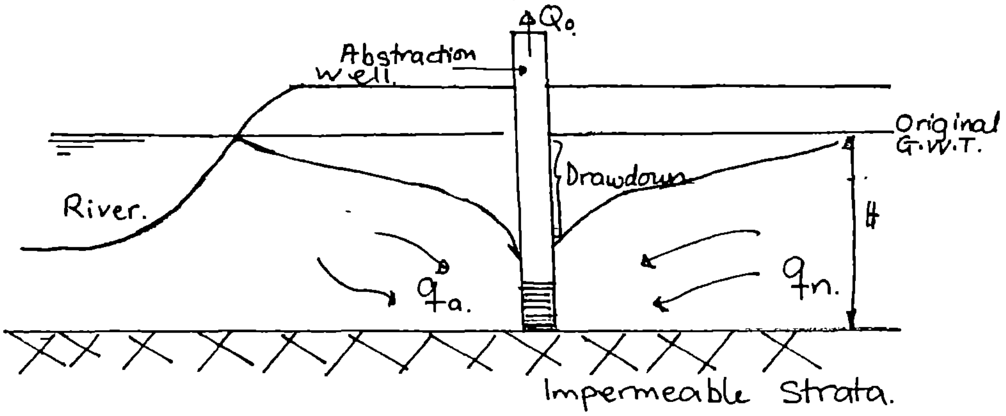

Fig. 4.3 Induced Infiltration to a Well
(After Bize, 1979)

The distance, L, between the river and the abstraction well, may be obtained from Table A2. In this case, the distance L has been obtained from two equations given in Chapter 2 for induced infiltration to wells. These are:

$$\text{(i)} \quad \frac{1}{\lambda}\left[\frac{\lambda}{\sqrt{(\lambda-1)}}\left(\tan^{-1}\frac{1}{\sqrt{(\lambda-1)}}\right) - 1\right] = \pi q n^2 T d / pHQ_o$$

and

(ii) $L = Q_o / \pi \alpha q_n$

For equation (i), pH, T_d are constants. Porosity, p, is presumed constant because within the range of 0.30 to 0.50 it will not significantly influence the value of α. Similarly, H has a constant value of 30m, which should be adequate for shallow aquifers.

The length, L, may therefore be obtained for different combinations of Qo and q_n. Q_o covers the range of requirements of populations from 100 to 10,000 people, with a per capita consumption of 50 litres per head of water. These are to be found in Table A2.

Having established the position of the well, the drawdown of water in the vicinity of the well must be calculated. This will indicate the minimum depth to which the well must be sunk. It is important to keep the screen length of the well always below the groundwater table, to ensure that oxygen does not enter the well and cause the precipitation of chemical deposits around the screen. The method for calculation of the drawdown associated with wells has already been described in Chapter 2.

4.7 Infiltration from Basins to Galleries

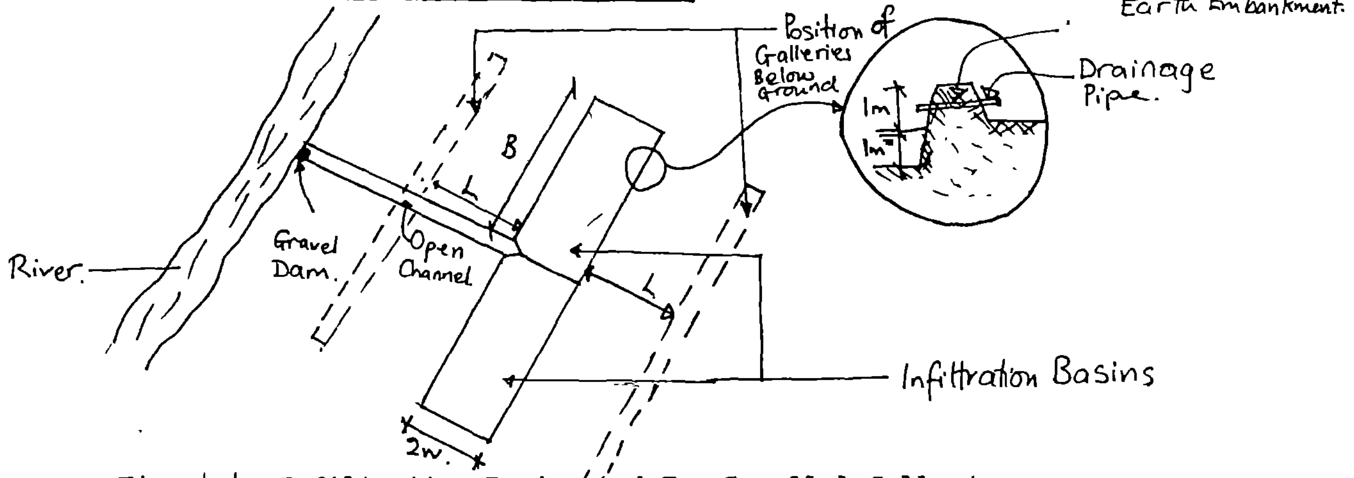

Fig. 4.4 Infiltration Basins and Two Parallel Galleries

The distance bwtween the outer edge of the basin and either of the galleries, L, is the length L, where $L = \sqrt{k S_o T_d/p}$.

For any given scheme, this value may be obtained from Table A3, using the values of permeability and porosity characteristic of the area, where the scheme is to be situated. Here, as in Section 4.5, the detention time, T_d, is 80 days, and the maximum drawdown at each abstraction gallery, So, is 1.5m.

The length of the spreading basins is equal to the adjacent gallery length, which is calculated in a similar way to that for induced infiltration in Section 4.5. However, in this case, $B = Q_o/2q_o$, as the abstraction of water per unit length of infiltration is doubled with the presence of two galleries. To obtain q_o, the same Table A4 may be used, as q_o for induced infiltration and basin infiltration is approximately equal. The same principle for correcting qo to suit different saturated aquifer depths applies here. Thus by obtaining B, both the gallery and the basin lengths are known. The basin width depends on the infiltration rate chosen for the entry of water from the basin into the soil. Values representing the basin width are to be found in Table A5. These are based on the relationship

$$2 \times \tfrac{1}{2} \times \text{width of basin} = \frac{2 \times q_o}{(0.40/86400)}$$

where 0.40/86400 is the infiltration rate in m/s. As the operation of basins is significantly improved by intermittent operation, and bearing in mind also the need to clean the basins, it is necessary to provide a second basin of equal capacity. This can be done simply by doubling B, the length of the original basin, to allow for a second basin, such that the two are laid end to end, abbutting each other, as shown in Fig. 4.4.

The depth of the basin is chosen as a compromise between one that is too deep, in which case it is difficult to drain (that is, unless there is easy access to the river from which the water is drawn), and making it too shallow which makes it more susceptible to the growth of rooted aquatic plants (Huisman, 1983).

Izatt et al (1979) in their report on lagoon recharge state that a depth of 2.5m was used for the lagoons. This figure is about as deep as is possible without encountering the problem of drainage mentioned earlier. It is suggested that a figure of 2m total depth of basin will be adequate in tropical climates, made up of an excavation depth of 1m and an earth embankment 1m high.

Sand is used to line the basins, to prevent clogging taking place in the upper layers of the aquifer where it cannot easily be removed, and also to allow for an adequate infiltration rate. The sand layer may be from 500-700mm thick (Frank, 1970), and should be made up of uniformly graded sand.

The design of river intakes and channels to transport the raw water from rivers to basins is discussed in Sections 4.12 and 4.13 respectively.

4.8 Modification of Infiltration Systems for Iron and Manganese Removal

While infiltration systems do give a substantially improved water supply, there may sometimes be specific problems with high Iron, and to a lesser extent Manganese levels in the water. Although bacteriological criteria generally override aesthetic and similar requirements for water in developing countries, it is necessary for the water to be appealing enough for consumers to use. Excessive concentrations of Iron and Manganese may give the abstracted water an unpalatable taste and add colour to the water (AWWA 1980). Furthermore, Iron

fixing bacteria may be induced to grow and form deposits in the water distribution system.

The highest desirable concentration of Iron (ferrous) is 0.1 mg/L, and for Manganese 0.05 mg/L (WHO 1971). Where much higher concentrations are present in the abstracted water, some attempt must be made to reduce these elements to an acceptable level if the water is not to be unfit for use.

The main criterion is to find a method that is in line with the simplicity of the original infiltration system; otherwise, the advantages of infiltration over other methods of water treatment will be diminished. Aeration of abstracted water is often used to treat such water, but aeration alone is not always sufficient. There are times when it is not possible to achieve the desired oxidation of Iron or Manganese compounds to precipitates (IRC, 1981).

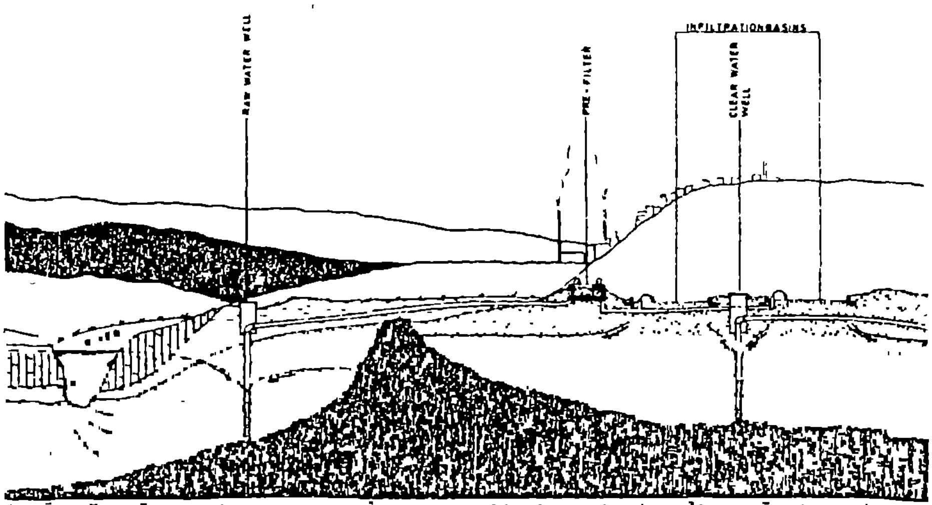

Fig. 4.5 Re-Infiltration of Water Abstracted after Induced Infiltration to a Well (Agerstrand, 1979)

Agerstrand (1979) reports on a method which significantly reduces the concentration of Iron or Manganese compounds, and a diagram of the method is shown in Fig. 4.5. The method was developed by Consulting Engineers at Viak in Sweden. The principle of the method is that water abstracted by induced infiltration to

wells is then pumped to infiltration basins, where, after passing through an aeration cascade, the water flows into infiltration basins from where it re-infiltrates into the ground. When the water is again abstracted, it has an appreciably lower concentration of Iron and Manganese ions in solution. Where there are particularly high concentrations of Iron and Manganese (above 0.5 mg/L and 1 mg/L respectively), a pre-filter containing 30-50mm macadam, with a detention time of up to 30 minutes, is used. This has the effect of prolonging the running time of the basins. Fig. 4.6 is a sketch of the filter system used in the re-infiltration system.

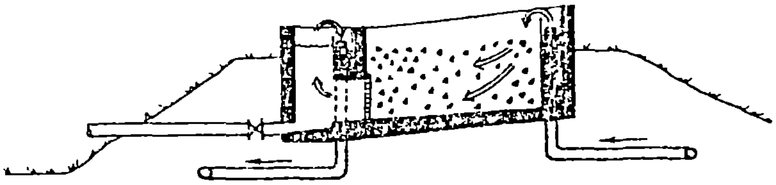

Fig. 4.6 Pre-Filter Used for Water with High Concentrations of Iron or Manganese Compounds in Solution (Agerstrand, 1979)

The purpose of re-infiltration is to allow the water a sufficient retention time for the oxidation process to take place. This is because it is a time dependent reaction (Warner and Doty, 1967).

The infiltration basins become clogged with Iron and Manganese precipitates in time, and to minimise this tendency, the basins are run intermittently, as with the normal operation of basins, with a drying time of 6 - 24 hours between runs. When the water level rises to 0.5m, the basin is cleaned by removing the sand layer. The detention time of water during re-infiltration is 14 days for one Swedish plant, and after this time, the soluble Iron concentration was found to

have been reduced from 3.9 mg/L to less than 0.09 mg/L, and the Manganese from 0.21 mg/L to 0.01 mg/L, well below recommended WHO standards.

A slightly modified form of this treatment process will be suggested for use in developing countries. There are two main adaptations. These are that aeration is by means of a Venturi Meter instead of a cascade, and that it may be preferable to accept the need for more frequent cleaning as opposed to using a pre-filter of macadam. A diagram of the Venturi Meter is shown below in Fig. 4.7.

4.9 Design of Re-Infiltration Systems

The design of re-infiltration systems will follow the same basic rules as described earlier in this chapter from induced and basin infiltration. The difference in the case of the basin is that it receives pipeborne aerated water instead of surface water through an open channel. Detention time for re-infiltration however, should be much shorter than the original process, as most of the reduction in soluble Iron and Manganese takes place in the basin. Furthermore, pathogenic bacteria and other undesirable constituents of the water would already have been reduced to an acceptable level during induced infiltration. If the detention time of 14 days for the Swedish example is used, the distance between the basin and abstraction system will be reduced accordingly. This may be done by multiplying the distance obtained with a detention time of 80 days by a suitable factor. Where the abstraction system is a gallery, $L = \sqrt{k/p\ S_o}\ \sqrt{T_d}$, with a reduction of T_d from 80 to 14 days, where $80/14 = 5.71$, $L' = \sqrt{k/p\ S_o}\ \sqrt{T_d/5.71}$ from which $T_d/5.71 \big/ \sqrt{T} = 0.42$. Thus $L' = 0.42\ L$, where L' is the distance of infiltration for a detention time of 14 days. Thus to obtain the distance between the infiltration basin

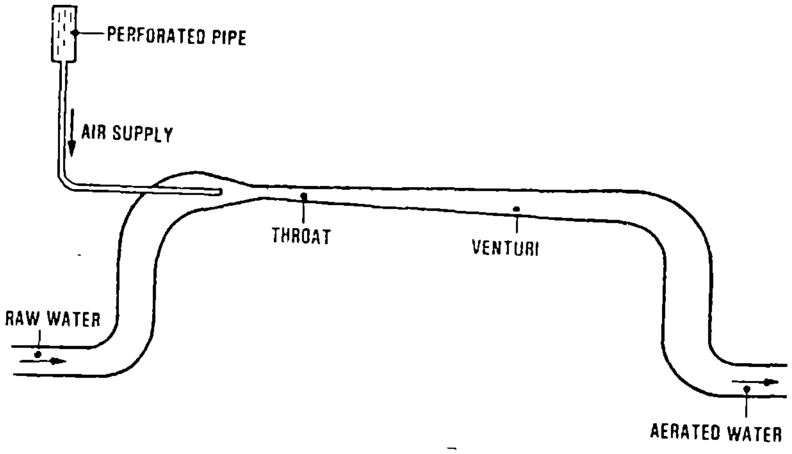

Fig. 4.7 Venturi Device for Aeration (IRC, 1981)

and the abstraction gallery, the distance in Table A3 must be multiplied by 8.42. Fig. 4.8 below shows the arrangement for such a system, in which the abstraction gallery is on one side of the basin only. To obtain the basin width, this must be taken into account. Table A5 in this case will represent two times the full basin width. This is because, whereas in the case of the basin with two galleries, $2w = 2\,q_o/(0.4 \times 86400)$. $2\,q_o$ is replaced here by q_o, and therefore $w' = q_o'/(0.4 \times 86400)'$, w' being the full width of the basin for re-infiltration. All other details of the design process remain the same as described in this chapter for the initial process.

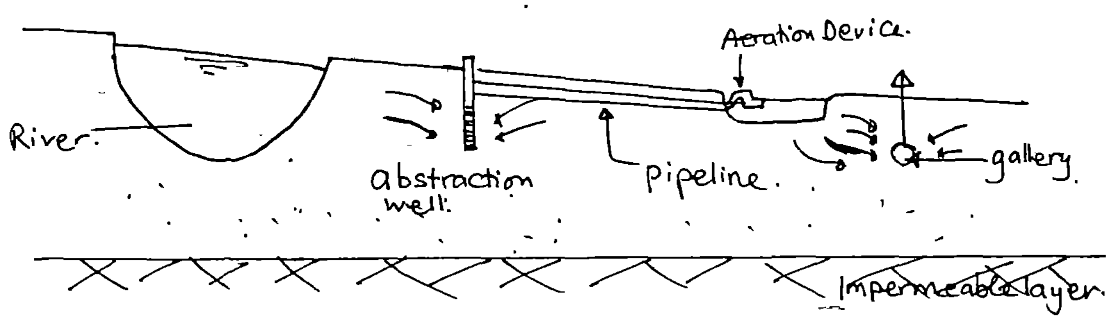

Fig. 4.8 Re-Infiltration of Water to an Abstraction Gallery

4.10 Design of Infiltration Galleries

Galleries are normally suitable for shallow aquifers (Buss, 1981). They may be laid at depths of up to 8m below ground (Bennett, 1970). They are also useful where the aquifer is of narrow width (IRC, 1981). The galleries consist of slotted, or open jointed, pipes laid in trenches and surrounded by a gravel packing. The material for pipes should be such that they are not attacked by chemical constituents of subsurface water. When this is taken into account, the type of pipe chosen then depends largely on local availability. Suitable pipe materials are: stainless steel, vitrified clay, and plastics, all of which are suitable for slotting. The choice of gravel diameter and slot width is determined by the following relationships (Bennett, 1970):

(i) The particle size distribution curve for aquifer material should be fairly similar to that for the gravel pack;

(ii) $$\frac{D_{15} \text{ for the filter}}{D_{85} \text{ for aquifer grains}} \leqslant 5 \quad \text{——} \quad ①$$

(iii) $$\frac{D_{85} \text{ for the filter}}{\text{Slot width of pipes}} \geqslant 2 \quad \text{——} \quad ②$$

D_x for any material is such that x% by weight of the material is smaller in diameter than this value. Slot lengths, however, can be of any magnitude compatible with maintaining the structural strength of the pipe.

To obtain the filter size, it is necessary first to choose a convenient slot width of a few millimetres, and then calculate the gravel pack diameters based on the equations ① and ② above, using the boundary conditions. The gravel pack may need to be two or more layers of differently sized gravel, depending on

the size of aquifer grains.

As an example, for a pipe with slots size 5mm x 5mm, to be laid in a sandy aquifer with grain size D_{85} = 0.25mm, the coarsest gravel layer, from equation ② must have a size D_{85} = 2 x 5mm = 10mm.

From equation ①, D_{15} for the filter = 5 x 0.25mm = 1.25mm. Thus the first layer of the pack has a size D_{15} = 1.25mm. If D_{85} for this pack is, say, 2.10mm again using equation ①, 5 x 2.10 = 10.50mm Thus, for the second filter layer D_{15} = 10.50mm. D_{85} will therefore be greater than this. As the coarsest gravel size required is one where D_{85} is at least 10mm, this size satisfies the conditions. The gravel pack will then be made up with the finer layer closest to the pipe. This arrangement is shown in Fig. 4.9, with the minimum thickness required for each layer. Where slotted pipes are not readily available, open jointed pipes present a much simpler solution. The method of sizing the gravel pack is the same as for slotted pipes, with the joint width equivalent to the slot width in calculations. For a total openable area of approximately 20%, a metre run of pipe may be composed of twenty 50mm long pipes with 10mm joints between them. When pipes cannot be ordered in such lengths, they can be cut to suit the purpose. In this respect, plastic pipes would be the best choice, followed by vitrified clay pipes.

The pipe diameter is chosen on the basis of the flow of water expected, the fall to which the pipe is laid, and the velocity of flow required. The minimum recommended velocity to prevent the accumulation of deposits within the pipe is 0.5m/s (IRC, 1981). For water collection a sump is needed, at the lower end of the gallery from which water can be pumped. Where the sump is only required for water collection and occasional gallery maintenance, a size of 0.80m x 0.80m should be sufficient. For very small communities of, say, 500 people with a low

water demand of 30L/h.d, the sump can be made large enough to act as a storage tank, for 50% of the total daily water demand. This can then cover periods of maximum water demand during the day.

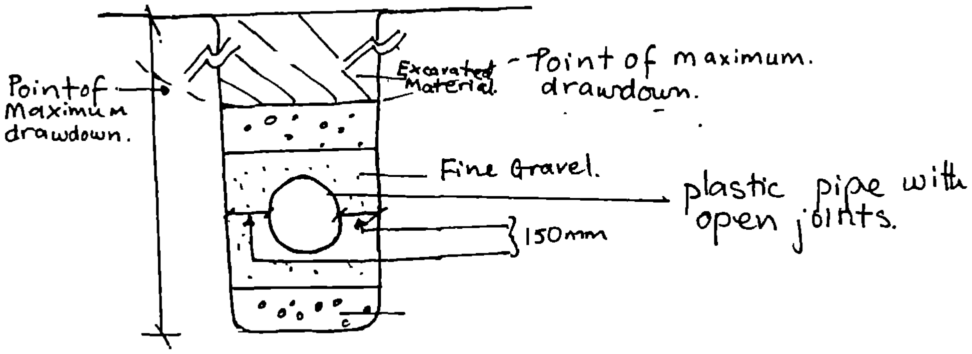

Fig. 4.9 Infiltration Gallery Design

4.11 Design of Wells

The design and construction of abstraction wells for induced infiltration follows the same principles as design for wells receiving natural groundwater alone. These are well documented in specialist publications, and are not covered in detail in this study.

4.12 River Intake Devices

For the transportation of river water to infiltration basins in open channels, the detail at the junction between the river and channel will depend mainly on the high and low water levels in the river. Where the difference between the two levels is not very great, it is possible to have the channel leading off from the river, with a dam of fine gravel, 5mm effective diameter, at the

entrance to the channel, about 100mm thick. This should ensure that larger suspended solids particles do not enter the channel. Where the difference in river levels is so large that allowing for low water levels would result in a channel too deep for the spreading basins, provision may need to be made for pumping the water up to a higher channel level, during the periods of low water flow.

4.13 River Water Transportation

The design of open channels for transporting river water to basins is based on the flow of water required through the channel. Unless the channels are cut in an impermeable layer of soil, they must be lined. As clay is most likely to be available, it is recommended that this should be used as a lining.

CHAPTER 5

OPERATION AND MAINTENANCE

5.1 General Operation of Plant

Day to day operation of any infiltration system chosen is a straightforward process. It consists of checking to see that the abstraction pump is in working order. It is also useful to make a daily visual check on the turbidity of the water. Sudden increases in turbidity may be a sign that fine particles from the aquifer have entered the gallery or well, due to failure of the gravel pack or screen to retain them. In a well-designed abstraction system, this should not normally happen. However, where it does occur, the gallery or well must be cleaned out. The cleaning of galleries and wells is discussed under Sections 5.4 and 5.5 respectively.

5.2 Tests for Water Quality

Water quality tests are in a sense the test of the whole infiltration system. In the final analysis, the abstracted water must meet the statutory requirements for small community supplies in the countries where they are situated.

WHO recommends, for small communities of up to 20,000 people, at least a bacteriological check on the water, preferably once a week, but at least once a month (WHO, 1971). In addition, it is advisable that if the galleries or wells are cleaned, this should be followed by bacteriological testing.

A simplified chemical examination of the water may be undertaken at the same time as the bacteriological examination.

5.3 Operation of Infiltration Basins

Basins will normally be run in pairs, intermittently. The shorter the wet and dry cycles, the more oxygen is taken into the ground, as discussed in Chapter 3. However, as each basin will need to be shut off manually, the cycles should not be too short. Bouwer (1970) reports on infiltration plants where cycles range from 2 wet days/3 dry days, to 14 wet days/10 dry days. Rather longer drying cycles would however be simpler to operate. Cycles of at least 14 days, wet and dry, and at most monthly wet and dry periods, are likely to be more suitable to small plants in developing countries.

When a basin is to be taken out of use, access to the channel should be shut off by putting a plate across the entrance to the channel, so that water flows into the adjacent basin. The basin should then be left to dry out naturally; where the water level is high, and the basin has become badly clogged, some of the excess water should be able to drain away through drainage holes provided in the surrounding embankment above the normal head loss expected, say 0.5m above ground level. So for a basin with 1m deep excavation, water in excess of a 1.5m depth will be drained off. When after a number of cycles, a basin requires cleaning, as much of the sand layer, after drying out, can be removed as necessary, and the sand replaced. This operation should not need to occur very often, but the number of times it is necessary is very much dependent on the nature of the river water, though intermittent basin operation reduces the number of cleaning times required.

In addition to cleaning the basins, the gravel dam at the entrance to the channel must be cleaned at regular intervals, to maintain a steady flow of water from the river to the channel.

5.4 Maintenance of Galleries

Galleries do not require regular maintenance, but when they are clogged with silt, or chemical deposits, the result will be either a deterioration in water quality or reduction in the quantity of water abstracted. In such cases, abstraction from the gallery will need to be halted so that cleaning of the gallery may take place. Where there are two sets of galleries, abstraction from the other gallery will then provide continuing, though reduced, water supply.

Provided the gallery is not very long, say up to 20m, cleaning should not be very difficult. The sump should first be dewatered, and solids loosened from the gallery by jetting water from a pipe lowered through the sump into the gallery. Loosened material will then be washed into the sump, from where it can be removed (Bennett, 1970). This method should take care of clogging of a physical nature.

Where the problem is due to chemical deposits, it becomes rather more difficult to resolve, as these have to be dissolved by various chemicals. By conducting a chemical analysis, and comparing it to the results of previous ones, the cause of the problem may be identified. For treatment of ferric, magnesium and calcium carbonates, Bennett (1970) recommends the use of a 15% solution of commercial Hydrochloric acid, used in conjunction with an inhibitor, to prevent acid from attacking the pipe. This can be applied through a small diameter perforated pipe laid for the full length of the gallery. It should be left for at least

eight hours, at the end of which the gallery may be pumped for some time, and pH measurements taken. When the pH has returned to its normal value, the gallery will be ready for use.

Accumulations of organic slime can be similarly treated, with a chlorine dose at a level suitable for drinking water. In this case, the abstraction of water for use can continue.

It can be seen, however, that the use of chemicals for cleaning reduces the advantages of the system, and even for occasional cleaning such as this, it may be difficult, if not impossible, for some communities to get the chemicals required.

This is one of the main reasons why the design and construction of the gallery is so important.

5.5 Cleaning of Wells

Wells are more likely to require cleaning than galleries, as water is abstracted through a smaller total surface area. Cleaning is effected by pumping the well at double the capacity (Hasnoot and Leeflang, 1970). This should loosen accumulated particles which have adhered to the screen. Where clogging is due to chemical precipitates, cleaning will need to be, as for galleries, by chemical means. The disadvantages of this are the same, and the likelihood of its occurrence is rather high.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The previous chapters have evaluated a selection of the available methods of infiltration used in water treatment, prior to the preparation of a handbook for their design and operation. The methods have been chosen to cover as wide a range of situations as possible.

There are five main stages in the development of an infiltration system. These are: the preliminary survey of the infiltration area, selection of a method of infiltration on the basis of survey results, design of the chosen system, construction, and operation. At each stage, there are certain important factors that must be borne in mind.

During the survey, tests and observations must be carried out with reasonable accuracy, otherwise at the design stage, very inaccurate results may be obtained. In designing the system, it must be noted that the calculations are an estimate, as they represent idealised aquifer and flow conditions which do not prevail in practice. Proper construction of the infiltration system has been shown to have an important effect on the operating efficiency of abstraction wells and galleries. Similarly, the infiltration rate for basins can be reduced if the basin floor is inadvertently compacted during construction. Finally, in operating each method, basins need to be carefully monitored, particularly in the early stages of operation, to ensure that the most suitable time periods are chosen for cleaning. As regards infiltration galleries, they emerge as a particularly suitable means of recovering water, as they are highly unlikely to become clogged throughout their lengths.

The water quality that emerges after abstraction is bacteriologically safe, and provided it is of reasonable aesthetic appeal, should be suitable for distribution to the community.

An important question that remains unanswered is whether, given the fact that tropical surface water suffers from a relatively low dissolved oxygen content, the detention time of the surface water can be decreased. The rate of activity of micro-organisms increases with an increase in temperature, and the unsaturated zone, where most activity takes place, is warmer than in temperate countries. Thus, it may be that the same degree of upgrading can be achieved with a shorter detention time. This, however, is a question that can only adequately be answered by the operating experiences of any systems that may be set up in developing countries.

There is, nevertheless, enough information at present to provide an adequate basis for design and operation. A lot, however, still depends on the judgement of the individual designer. The essential design principles drawn from the study have been incorporated in a simple handbook for the use of Engineers in designing infiltration systems. It is not an exhaustive description of the system, nor does it attempt to identify every problem that may arise. What it does is to set out the basic descriptions of the selected systems, and the method of their design, with advice on general and special operating and maintenance requirements. Local conditions may vary considerably, but it is hoped that the handbook will provide a framework within which the information can be adapted where necessary to suit local needs.

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APPENDIX A

HANDBOOK FOR THE DESIGN OF

SURFACE WATER INFILTRATION SYSTEMS

FOR DEVELOPING COUNTRIES

LIST OF SYMBOLS

A	Area (m^2)
B	Length of Basin, Gallery (m)
C	Consumption of water per head ($m^3/h.s$)
H	Average saturated aquifer depth (m)
h	Aquifer depth at a distance x from the river (m)
K	Coefficient of permeability (m/day)
L	Length (m)
P	Residual Rainfall (m/s)
p	Porosity (dimensionless), penetration fraction (dimensionless)
q_o	Flow of water per unit aquifer width (m^2/s)
q_a	Flow of surface water per unit aquifer width (m^2/s)
q_n	Flow of natural groundwater per unit aquifer width (m^2/s)
Q_o	Flow of water from a well (m^3/s)
R	A constant
r_o	Radius of well
S_o	Maximum allowable drawdown of water level (m)
ΔS	Additional drawdown in level due to partial penetration of well (m)
S_T	Total drawdown including effect of partial penetration (m)
T_d	Detention time of water underground (s)
V	Velocity (m/s)
W	Width of aquifer (km)
X	Orthogonal co-ordinate
Y	Orthogonal co-ordinate
α	A constant greater than 1

LIST OF SPECIAL SYMBOLS FOR COMPUTER PROGRAMMES

The following symbol changes have been made for the computer programmes:

α = A

p = P

Q_o = Q (Table A2)

q_n = Q1 (Table A2)

q_o = Q (Tables A4, A5)

S_o = S

T_d = T

Vq = entry rate of water into soil (m/s)

CHAPTER 1

INTRODUCTION

1.1 Relative Advantages of Surface Water Infiltration

Surface water is often found in abundance in the wetter regions of the tropics, where virtually all developing countries are located. For many communities, untreated surface water in the form of streams and rivers are the only source of household water supply. However, the water is often grossly polluted, and requires treatment if it is to be safe for domestic use. Conventional methods of water treatment are often inappropriate for small communities in such countries, being both expensive to set up and operate. They also require skilled personnel who will probably not be available within the community. Groundwater is often used as an alternative source of water. It is bacteriologically safe, and normally requires no treatment. It may, however, be difficult and expensive to locate, or the yield may be poor. Occasionally, the quality of the water may be such as to render it unfit for use. It is therefore suggested that for communities where there is a perennial river or stream, treatment of surface water by infiltration should be used.

In the infiltration of surface water, the water enters the ground either directly through the river bed, or through a basin, ditch or well. It then percolates through the ground until it reaches the groundwater table, from where the water is transported, with the natural groundwater, for a period of time, to the point where it is abstracted from the ground. The water that is abstracted is therefore a mixture of ground and surface water. The treatment facility is provided during the passage of the water underground, by a combination of physical and biological processes, such that the water that is abstracted is

much improved in quality and should meet the usual bacteriological and chemical standards without further treatment.

The main advantages of surface water infiltration are:

(i) It provides a steady source of water;

(ii) The water does not require chemical treatment;

(iii) The maintenance requirements of most such systems are minimal;

(iv) It is relatively simple to increase the capacity of the system.

1.2 Types of Infiltration Systems

There are several possible forms that infiltration systems may take. These include infiltration directly through the river bed to an adjacent well, or infiltration gallery for abstraction, or through basins, ditches or wells, as mentioned earlier, with subsequent abstraction from galleries or wells. Alternatively, galleries may be placed directly beneath the river, such that river water travels a short distance vertically downwards to the gallery, from which the water can then be recovered. The different methods each have their advantages and disadvantages, and vary in complexity. From the above methods, three of the simplest systems have been selected, and it is the design and operation of these that will be explained further in subsequent sections. They are: the infiltration of water directly from rivers to wells; infiltration to galleries; and infiltration of transported river water through basins to adjacent galleries.

1.3 Induced Infiltration to Wells

Induced infiltration to wells takes place when a well, placed adjacent to a river, is pumped. The result is a lowering of the water table in the vicinity of the well, such that a cone of depression is formed around the well, and this induces water from the river into the well, as well as some natural groundwater. This situation is depicted in Figs. 1.1 and 1.2, which show the direction of water flow before and after the installation of the pumping well respectively.

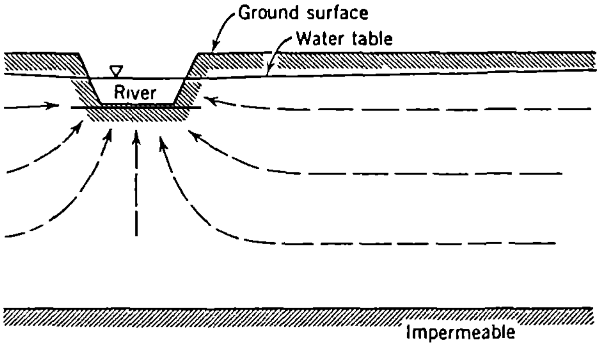

Fig. 1.1 Natural Pattern of Groundwater Flow without Pumped Well (Todd, 1980)

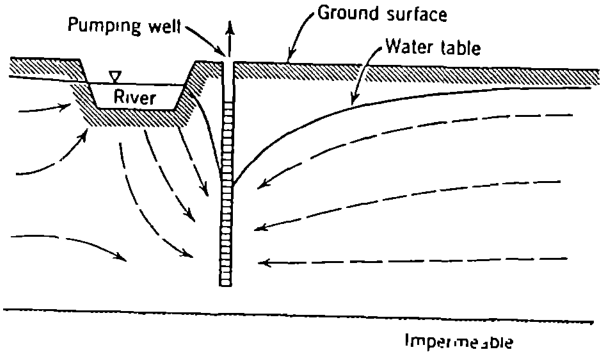

Fig. 1.2 Induced Infiltration Resulting From Pumped Well (Todd, 1980)

The amount of water that is abstracted depends on the natural flow of groundwater, the permeability of the aquifer, and the distance at which the well is placed. The distance is influenced by the detention time of the water under-

ground required to achieve a satisfactory improvement in water quality.

The drawdown of the water table at the well face produced by abstraction is primarily related to the quantity of water abstracted and the permeability of the aquifer. The higher the abstraction rate, the greater the fall in the water table.

1.4 Induced Infiltration to Galleries

This method is very similar to the infiltration of water to wells described under Section 1.3. Here, however, the water is recovered over a wider horizontal distance. Fig. 1.3 shows a series of stages in the abstraction of water from galleries where the water table slopes towards the gallery.

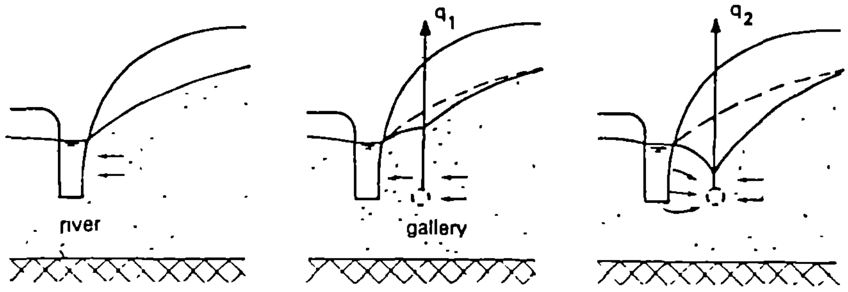

Fig. 1.3 Induced Infiltration to a Gallery

In the first instance, the flow of natural groundwater is towards the river. Thus the river water is being augmented by natural groundwater. However, when a small amount of groundwater is abstracted from the gallery, there is a reduction in the amount of natural groundwater entering the river. With a

further increase in the rate of abstraction, the direction of flow of water between the river and gallery is reversed, such that water from the river begins to enter the gallery. Associated with the abstraction, there is also a corresponding reduction in the water table around the gallery, as in the case of wells.

The advantage of galleries is that they are simple to construct, and they normally require no maintenance, as opposed to wells, which may become clogged with silt or other deposits occasionally. The quantity of water abstracted by galleries also depends upon the hydrogeological characteristics of the aquifer, and detention time of the water underground.

In the descriptions for induced infiltration, there is the implicit assumption that the river bed is permeable. This must be so, otherwise it will act as a barrier to the outflow of river water and infiltration will not take place.

1.5 Infiltration from Basins to Galleries

Infiltration by means of basins is an alternative choice to induce infiltration when the permeability of the area adjacent to the river is too low to sustain a steady flow of water. It requires the construction of shallow basins up to 1m deep, with surrounding earth embankments. The basins are then lined with a sand layer, and river water may be transported to them through open channels. When water enters the basin, it permeates the ground in the same manner as for the river bed in induced infiltration. The water then percolates down to the water table and is transported, as described in Section 1.1. This method requires regular maintenance of the infiltration basins, achieved by removing the sand layer from the basin when it becomes clogged with suspended matter from the river, for unlike the river, there are no strong currents to remove

accumulated material from its bed. Because of the extra maintenance required, and the need to construct basins and channels, this method must only be considered where induced infiltration is not likely to be viable. Fig. 1.4 below is a section through a basin with two parallel galleries on each side.

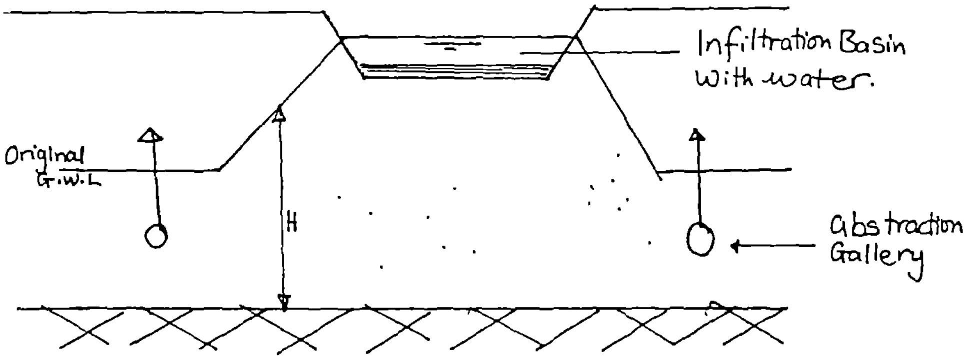

Fig. 1.4 Basin Infiltration to Galleries

Sections 1.3 to 1.5 are an introduction to the infiltration systems that will be discussed in the remainder of the handbook. Subsequent chapters will describe the biological and chemical changes undergone by surface water during its passage underground, the method of design for each system, and its operation and maintenance requirements.

CHAPTER 2

BIOLOGICAL CHEMICAL ASPECTS OF WATER QUALITY

2.1 Biological and Chemical Changes in Surface Water Quality

Water quality changes begin at different stages, depending on whether infiltration is through basins or a river bed. In basins, micro-organisms, including pathogenic bacteria and viruses begin to die-off during their short period of storage. When surface water enters the ground, either through a basin or river bed, it first passes through the unsaturated zone of soil above the groundwater table. Movement of water is much slower here than in the saturated zone, and as improvement in water quality is related to detention time, most of the upgrading in water quality takes place in the unsaturated zone.

There are two main types of processes that occur in the unsaturated zone. These are biological processes, and chemical processes. Biological processes are preceded by the removal of organic pollutants from the percolating surface water onto soil grains within the aquifer, by filtration, sedimentation or adsorption. This is followed by the breakdown of the organic matter under aerobic conditions by bacteria. Filtration and sedimentation of particles from the water occurs at the basin surface or river bed, and the largest particles are retained here. Particles smaller than the pore size of the soil, however, progress further downward, where they may settle on individual soil grains. The total surface area of these grains is very large, and as such, there is considerable scope for the removal of suspended solids from the water. Particles not removed by filtration or sedimentation may be eliminated by adsorption. Adsorption is a particularly useful method for the removal of viruses from the water. It occurs either through electrostatic attraction or

physical attraction to slimes on the surface of soil grains. Viruses are usually negatively charged, and they are therefore attracted to positively charged soil particles. This process continues until the soil grains are covered with negatively charged matter, and the soil grains therefore take on a negative charge, and begin to attract positively charged particles such as Iron and Manganese ions. Thus, adsorption plays a significant part in the removal of viruses and other pollutants. Bacteria also steadily decrease in number with increasing distance because of the decrease in organic matter which is their food supply. To survive, they are forced to consume part of their own cell tissue, and after a while die off.

The breakdown of organic matter by bacteria results in the production of several end products. The major ones include: Carbon dioxide, bicarbonates, sulphates, phosphates, and nitrates. Nitrates are an end product of the oxidation of ammonia, and both ammonia and nitrates are undesirable in high concentrations in drinking water.

Chemical processes involve several simultaneously occurring reactions, the most important being oxidation-reduction, solution-precipitation, and ion-exchange reactions. Under oxidation reduction reactions, the most important processes include the oxidation of soluble ferrous and manganous ions to form insoluble Ferric and manganese oxides. These precipitate within the aquifer, and may be found in the vicinity of abstraction wells or galleries, where these are not fully below the groundwater table, thus allowing oxygen to enter the aquifer. For this reason, it is important that the galleries and the permeable length of wells should always be located below the lowest possible level of the water table, taking account of dry weather conditions. Failure to do so may result in severe clogging of the abstraction system with chemical deposits. Other possible precipitates include magnesium and barium, in the form of insoluble carbonates. The chemical processes that take place result in a

steady breakdown of complex inorganic compounds to simpler forms. This process does not end in the unsaturated zone, but continues when the water reaches the groundwater table, the beginning of the saturated zone.

In the saturated zone, there is a much lower oxygen concentration than before, due to the fact that most of the available oxygen supply has previously been used up in the breakdown of organic matter by bacteria. The rate of adsorption is also much less, as the state of saturation allows less contact between particles in the water and the soil grains of the aquifer. While oxygen is still present, the breakdown of organic and inorganic matter continues as in the unsaturated zone. If the oxygen supply should become exhausted, however, anaerobic reactions begin to occur. Among the most important of these are: the conversion of nitrates and nitrites to ammonia, and at a much slower rate, carbonaceous material to carbon dioxide and methane. Bicarbonates are also converted to carbonates, and the precipitation of calcium carbonate, for example means the water becomes less hard. However, anaerobic reactions cause an overall deterioration in water quality, particularly with the re-formation of ammonia. For this reason, it is important that anaerobic conditions should be avoided wherever possible, by ensuring that there is enough oxygen to last the detention time of water underground.

The biological and chemical reactions described above do not all occur to the same extent. The types of reactions, and their relative significance in the final composition of the water, depends on the original constituents of the water. Generally speaking, surface water is much less mineralised than natural groundwater, and the water that is abstracted being mostly composed of surface water, will reflect this, with the chemical changes resulting in a substantial improvement in water quality. The only exception to this would be where anaerobic conditions have persisted for some time in the aquifer.

Where bacteriological quality is concerned, however, the abstracted water should be able to meet the Internationally accepted standards for drinking water supply, set by the WHO.

2.2 Oxygen Supply During Infiltration

The presence or absence of oxygen during infiltration has been shown to have an important effect on the overall water quality, and therefore the characteristics of abstracted water. Important factors that determine whether or not anaerobic conditions will occur are:

(i) The oxygen content of the surface water;

(ii) The oxygen present in the unsaturated zone;

(iii) Concentration or Organic Matter in the surface water.

For rivers in developing countries, there are a number of problems, in that as the saturation concentration of oxygen in water decreases with increasing temperature, the rivers will have a low dissolved oxygen concentration. In addition, they are likely to be highly polluted, and will therefore have a high organic content, which in turn exerts a high oxygen demand.

There are two approaches to the problem of insufficient oxygen. One is to decrease the oxygen demand of the water, and the other is to increase the oxygen supply. However, neither of these methods is relevant to induced infiltration by its very nature. The solution in the case of induced infiltration is therefore to keep the detention time to the minimum necessary to achieve a satisfactory improvement in water quality. Where infiltration is through basins, however, there is more scope for increasing the supply of

oxygen. It is necessary to bear in mind, however, that the penetration of oxygen from the atmosphere into the soil is limited to only a couple of metres or so, and this determines the total distance over which maximum aerobic activity is likely to take place.

Decreasing the organic content of the water may be achieved by screening suspended water from the raw water, and this is referred to in Section 3.9 Where the oxygen content of the water is to be increased, an effective method is to construct basins in pairs and operate them intermittently, with resting periods where each basin is allowed to dry out. When the basin dries out, oxygen is able to enter the soil from the atmosphere, and this, with the accompanying lowering of the groundwater table due to the cessation of infiltration, results in additional oxygen entering the soil. The oxygen is equivalent in volume to the displacement of water under the basin. Intermittent infiltration also allows the aerobic degradation of organic matter on the basin surface by bacteria to take place, and reduces the incidence of clogging of the sand bed in the basin. The lengths of use and resting periods for basins are chosen to minimise the rate of clogging. However, after a resting period, in subsequent flooding of the basin, a period of time is required for the maximum rate of infiltration to be achieved. It is therefore advisable that the wet and dry cycles for basins should not be too short.

Another important source of increased oxygen supply in basins is from the photosynthetic activity of algae. Algae grow rapidly under tropical conditions, and during the day, when photosynthesis occurs, large amounts of oxygen may be produced, increasing the concentration of oxygen in the water. This is to some extent offset by the consumption of oxygen by algae during the dark, in respiration, when oxygen production has ceased. However, overall, algae do provide a net benefit in oxygen production.

CHAPTER 3

DESIGN OF INFILTRATION SYSTEMS

3.1 Preliminary Survey

The selection of an infiltration system depends largely on the hydrogeological characteristics of the area adjacent to the surface water. The first step in choosing an infiltration system, therefore, is to conduct a survey of the area over which infiltration is to take place. As a rough estimate, this may be taken as 100m x 150m as shown in Fig. 3.1, although the actual area for infiltration is likely to be considerably less.

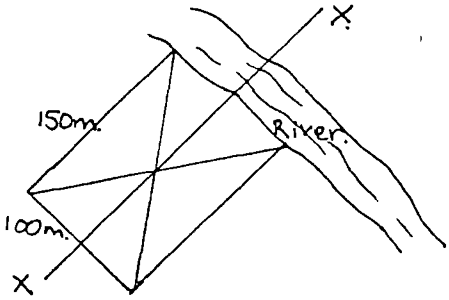

Fig. 3.1 Area for Survey

Table 1, below, sets out the information required from the survey. In addition to assisting in the choice of an infiltration system, the survey also provides data which will be used in designing the chosen system. It is useful if initial information on the hydrogeological characteristics of the site can be obtained before the survey, to assist in deciding the spacing and location of boreholes. In the absence of such information, however, the first two or three boreholes, widely spaced, are likely to reveal whether there is a need for further investigative work. The essential requirements are to establish the profile of the water table, and the overall permeability of the

TABLE 1

INFORMATION REQUIRED FROM SURVEY

General	Boreholes	River
Topography of Land	Geological Profile	Bacteriological analysis of water
Approximate aquifer width	Direction of slope of groundwater table along x - x axis (see Fig. 3.1)	Chemical analysis of water
	Average Saturated Aquifer depth, H	Difference between high and low water levels
	Depth to groundwater table	
	Horizontal permeability	
	Particle size Distribution analysis	
	Porosity, p	

area, thus the geological information required is not very detailed. In the case of the river survey, the analyses of water will provide a means of comparison with the abstracted water.

The determination of permeability is particularly important, and as such it must be done as accurately as circumstances will permit. It is suggested that it should be determined by laboratory methods, backed up by visual identification of geological materials and the likely permeability range into which they fall, as this is likely to be quicker and cheaper than conducting pumping tests.

Particle size distribution analyses, in addition to assisting in the classification of unconsolidated material, is also used in the design of gravel packings for infiltration galleries.

3.2 Selection of an Infiltration System

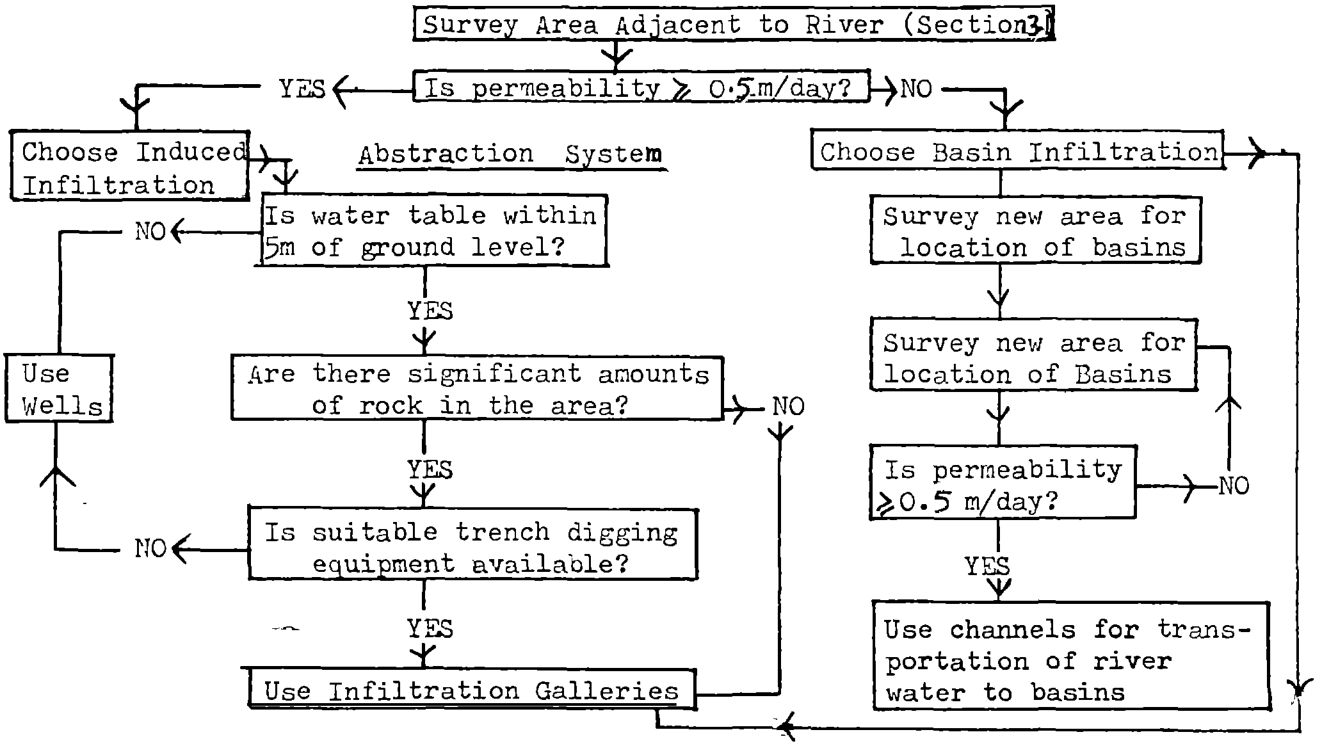

Fig. 3.2 Guidelines for Choosing an Infiltration System

The choice of an infiltration system is based upon the relative advantages of each method in terms of technical feasibility, the ease with which it can be constructed, operating and maintenance requirements, together with associated costs.

It is not possible to take into account many of the factors that may arise to influence the choice of one method of infiltration over another. However, the most important factors are included in a flowchart set out in Fig. 3.2, to act as a guide in choosing a system. The chart should be used in conjunction with information obtained from the survey, and the description of the methods in Chapter 1, to arrive at a final decision.

3.3 Induced Infiltration to Galleries

There are three main aspects to the design of this system. The first requirement is to estimate the distance, L, at which the gallery will be placed from the river. It is then necessary to obtain the length of the gallery. The final step is the detailed design of the gallery.

The distance L is given by the equation $L \hat{=} 0.9\sqrt{{}^{K}/_{p} \; S_o \; T_d}$, where K is horizontally permeability in m/sec, P is porosity, and S_o is the maximum drawdown allowed, and T_d is the detention time of the water underground. S_o has been given a constant value of 1.5m, and T_d a value of 80 days throughout the rest of the chapter.

Table A1 in the Appendix gives values for L, for values of permeability in m/days, and porosity obtained from the preliminary survey. The conversion

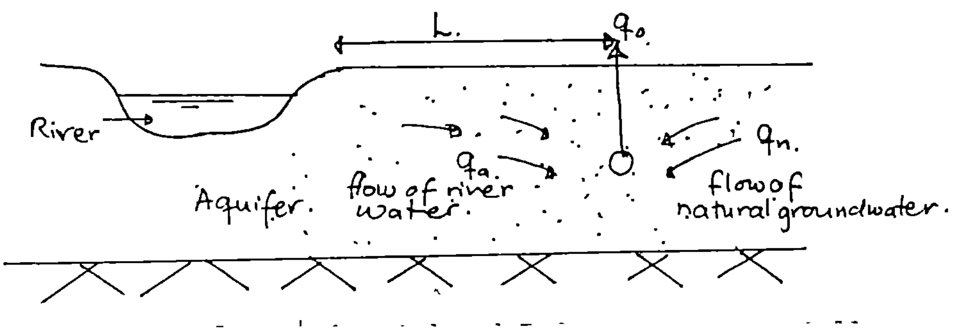

Fig. 3.3 Induced Infiltration to a Gallery
(After Huisman, 1983)

of permeability from m/day to m/sec has been allowed for in the table.

The required length of the infiltration gallery is given by $B = {}^{Q}o/q_o$, where B is the length of the gallery in metres, Q_o is the required abstraction rate of water in m^3/s, and q_o the flow per unit aquifer width in m^2/s. The value of Q_o is C x P, where C is the consumption of water per head of population, and P is the population for which the system is designed.

To calculate the length B, Q_o must first be estimated, from information on water use by the community, and a projection of future water demand. The flow of water per unit length of infiltration, q_o, may be obtained from Table A4 in the Appendix, by using the same values for k and p as in the determination of L. q_o is given by the equation $q_o \simeq H\sqrt{K\ S_o\ p/T_d}$. These are values for H = 10m, and q_o may therefore be adjusted for different values of H, the saturated aquifer depth. For H = 15m, for example, q_o is 1.5 times the value given in the table. The detailed design of infiltration galleries is given in Section 4.9.

3.4 Induced Infiltration to Wells

The distance L, between the river and the abstraction well, may be obtained from

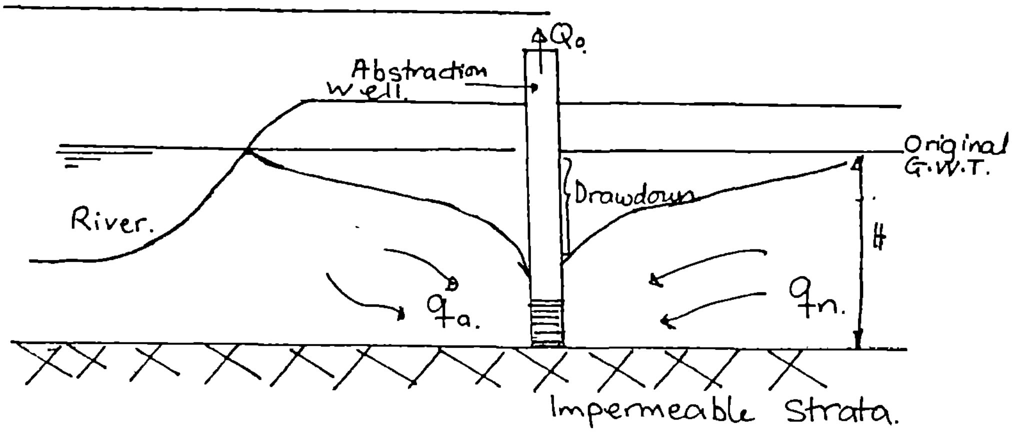

Fig. 3.4 Induced Infiltration to a Well (After Bize, 1979)

Table A2. In this case, the distance L has been obtained from two equations. These are:

(i) $$\frac{1}{\alpha}\left[\frac{\alpha}{\sqrt{(\alpha-1)}}\left(\tan^{-1}\frac{1}{\sqrt{(\alpha-1)}}\right)-1\right] = \pi q_n^2 T_d / pH\, Q_o$$

(ii) $$L = Q_o / \pi \alpha q_n$$

α is a dimensionless factor, and q_n is the flow per unit length of natural ground

For equation (i), p, H and T_d are constants. Porosity, p, is presumed constant because within the range of 0.30 to 0.50 it will not significantly influence the value of α. Similarly, H, the saturated aquifer depth, has been given a constant value of 30m. The length, L, may therefore be obtained for different combinations of Q_o and q_n from Table A2 in the Appendix. Q_o covers the range of requirements of population from 100 to 10,000 people, with a per capita consumption of 50 litres per head, and is given in m^3/d. The values of q_n correspond to aquifer widths, W, 5, 10, 15 and 20 km.

Having established the position of the well, the drawdown of water in the vicinity of the well must be calculated. This will indicate the minimum depth to which the well must be sunk. It is important to keep the screen length of the well always below the groundwater table, to ensure that oxygen does not enter the well and cause the precipitation of chemical deposits around the screen. The total drawdown is given by: $S_T = S_o + \Delta S$, where S_o is the drawdown due to a fully penetrating well, and ΔS is the additional correction required if the well does not fully penetrate the gallery.

The drawdown, $S_o = h_1 - h_2$, h_1 and h_2 being the saturated aquifer depths at the well face before and after abstraction begins respectively.

$$h_1 = \sqrt{\frac{2 q_n L}{K} + H^2}$$

$$h_2 = \sqrt{\frac{2 q_n L}{K} - \frac{Q_o}{2\pi K} \ln\left(\frac{2L}{r_o}\right)^2 + H^2}$$

$$\Delta S = \frac{Q_o (1-p)}{2\pi kHp} \ln \frac{\cancel{(1-p)h}}{2r_o}$$

p is the ratio between the length of the well and the saturated aquifer depth H, and r_o is the radius of the well.

3.5 Infiltration from Basins to Galleries

The distance between the outer edge of the basin and either of the galleries, L, is the length L, where $L = \sqrt{k/p\ S_o\ T_{d/p}}$. For any given scheme, this value may be obtained from Table A3, using the values of permeability and porosity characteristic of the area where the scheme is to be situated. The length of the spreading basins is equal to the adjacent gallery length,

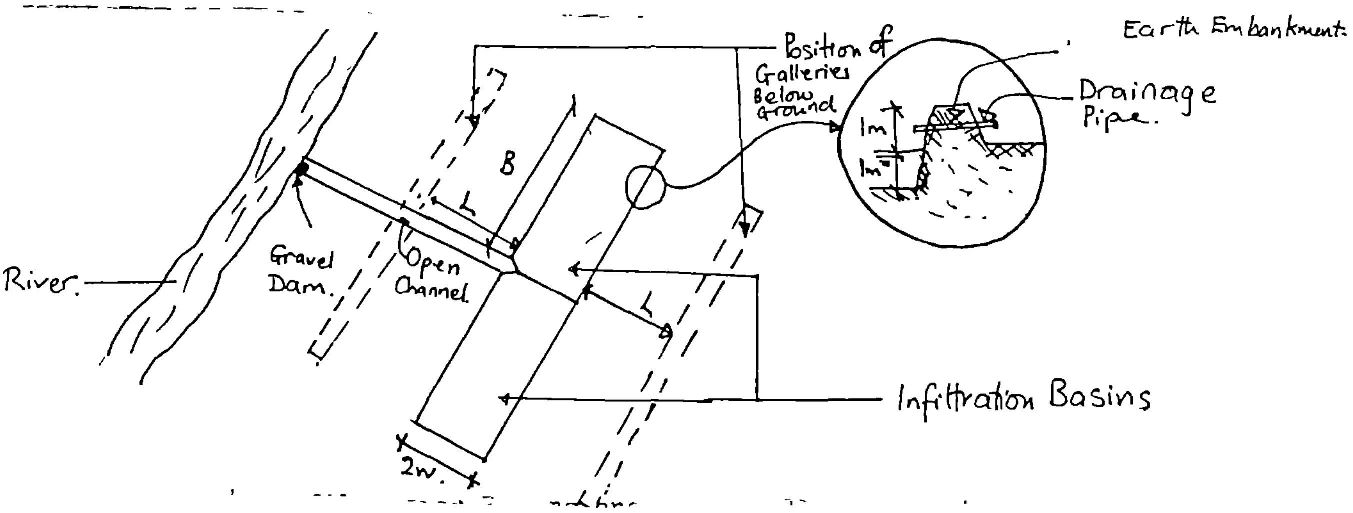

Fig. 3.5 Infiltration Basins and Two Parallel Galleries

which is calculated in a similar way to that for Induced infiltration in Section 3.3. However, in this case, $B = Q_o/2q_o$, as the abstraction of water per unit length of infiltration is doubled with the presence of two galleries.

To obtain q_o, the same Table A4 may be used, as q_o for induced infiltration and basin infiltration is approximately equal. The same principle for correcting q_o to suit different saturated aquifer depths applies here. Thus by obtaining B, both the gallery and basin lengths are known.

The basin width depends on the infiltration rate chosen for the entry of water from the basin into the soil. Values representing the basin width are to be found in the Table A5. These are based on the relationship

$$2 \times \tfrac{1}{2} \times \text{width of basin} = \frac{2 \times q_o}{(0.40/86400)},$$

where 0.40/86400 is the infiltration rate in m/s.

As the operation of basins is significantly improved by intermittent operation, and bearing in mind also the need to clean the basins, it is necessary to

provide a second basin of equal capacity. This can be done simply by doubling B, the length of the original basin, to allow for a second basin, such that the two are laid end to end, abbutting each other, as shown in Fig. 3.5

It is suggested that a figure of 2m total depth of basin will be adequate for the depth of the basin, made up of an excavation depth of 1m and an earth embankment 1m high. Sand is used to line the basins, to prevent clogging from taking place in the upper layers of the aquifer where it cannot be easily removed, and also to allow for an adequate infiltration rate. The sand layer should be 500-700mm thick, and made up of uniformly graded sand.

The design of river intakes and channels to transport the raw water from rivers to basins is discussed in Sections 3.9 and 3.10 respectively.

3.6 Design of Re-Infiltration Systems

Re-infiltration is a method of treating water with an unacceptably high Iron or manganese concentration, which may not respond to treatment by aeration alone. The method consists of transporting water which has been abstracted after induced infiltration, and transporting it a short distance by pipeline to a nearby basin. The water is aerated just before it enters the basin, and it then re-enters the ground through the basin, to be abstracted again after a short detention time.

The purpose of re-infiltration after abstraction is to allow enough time for the oxidation reaction necessary for the precipitation of the iron and manganese compounds to take place. The result of the process should be water which is greatly improved with regard to iron and manganese levels.

The design of re-infiltration systems will follow the same basic rules as described earlier in this chapter for induced and basin infiltration.

The difference in the case of the basin is that it will receive pipeborne aerated water instead of surface water through an open channel. Aeration is by means of a Venturi device, as shown in Fig. 3.6. Detention time for re-infiltration, however, will be much shorter than the original process, as most of the reduction in soluble Iron and Manganese takes place in the basin.

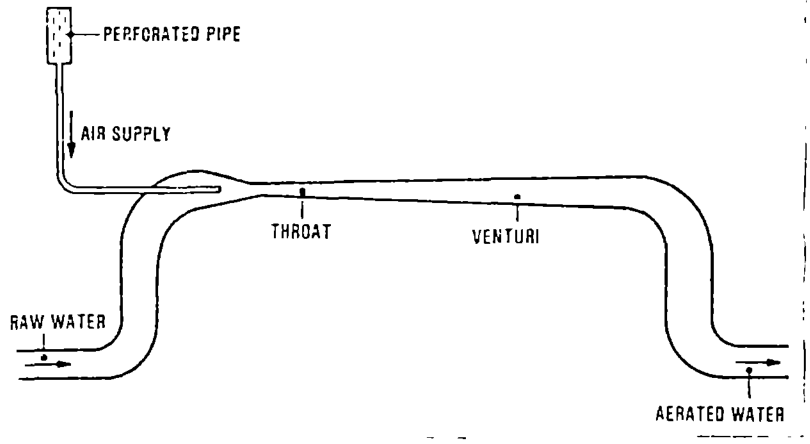

Fig. 3.6 Venturi Device for Aeration (IRC 1981)

Furthermore, pathogenic bacteria and other undesirable constituents of the water would already have been reduced to an acceptable level during induced infiltration. A detention time of 14 days is used in this case, and the distance between the basin and abstraction system obtained from Table A3 will need to be reduced accordingly. This may be done by multiplying the distance obtained with a detention time of 80 days by a suitable factor. Where the abstraction system is a gallery, $L = \sqrt{{}^{k}/_{p}\, S_o}\sqrt{T_d}$. With a reduction of T_d from 80 to 14 days, where 80/14 = 5.71,

$$L' = \sqrt{{}^{k}/_{p}\, S_o}\ \sqrt{{}^{T_d}/_{5.71}}$$

from which $\sqrt{{}^{T_d}/_{5.71}} \Big/ \sqrt{T_d} = 0.42$

Thus $L' = 0.42\ L$, where L' is the distance of infiltration for a detention time of 14 days. Thus, to obtain the distance between the infiltration basin and the abstraction gallery, the distance in Table A3 must be multiplied by 0.42. Fig. 3.7 below shows the arrangement for such a system, in which the abstraction gallery is on one side of the basin only. To obtain the basin width, this must be taken into account. Table A5 in this case will represent two times the basin width. This is because, whereas in the case of the basin with two galleries,

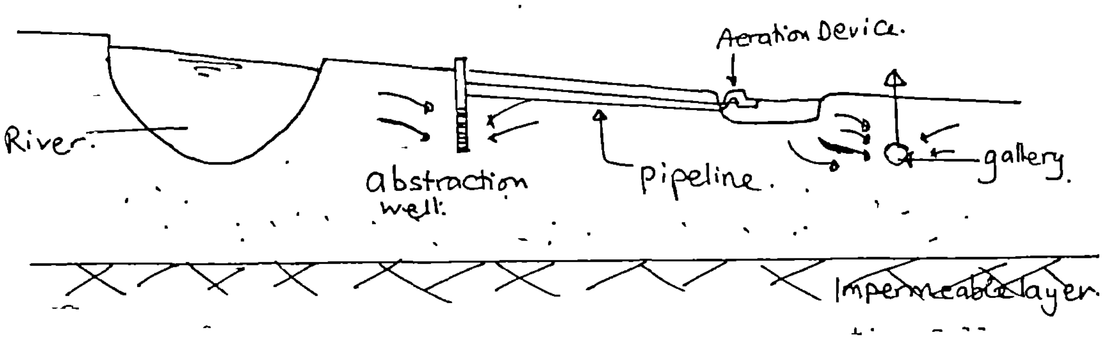

Fig. 3.7 Re-Infiltration of Water to an Abstraction Gallery

$$\text{Width of basin} = 2\ q_o / (0.4 \times 86400)$$

$2\ q_o$ is replaced here by q_o, and therefore $w' = q_o' / (0.4 \times 86400)'$, w' being the full width of the basin for re-infiltration. The value obtained from Table A5 must therefore be halved. All other details of the design process remain the same as described in this chapter for the initial process.

3.7 Design of Infiltration Galleries

Galleries are normally most suitable for shallow aquifers and may be laid at depths of up to 8m below ground. Galleries may consist of slotted, or open jointed pipes laid in trenches and surrounded by a gravel packing. The purpose of the gravel packing is to prevent fine material from the aquifer

entering the infiltration pipe. The material for pipes should be such that they are not readily attacked by chemical constituents of subsurface water. When this is taken into account, the type of pipe chosen then depends largely on local availability. Suitable pipe materials are: stainless steel, vitrified clay, and plastic, all of which are suitable for slotting. The choice of gravel diameter and slot width is determined by the following relationships:

(i) The particle size distribution curve for the aquifer material should be fairly similar to that for the gravel pack;

(ii) $$\frac{D_{15} \text{ for the filter}}{D_{85} \text{ for aquifer grains}} \leqslant 5 \quad \text{———} \quad ①$$

(iii) $$\frac{D_{85} \text{ for the filter}}{\text{Slot width of pipes}} \geqslant 2 \quad \text{———} \quad ②$$

D_x for any material is such that X% by weight of the material is smaller in diameter than this value. Slot lengths, however, can be of any magnitude compatible with maintaining the structural strength of the pipe.

To obtain the filter size, it is necessary first to choose a convenient slot width of a few millimetres, and then calculate the gravel pack diameters based on the equations 1 and 2 above, using the boundary conditions given. The gravel pack may need to be two or more layers of differently sized gravel, depending on the size of aquifer grains. As an example, for a pipe with slots size 5mm x 5mm, to be laid in a sandy aquifer with grain size D_{85} = 0.25mm, the coarsest gravel layer, from equation 2 , must have a size D_{85} = 2 x 5mm = 10mm.

From equation 1 , D_{15} for the filter = 5 x 0.25mm = 1.25mm. Thus the first layer of the pack has a size D_{15} = 1.25mm. If D_{85} for this pack is, say,

2.10mm, again using equation 1 , 5 x 2.10 - 10.50mm. Thus, for the second filter layer D_{15} = 10.50mm. D_{85} will therefore be greater than this. As the coarsest gravel size required is one where D_{85} is at least 10mm, this size satisfies the conditions. The gravel pack will then be made up with the finer layer closest to the pipe.

This arrangement is shown in Fig. 3.8, with the minimum thickness required for each layer. Where slotted pipes are not readily available, open jointed pipes present a much simpler solution. The method of sizing the gravel pack is the same as for slotted pipes, with the joint width equivalent to the slot width in calculations. For a total openable area of approximately 20%, a metre run of pipe may be composed of twenty 50mm long pipes with 10mm joints between them. When pipes cannot be ordered in suchlengths, they can be cut to suit the purpose. In this respect, plastic pipes would be the best choice, followed by vitrified clay pipes.

The pipe diameter is chosen on the basis of the flow of water expected, the fall to which the pipe is laid, and the velocity of flow required. The minimum recommended velocity to prevent the accumulation of deposits within the pipe is 0.5m/s.

For water collection a sump is needed, at the lower end of the gallery, from which water can be pumped. Where the sump is only required for water collection and possible gallery maintenance, a size of 0.80m x 0.80m should be sufficient. For very small communities of, say, 500 people with a low water demand of 30L/h.d, the sump can be made large enough to act as a storage tank, for 50% of the total daily water demand. This can then cover periods of maximum water demand during the day.

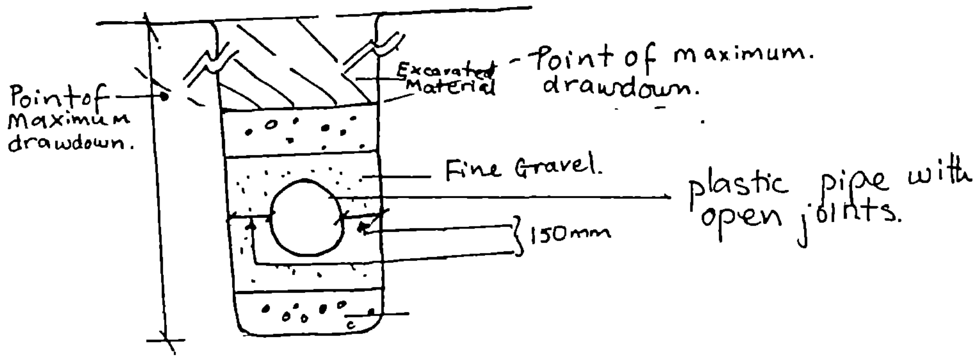

Fig. 3.8 Infiltration Gallery Design

3.8 Design of Wells

The design and construction of abstraction wells for induced infiltration follows the same principles as for wells receiving natural groundwater alone. It is, however, essential that as the well will be used for the supply of the whole community, it should be kept well protected, in such a way that it cannot be tampered with.

3.9 River Intake Devices

For the transportation of river water to infiltration basins in open channels, the detail at the junction between the river and channel will depend mainly on the high and low water levels of the river. Where the difference between the two levels is not very great, it is possible to have the channel leading off from the river, with a dam of fine gravel, 5mm effective diameter, at the entrance to the channel, about 100mm thick. This should ensure that larger suspended solids particles do not enter the channel. Where the difference in river levels is so large that allowing for low water levels would result in a channel too deep for the spreading basins, provision may need to be made for pumping the water up to a higher channel level during periods of low

water flow.

3.10 River Water Transportation

The design of open channels for transporting river water to basins is based on the flow of water required through the channel, which in turn depends on the required abstraction rate. Unless the channels are cut in an impermeable layer of soil, they must be lined. As clay is most likely to be available, it is recommended that this should be used as a lining.

CHAPTER 4

OPERATION AND MAINTENANCE

4.1 General Operation of Infiltration Systems

Day to day operation of each infiltration system is a straightforward process. It consists of checking to see that the abstraction pump is in working order. It is also useful to make a daily visual check on the turbidity of the water. Sudden increases in turbidity may be a sign that fine particles from the aquifer have entered the gallery or well, due to failure of the gravel pack or screen to retain them. In a well-designed abstraction system, this should not normally happen. However, where it does occur, the gallery or well must be cleaned out. The cleaning of galleries and wells is discussed under Sections 4.4 and 4.5 respectively.

4.2 Tests for Water Quality

Water quality tests are in a sense the test of the whole infiltration system. In the final analysis, the abstracted water must meet the statutory requirements for small community supplies in the countries where they are situated.

WHO recommends, for smaller communities of up to 20,000 people, at least a bacteriological check on the water, preferably once a week, but at least once a month. In addition, it is advisable that if the galleries or wells are cleaned, this should be followed by bacteriological and chemical examinations of the water. Chemical testing is not usually required very often. A comprehensive test may be conducted only one or two times a year, though

shorter tests may be conducted more often. The required number of times for tests will normally be determined by local guidelines in the country where the system is installed.

4.3 Operation of Infiltration Basins

Basins will normally be run in pairs, intermittently. As each basin will need to be shut off manually, the cycles should not be too short. Cycles of at least 14 days, wet and dry, and at most monthly wet and dry periods, are likely to be reasonable for most small communities.

When a basin is to be taken out of use, access to the channel should be shut off by putting a plate across the entrance to the channel, so that water flows into the adjacent basin. The basin should then be left to dry out naturally. Where the water level is high, and the basin has become badly clogged, some of the excess water should be able to drain away through drainage holes provided in the surrounding embankment above the normal head loss expected, say 0.5m above ground level, so for a basin with 1m deep excavation, water in excess of 1.5m depth will be drained off. When after a number of cycles, a basin requires cleaning, as much of the sand layer, after drying out, can be removed as necessary, and the sand replaced. This operation should not need to occur very often, but the number of times it is necessary is very much dependent on the nature of the river water, though intermittent basin operation reduces the number of cleaning times required.

In addition to cleaning the basins, the gravel dam at the entrance to the channel must be cleaned at regular intervals, to maintain a steady flow of water from the river to the channel.

4.4 Maintenance of Galleries

Galleries should not normally require maintenance, but when they are clogged with silt, or chemical deposits, the result will be either a deterioration in water quality or reduction in the quantity of water abstracted. In such cases, abstraction from the gallery will need to be halted so that cleaning of the gallery may take place. Where there are two sets of galleries, as in the case of basins, abstraction from the other gallery will then provide a continuing, though reduced, water supply.

Provided the gallery is not very long, say up to 20m, cleaning should not be very difficult. The sump should first be dewatered, and solids loosened from the gallery by jetting water from a pipe lowered through the sump into the gallery. Loosened material will then be washed into the sump, from where it can be removed. This method should take care of clogging of a physical nature.

Where the problem is due to chemical deposits, it becomes rather more difficult to resolve, as these have to be dissolved by various chemicals. By conducting a chemical analysis, and comparing it to the results of previous ones, the cause of the problem may be identified. For treatment of ferric, magnesium and calcium carbonates, a 15% solution of commercial Hydrochloric acid is recommended, used in conjunction with an inhibitor, to prevent acid attacking the pipe. This can be applied through a small diameter perforated pipe laid for the full length of the gallery. It should be left for at least eight hours, at the end of which the gallery may be pumped for some time, and pH measurements taken. When the pH has returned to its normal value, the gallery will be ready for use.

Accumulations of organic slime can be similarly treated, with a chlorine dose at a level suitable for drinking water. In this case, the abstraction of water

for use can continue.

It can be seen, however, that the use of chemicals for cleaning is a specialist operation, and reduces the advantages of the system, and even for occasional cleaning such as this, it may be difficult, if not impossible, for some communities to get the chemicals required. This is one of the main reasons why the adequate design and construction of the gallery is particularly important. It is unlikely, however, that the whole length of the gallery will become clogged, and if sufficient excess capacity has been allowed for, the decision may be taken to accept the reduction in the quantity of water.

4.5 Cleaning of Wells

Wells are more likely to require cleaning than galleries, as water is abstracted through a smaller total surface area. Cleaning is effected by pumping the well at double the normal capacity. This should loosen accumulated particles which have adhered to the screen. Where clogging is due to chemical precipitates, cleaning will need to be, as for galleries, by chemical means. The disadvantages of this are the same, but the reduction in the rate of abstraction is likely to be greater for wells.

The general requirements for the operation and maintenance of the three types of infiltration methods described are summarised in Table 2, together with the systems in each case to which the requirement applies. In practice, however, each infiltration system is likely to have additional special requirements for maintenance, depending particularly on the way the original construction was carried out, the hydrogeological characteristics of the site, and the nature

TABLE 2

OPERATION AND MAINTENANCE REQUIREMENTS FOR INFILTRATION SYSTEMS

A - Induced Infiltration to Wells

B - Induced Infiltration to Galleries

C - Basin Infiltration

Requirements	System where applicable
1. Visual Check on Turbidity of Water	A, B, C
2. Maintenance of Pump for Abstraction Well or sump	A, B, C
3. Weekly or monthly bacteriological examination of water	A, B, C
4. Chemical Examination of Water	A, B, C
5. Occasional cleaning of Well if necessary	A
6. Occasional cleaning of Basins	C
7. Cleaning of gravel dam	C

of its surface water source. These can only be discovered with increasing experience in the running of the system.

Design Tables

Tables for the design of Infiltration Systems

The following tables have been prepared for use in conjunction with the descriptions for the design of induced infiltration, basin infiltration, and re-infiltration systems. The computer programs used in their preparation are written in BASIC, and have been included in Appendix B. However, these are not required for the use or understanding of the tables.

Table A1 is used in conjunction with the design of induced infiltration to galleries, an explanation of which is given in section 3.3 of the handbook. The values represent the distance, L, between the gallery and river, for values of permeability K, and porosity p.

The values in Table A2, are distances between a river and well, for varying aquifer widths and abstraction rates of water. The use of the table is described under Induced Infiltration to Wells, section 3.4.

The distance between an infiltration basin and gallery for specific values of K and p, may be obtained from Table A3. The design of infiltration systems from basins to galleries is discussed in section 3.5.

Table A4 is for the estimation of both the length of galleries, and, where basins are used, the length of the basin. The values represent q_o, the flow of water per unit aquifer width to galleries, and are used in the design of both induced infiltration to wells, (section 3.4), and basin infiltration (section 3.5).

The final Table, A5, is used to estimate the width of infiltration basins, the explanation of which may be found in section 3.5.

Re-infiltration systems for the removal of iron and manganese are a combination of induced and basin infiltration, and as such the use of the tables are the same as for those methods.

However, Table 5A, when used for the design of re-infiltration systems (section 3.6) represents twice the basin width. The value obtained from the table must therefore be halved accordingly.

Data required for the use of the tables is obtained from the preliminary survey (section 3.1), and the water supply requirements of the community. In the table, the data has been given in the form likely to be most appropriate. Thus, in Table A2, for example, Q_o, the abstraction rate, is in m^3/day instead of m^3/sec. Similarly, permeability K, in table A1, is in m/day, instead of m/sec.

TABLE A1-DISTANCE BETWEEN GALLERY AND RIVER (m)

p	0·30	0·35	0·40	0·45	0·50	K(m/day)
	12.72	11.78	11.02	10.39	9.85	.50
	18.00	16.66	15.58	14.69	13.94	1.00
	22.04	20.41	19.09	18.00	17.07	1.50
	25.45	23.56	22.04	20.78	19.71	2.00
	28.46	26.34	24.64	23.23	22.04	2.50
	31.17	28.86	27.00	25.45	24.14	3.00
	33.67	31.17	29.16	27.49	26.08	3.50
	36.00	33.32	31.17	29.39	27.88	4.00
	38.18	35.35	33.06	31.17	29.57	4.50
	40.24	37.26	34.85	32.86	31.17	5.00
	42.21	39.08	36.55	34.46	32.69	5.50
	44.09	40.82	38.18	36.00	34.15	6.00
	45.89	42.48	39.74	37.46	35.54	6.50
	47.62	44.09	41.24	38.88	36.88	7.00
	49.29	45.63	42.69	40.24	38.18	7.50
	50.91	47.13	44.09	41.56	39.43	8.00
	52.47	48.58	45.44	42.84	40.64	8.50
	54.00	49.99	46.76	44.09	41.82	9.00
	55.47	51.36	48.04	45.29	42.97	9.50
	56.92	52.69	49.29	46.47	44.09	10.00
	58.32	54.00	50.51	47.62	45.17	10.50
	59.69	55.27	51.70	48.74	46.24	11.00
	61.04	56.51	52.86	49.83	47.28	11.50
	62.35	57.72	54.00	50.91	48.29	12.00
	63.63	58.91	55.11	51.96	49.29	12.50
	64.89	60.08	56.20	52.99	50.27	13.00
	66.13	61.23	57.27	54.00	51.22	13.50
	67.34	62.35	58.32	54.99	52.16	14.00
	68.54	63.45	59.35	55.96	53.09	14.50
	69.71	64.54	60.37	56.92	54.00	15.00
	70.86	65.60	61.37	57.86	54.89	15.50
	72.00	66.65	62.35	58.78	55.77	16.00
	73.11	67.69	63.32	59.69	56.63	16.50
	74.21	68.71	64.27	60.59	57.48	17.00
	75.29	69.71	65.21	61.48	58.32	17.50
	76.36	70.70	66.13	62.35	59.15	18.00
	77.42	71.67	67.04	63.21	59.96	18.50
	78.46	72.64	67.94	64.06	60.77	19.00
	79.48	73.58	68.83	64.89	61.56	19.50
	80.49	74.52	69.71	65.72	62.35	20.00
	81.49	75.45	70.57	66.54	63.12	20.50
	82.48	76.36	71.43	67.34	63.89	21.00
	83.46	77.27	72.28	68.14	64.64	21.50
	84.42	78.16	73.11	68.93	65.39	22.00
	85.38	79.04	73.94	69.71	66.13	22.50
	86.32	79.92	74.75	70.48	66.86	23.00
	87.25	80.78	75.56	71.24	67.58	23.50
	88.18	81.64	76.36	72.00	68.30	24.00
	89.09	82.48	77.15	72.74	69.01	24.50
	90.00	83.32	77.94	73.48	69.71	25.00
	90.89	84.15	78.71	74.21	70.40	25.50
	91.78	84.97	79.48	74.93	71.09	26.00
	92.66	85.78	80.24	75.65	71.77	26.50
	93.53	86.59	81.00	76.36	72.44	27.00
	94.39	87.39	81.74	77.07	73.11	27.50

TABLE III CONTINUED

P 0·30	0·35	0·40	0·45	0·50	K(m/day)
96.09	88.96	83.21	78.46	74.43	28.50
96.93	89.74	83.94	79.14	75.08	29.00
97.76	90.51	84.66	79.82	75.72	29.50
98.59	91.27	85.38	80.49	76.36	30.00
99.40	92.03	86.09	81.16	77.00	30.50
100.21	92.78	86.79	81.82	77.62	31.00
101.02	93.53	87.48	82.48	78.25	31.50
101.82	94.27	88.18	83.13	78.87	32.00
102.61	95.00	88.86	83.78	79.48	32.50
103.40	95.73	89.54	84.42	80.09	33.00
104.18	96.45	90.22	85.06	80.69	33.50
104.95	97.17	90.89	85.69	81.29	34.00
105.72	97.88	91.56	86.32	81.89	34.50
106.48	98.59	92.22	86.94	82.48	35.00
107.24	99.29	92.87	87.56	83.07	35.50
108.00	99.98	93.53	88.18	83.65	36.00
108.74	100.68	94.17	88.79	84.23	36.50
109.48	101.36	94.82	89.39	84.81	37.00
110.22	102.05	95.45	90.00	85.38	37.50
110.95	102.72	96.09	90.59	85.94	38.00
111.68	103.40	96.72	91.19	86.51	38.50
112.40	104.07	97.34	91.78	87.07	39.00
113.12	104.73	97.97	92.36	87.62	39.50
113.84	105.39	98.59	92.95	88.18	40.00
114.55	106.05	99.20	93.53	88.73	40.50
115.25	106.70	99.81	94.10	89.27	41.00
115.95	107.35	100.42	94.67	89.81	41.50
116.65	108.00	101.02	95.24	90.35	42.00
117.34	108.64	101.62	95.81	90.89	42.50
118.03	109.27	102.22	96.37	91.42	43.00
118.71	109.91	102.81	96.93	91.95	43.50
119.39	110.54	103.40	97.48	92.48	44.00
120.07	111.16	103.98	98.04	93.00	44.50
120.74	111.79	104.57	98.59	93.53	45.00
121.41	112.40	105.14	99.13	94.04	45.50
122.08	113.02	105.72	99.67	94.56	46.00
122.74	113.63	106.29	100.21	95.07	46.50
123.40	114.24	106.86	100.75	95.58	47.00
124.05	114.85	107.43	101.29	96.09	47.50
124.70	115.45	108.00	101.82	96.59	48.00
125.35	116.05	108.56	102.35	97.09	48.50
126.00	116.65	109.11	102.87	97.59	49.00
126.64	117.24	109.67	103.40	98.09	49.50
127.27	117.83	110.22	103.92	98.59	50.00
127.91	118.42	110.77	104.44	99.08	50.50
128.54	119.01	111.32	104.95	99.57	51.00
129.17	119.59	111.86	105.47	100.05	51.50
129.79	120.17	112.40	105.98	100.54	52.00
130.42	120.74	112.94	106.48	101.02	52.50
131.04	121.32	113.48	106.99	101.50	53.00
131.65	121.89	114.01	107.49	101.98	53.50
132.27	122.46	114.55	108.00	102.45	54.00
132.88	123.02	115.08	108.49	102.93	54.50
133.49	123.58	115.60	108.99	103.40	55.00
134.09	124.14	116.13	109.48	103.87	55.50
134.69	124.70	116.65	109.98	104.33	56.00
135.29	125.26	117.17	110.47	104.80	56.50
135.89	125.81	117.69	110.95	105.26	57.00
136.49	126.36	118.20	111.44	105.72	57.50
137.08	126.91	118.71	111.92	106.18	58.00
137.67	127.46	119.22	112.40	106.64	58.50
138.26	128.00	119.73	112.88	107.09	59.00
138.84	128.54	120.24	113.36	107.54	59.50

TABLE A1 CONTINUED

P 0.30	0.35	0.40	0.45	0.50	K(m/day)
139.42	129.08	120.74	113.84	108.00	60.00
140.00	129.62	121.24	114.31	108.44	60.50
140.58	130.15	121.74	114.78	108.89	61.00
141.15	130.68	122.24	115.25	109.34	61.50
141.73	131.21	122.74	115.72	109.78	62.00
142.30	131.74	123.23	116.18	110.22	62.50
142.87	132.27	123.72	116.65	110.66	63.00
143.43	132.79	124.21	117.11	111.10	63.50
144.00	133.31	124.70	117.57	111.54	64.00
144.56	133.83	125.19	118.03	111.97	64.50
145.12	134.35	125.67	118.49	112.40	65.00
145.67	134.87	126.16	118.94	112.84	65.50
146.23	135.38	126.64	119.39	113.27	66.00
146.78	135.89	127.12	119.84	113.69	66.50
147.33	136.40	127.59	120.29	114.12	67.00
147.88	136.91	128.07	120.74	114.55	67.50
148.43	137.42	128.54	121.19	114.97	68.00
148.97	137.92	129.01	121.63	115.39	68.50
149.51	138.42	129.48	122.08	115.81	69.00
150.05	138.92	129.95	122.52	116.23	69.50
150.59	139.42	130.42	122.96	116.65	70.00
151.13	139.92	130.88	123.40	117.06	70.50
151.67	140.41	131.35	123.83	117.48	71.00
152.20	140.91	131.81	124.27	117.89	71.50
152.73	141.40	132.27	124.70	118.30	72.00
153.26	141.89	132.73	125.13	118.71	72.50
153.79	142.38	133.18	125.57	119.12	73.00
154.31	142.87	133.64	126.00	119.53	73.50
154.84	143.35	134.09	126.42	119.93	74.00
155.36	143.83	134.54	126.85	120.34	74.50
155.88	144.32	135.00	127.27	120.74	75.00
156.40	144.80	135.44	127.70	121.14	75.50
156.92	145.28	135.89	128.12	121.54	76.00
157.43	145.75	136.34	128.54	121.94	76.50
157.94	146.23	136.78	128.96	122.34	77.00
158.46	146.70	137.23	129.38	122.74	77.50
158.97	147.17	137.67	129.79	123.13	78.00
159.48	147.65	138.11	130.21	123.53	78.50
159.98	148.11	138.55	130.62	123.92	79.00
160.49	148.58	138.99	131.04	124.31	79.50
160.99	149.05	139.42	131.45	124.70	80.00
161.49	149.51	139.86	131.86	125.09	80.50
162.00	149.98	140.29	132.27	125.48	81.00
162.49	150.44	140.72	132.68	125.87	81.50
162.99	150.90	141.15	133.08	126.25	82.00
163.49	151.36	141.58	133.49	126.64	82.50
163.98	151.82	142.01	133.89	127.02	83.00
164.48	152.27	142.44	134.29	127.40	83.50
164.97	152.73	142.87	134.69	127.78	84.00
165.46	153.18	143.29	135.09	128.16	84.50
165.95	153.64	143.71	135.49	128.54	85.00
166.43	154.09	144.14	135.89	128.92	85.50
166.92	154.54	144.56	136.29	129.29	86.00
167.40	154.99	144.98	136.68	129.67	86.50
167.89	155.43	145.39	137.08	130.04	87.00
168.37	155.88	145.81	137.47	130.42	87.50
168.85	156.32	146.23	137.86	130.79	88.00
169.33	156.77	146.64	138.26	131.16	88.50
169.81	157.21	147.06	138.65	131.53	89.00
170.28	157.65	147.47	139.03	131.90	89.50
170.76	158.09	147.88	139.42	132.27	90.00
171.23	158.53	148.29	139.81	132.63	90.50
171.70	158.97	148.70	140.19	133.00	91.00
172.18	159.40	149.11	140.58	133.37	91.50

TABLE A1 CONTINUED

P	0·30	0·35	0·40	0·45	0·50	K(m/day)
	172.64	159.84	149.51	140.96	133.73	92.00
	173.11	160.27	149.92	141.35	134.09	92.50
	173.58	160.70	150.32	141.73	134.45	93.00
	174.05	161.14	150.73	142.11	134.81	93.50
	174.51	161.57	151.13	142.49	135.17	94.00
	174.97	162.00	151.53	142.87	135.53	94.50
	175.44	162.42	151.93	143.24	135.89	95.00
	175.90	162.85	152.33	143.62	136.25	95.50
	176.36	163.28	152.73	144.00	136.61	96.00
	176.82	163.70	153.13	144.37	136.96	96.50
	177.27	164.12	153.52	144.74	137.32	97.00
	177.73	164.55	153.92	145.12	137.67	97.50
	178.19	164.97	154.31	145.49	138.02	98.00
	178.64	165.39	154.71	145.86	138.37	98.50
	179.09	165.81	155.10	146.23	138.72	99.00
	179.54	166.23	155.49	146.60	139.07	99.50
	180.00	166.64	155.88	146.96	139.42	100.00

TABLE A2-DISTANCE BETWEEN RIVER AND WELL (m)

W 5 km	
q_n 4.8E-05	Q_0 (m³/day)
.34	5
1.03	15
1.73	25
2.22	35
2.85	45
3.49	55
4.13	65
4.76	75
5.4	85
6.03	95
6.67	105
7.3	115
7.94	125
7.92	135
8.51	145
9.1	155
9.68	165
10.27	175
10.86	185
11.44	195
12.03	205
12.62	215
12.27	225
12.81	235
13.36	245
13.9	255
14.45	265
15	275
15.54	285
16.09	295
16.63	305
17.18	315
16.55	325
17.06	335
17.57	345
18.08	355
18.59	365
19.1	375
19.61	385
20.11	395
20.62	405
21.13	415
21.64	425
20.78	435
21.25	445
21.73	455
22.21	465
22.69	475
23.16	485
23.64	495
24.12	505

TABLE A2 CONTINUED

W 10 km.	Q_o (m^3/day)
q_n. 9.6E-05	
.17	5
.51	15
.86	25
1.21	35
1.55	45
1.9	55
2.25	65
2.59	75
2.94	85
3.29	95
3.33	105
3.65	115
3.97	125
4.29	135
4.6	145
4.92	155
5.24	165
5.56	175
5.87	185
6.19	195
6.51	205
6.83	215
7.15	225
7.46	235
7.78	245
8.1	255
8.42	265
8.74	275
9.05	285
9.37	295
9.69	305
10.01	315
10.32	325
10.64	335
10.96	345
11.28	355
11.6	365
11.91	375
12.23	385
12.55	395
12.87	405
13.18	415
13.5	425
13.82	435
14.14	445
14.46	455
14.77	465
15.09	475
15.41	485
15.73	495
14.82	505

TABLE A2 CONTINUED

W 15 Km	
q_n 1.44E-04	Q_0 (m^3/day)
.11	5
.34	15
.57	25
.8	35
1.03	45
1.27	55
1.5	65
1.73	75
1.96	85
2.19	95
2.42	105
2.65	115
2.88	125
3.11	135
3.34	145
3.57	155
3.81	165
4.04	175
4.27	185
4.5	195
4.73	205
4.96	215
5.19	225
5.42	235
5.19	245
5.4	255
5.61	265
5.82	275
6.03	285
6.25	295
6.46	305
6.67	315
6.88	325
7.09	335
7.3	345
7.52	355
7.73	365
7.94	375
8.15	385
8.36	395
8.58	405
8.79	415
9	425
9.21	435
9.42	445
9.64	455
9.85	465
10.06	475
10.27	485
10.48	495
10.7	505

TABLE A2 CONTINUED.

W 20 km	
q_n 1.92E-04	Q_o (m^3/day)
.08	5
.25	15
.43	25
.6	35
.77	45
.95	55
1.12	65
1.29	75
1.47	85
1.64	95
1.81	105
1.99	115
2.16	125
2.33	135
2.51	145
2.68	155
2.85	165
3.03	175
3.2	185
3.37	195
3.55	205
3.72	215
3.89	225
4.07	235
4.24	245
4.41	255
4.59	265
4.76	275
4.93	285
5.11	295
5.28	305
5.45	315
5.62	325
5.8	335
5.97	345
6.14	355
6.32	365
6.49	375
6.66	385
6.84	395
7.01	405
7.18	415
6.75	425
6.91	435
7.07	445
7.23	455
7.38	465
7.54	475
7.7	485
7.86	495
8.02	505

TABLE A3-DISTANCE BETWEEN BASIN AND GALLERY (m)

p	0.30	0.35	0.40	0.45	0.50	k (m/day)
	14.14	13.09	12.24	11.54	10.95	.50
	20.00	18.51	17.32	16.32	15.49	1.00
	24.49	22.67	21.21	20.00	18.97	1.50
	28.28	26.18	24.49	23.09	21.90	2.00
	31.62	29.27	27.38	25.81	24.49	2.50
	34.64	32.07	30.00	28.28	26.83	3.00
	37.41	34.64	32.40	30.55	28.98	3.50
	40.00	37.03	34.64	32.65	30.98	4.00
	42.42	39.27	36.74	34.64	32.86	4.50
	44.72	41.40	38.72	36.51	34.64	5.00
	46.90	43.42	40.62	38.29	36.33	5.50
	48.98	45.35	42.42	40.00	37.94	6.00
	50.99	47.20	44.15	41.63	39.49	6.50
	52.91	48.98	45.82	43.20	40.98	7.00
	54.77	50.70	47.43	44.72	42.42	7.50
	56.56	52.37	48.98	46.18	43.81	8.00
	58.30	53.98	50.49	47.60	45.16	8.50
	60.00	55.54	51.96	48.98	46.47	9.00
	61.64	57.07	53.38	50.33	47.74	9.50
	63.24	58.55	54.77	51.63	48.98	10.00
	64.80	60.00	56.12	52.91	50.19	10.50
	66.33	61.41	57.44	54.16	51.38	11.00
	67.82	62.79	58.73	55.37	52.53	11.50
	69.28	64.14	60.00	56.56	53.66	12.00
	70.71	65.46	61.23	57.73	54.77	12.50
	72.11	66.76	62.44	58.87	55.85	13.00
	73.48	68.03	63.63	60.00	56.92	13.50
	74.83	69.28	64.80	61.10	57.96	14.00
	76.15	70.50	65.95	62.18	58.99	14.50
	77.45	71.71	67.08	63.24	60.00	15.00
	78.74	72.89	68.19	64.29	60.99	15.50
	80.00	74.06	69.28	65.31	61.96	16.00
	81.24	75.21	70.35	66.33	62.92	16.50
	82.46	76.34	71.41	67.33	63.87	17.00
	83.66	77.45	72.45	68.31	64.80	17.50
	84.85	78.55	73.48	69.28	65.72	18.00
	86.02	79.64	74.49	70.23	66.63	18.50
	87.17	80.71	75.49	71.18	67.52	19.00
	88.31	81.76	76.48	72.11	68.41	19.50
	89.44	82.80	77.45	73.02	69.28	20.00
	90.55	83.83	78.42	73.93	70.14	20.50
	91.65	84.85	79.37	74.83	70.99	21.00
	92.73	85.85	80.31	75.71	71.83	21.50
	93.80	86.84	81.24	76.59	72.66	22.00
	94.86	87.83	82.15	77.45	73.48	22.50
	95.91	88.80	83.06	78.31	74.29	23.00
	96.95	89.76	83.96	79.16	75.09	23.50
	97.97	90.71	84.85	80.00	75.89	24.00
	98.99	91.65	85.73	80.82	76.68	24.50
	100.00	92.58	86.60	81.64	77.45	25.00
	100.99	93.50	87.46	82.46	78.23	25.50
	101.98	94.41	88.31	83.26	78.99	26.00
	102.95	95.31	89.16	84.06	79.74	26.50
	103.92	96.21	90.00	84.85	80.49	27.00
	104.88	97.10	90.82	85.63	81.24	27.50
	105.83	97.97	91.65	86.40	81.97	28.00

TABLE A3 CONTINUED

p	0·30	0·35	0·40	0·45	0·50	k (m/day)
	107.70	99.71	93.27	87.93	83.42	29.00
	108.62	100.56	94.07	88.69	84.14	29.50
	109.54	101.41	94.86	89.44	84.85	30.00
	110.45	102.26	95.65	90.18	85.55	30.50
	111.35	103.09	96.43	90.92	86.25	31.00
	112.24	103.92	97.21	91.65	86.94	31.50
	113.13	104.74	97.97	92.37	87.63	32.00
	114.01	105.55	98.74	93.09	88.31	32.50
	114.89	106.36	99.49	93.80	88.99	33.00
	115.75	107.17	100.24	94.51	89.66	33.50
	116.61	107.96	100.99	95.21	90.33	34.00
	117.47	108.75	101.73	95.91	90.99	34.50
	118.32	109.54	102.46	96.60	91.65	35.00
	119.16	110.32	103.19	97.29	92.30	35.50
	120.00	111.09	103.92	97.97	92.95	36.00
	120.83	111.86	104.64	98.65	93.59	36.50
	121.65	112.63	105.35	99.33	94.23	37.00
	122.47	113.38	106.06	100.00	94.86	37.50
	123.28	114.14	106.77	100.66	95.49	38.00
	124.09	114.89	107.47	101.32	96.12	38.50
	124.89	115.63	108.16	101.98	96.74	39.00
	125.69	116.37	108.85	102.63	97.36	39.50
	126.49	117.10	109.54	103.27	97.97	40.00
	127.27	117.83	110.22	103.92	98.59	40.50
	128.06	118.56	110.90	104.56	99.19	41.00
	128.84	119.28	111.57	105.19	99.79	41.50
	129.61	120.00	112.24	105.83	100.39	42.00
	130.38	120.71	112.91	106.45	100.99	42.50
	131.14	121.42	113.57	107.08	101.58	43.00
	131.90	122.12	114.23	107.70	102.17	43.50
	132.66	122.82	114.89	108.32	102.76	44.00
	133.41	123.51	115.54	108.93	103.34	44.50
	134.16	124.21	116.18	109.54	103.92	45.00
	134.90	124.89	116.83	110.15	104.49	45.50
	135.64	125.58	117.47	110.75	105.07	46.00
	136.38	126.26	118.11	111.35	105.64	46.50
	137.11	126.94	118.74	111.95	106.20	47.00
	137.84	127.61	119.37	112.54	106.77	47.50
	138.56	128.28	120.00	113.13	107.33	48.00
	139.28	128.95	120.62	113.72	107.88	48.50
	140.00	129.61	121.24	114.30	108.44	49.00
	140.71	130.27	121.86	114.89	108.99	49.50
	141.42	130.93	122.47	115.47	109.54	50.00
	142.12	131.58	123.08	116.04	110.09	50.50
	142.82	132.23	123.69	116.61	110.63	51.00
	143.52	132.88	124.29	117.18	111.17	51.50
	144.22	133.52	124.89	117.75	111.71	52.00
	144.91	134.16	125.49	118.32	112.24	52.50
	145.60	134.80	126.09	118.88	112.78	53.00
	146.28	135.43	126.68	119.44	113.31	53.50
	146.96	136.06	127.27	120.00	113.84	54.00
	147.64	136.69	127.86	120.55	114.36	54.50
	148.32	137.32	128.45	121.10	114.89	55.00
	148.99	137.94	129.03	121.65	115.41	55.50
	149.66	138.56	129.61	122.20	115.93	56.00
	150.33	139.18	130.19	122.74	116.44	56.50
	150.99	139.79	130.76	123.28	116.96	57.00
	151.65	140.40	131.33	123.82	117.47	57.50
	152.31	141.01	131.90	124.36	117.98	58.00
	152.97	141.62	132.47	124.89	118.49	58.50
	153.62	142.22	133.04	125.43	118.99	59.00
	154.27	142.82	133.60	125.96	119.49	59.50
	154.91	143.42	134.16	126.49	120.00	60.00
	[illegible]	[illegible]	[illegible]	127.01	120.49	60.50

TABLE A3 CONTINUED

p 0·30	0·35	0·40	0·45	0·50	k(m/day)
156.20	144.61	135.27	127.54	120.99	61.00
156.84	145.20	135.83	128.06	121.49	61.50
157.48	145.79	136.38	128.58	121.98	62.00
158.11	146.38	136.93	129.09	122.47	62.50
158.74	146.96	137.47	129.61	122.96	63.00
159.37	147.55	138.02	130.12	123.45	63.50
160.00	148.13	138.56	130.63	123.93	64.00
160.62	148.70	139.10	131.14	124.41	64.50
161.24	149.28	139.64	131.65	124.89	65.00
161.86	149.85	140.17	132.16	125.37	65.50
162.48	150.42	140.71	132.66	125.85	66.00
163.09	150.99	141.24	133.16	126.33	66.50
163.70	151.56	141.77	133.66	126.80	67.00
164.31	152.12	142.30	134.16	127.27	67.50
164.92	152.69	142.82	134.66	127.74	68.00
165.52	153.25	143.35	135.15	128.21	68.50
166.13	153.80	143.87	135.64	128.68	69.00
166.73	154.36	144.39	136.13	129.15	69.50
167.33	154.91	144.91	136.62	129.61	70.00
167.92	155.47	145.43	137.11	130.07	70.50
168.52	156.02	145.94	137.59	130.53	71.00
169.11	156.57	146.45	138.08	130.99	71.50
169.70	157.11	146.96	138.56	131.45	72.00
170.29	157.66	147.47	139.04	131.90	72.50
170.88	158.20	147.98	139.52	132.36	73.00
171.46	158.74	148.49	140.00	132.81	73.50
172.04	159.28	148.99	140.47	133.26	74.00
172.62	159.82	149.49	140.94	133.71	74.50
173.20	160.35	150.00	141.42	134.16	75.00
173.78	160.89	150.49	141.89	134.61	75.50
174.35	161.42	150.99	142.36	135.05	76.00
174.92	161.95	151.49	142.82	135.49	76.50
175.49	162.48	151.98	143.29	135.94	77.00
176.06	163.00	152.47	143.75	136.38	77.50
176.63	163.53	152.97	144.22	136.82	78.00
177.20	164.05	153.46	144.68	137.25	78.50
177.76	164.57	153.94	145.14	137.69	79.00
178.32	165.09	154.43	145.60	138.13	79.50
178.88	165.61	154.91	146.05	138.56	80.00
179.44	166.13	155.40	146.51	138.99	80.50
180.00	166.64	155.88	146.96	139.42	81.00
180.55	167.16	156.36	147.42	139.85	81.50
181.10	167.67	156.84	147.87	140.28	82.00
181.65	168.18	157.32	148.32	140.71	82.50
182.20	168.69	157.79	148.77	141.13	83.00
182.75	169.19	158.27	149.22	141.56	83.50
183.30	169.70	158.74	149.66	141.98	84.00
183.84	170.20	159.21	150.11	142.40	84.50
184.39	170.71	159.68	150.55	142.82	85.00
184.93	171.21	160.15	150.99	143.24	85.50
185.47	171.71	160.62	151.43	143.66	86.00
186.01	172.21	161.09	151.87	144.08	86.50
186.54	172.70	161.55	152.31	144.49	87.00
187.08	173.20	162.01	152.75	144.91	87.50
187.61	173.69	162.48	153.18	145.32	88.00
188.14	174.19	162.94	153.62	145.73	88.50
188.67	174.68	163.40	154.05	146.15	89.00
189.20	175.17	163.85	154.48	146.56	89.50
189.73	175.66	164.31	154.91	146.96	90.00
190.26	176.14	164.77	155.34	147.37	90.50
190.78	176.63	165.22	155.77	147.78	91.00
191.31	177.11	165.68	156.20	148.18	91.50
191.83	177.60	166.13	156.63	148.59	92.00

TABLE A3 CONTINUED

p	0·30	0·35	0·40	0·45	0·50	k(m/day)
	192.35	178.08	166.58	157.05	148.99	92.50
	192.87	178.56	167.03	157.48	149.39	93.00
	193.39	179.04	167.48	157.90	149.79	93.50
	193.90	179.52	167.92	158.32	150.19	94.00
	194.42	180.00	168.37	158.74	150.59	94.50
	194.93	180.47	168.81	159.16	150.99	95.00
	195.44	180.94	169.26	159.58	151.39	95.50
	195.95	181.42	169.70	160.00	151.78	96.00
	196.46	181.89	170.14	160.41	152.18	96.50
	196.97	182.36	170.58	160.83	152.57	97.00
	197.48	182.83	171.02	161.24	152.97	97.50
	197.98	183.30	171.46	161.65	153.36	98.00
	198.49	183.77	171.90	162.06	153.75	98.50
	198.99	184.23	172.33	162.48	154.14	99.00
	199.49	184.70	172.77	162.89	154.53	99.50
	200.00	185.16	173.20	163.29	154.91	100.00

TABLE A4-FLOW PER UNIT AQUIFER WIDTH (m^2/day) H=10m.

p 0.30	0.35	0.40	0.45	0.50	K (m/day)
.0000060	.0000060	.0000070	.0000070	.0000070	.5000000
.0000080	.0000090	.0000100	.0000100	.0000110	1.0000000
.0000100	.0000110	.0000120	.0000130	.0000130	1.5000000
.0000120	.0000130	.0000140	.0000150	.0000150	2.0000000
.0000130	.0000140	.0000150	.0000160	.0000170	2.5000000
.0000150	.0000160	.0000170	.0000180	.0000190	3.0000000
.0000160	.0000170	.0000180	.0000190	.0000200	3.5000000
.0000170	.0000180	.0000200	.0000210	.0000220	4.0000000
.0000180	.0000190	.0000210	.0000220	.0000230	4.5000000
.0000190	.0000200	.0000220	.0000230	.0000250	5.0000000
.0000200	.0000210	.0000230	.0000240	.0000260	5.5000000
.0000210	.0000220	.0000240	.0000260	.0000270	6.0000000
.0000220	.0000230	.0000250	.0000270	.0000280	6.5000000
.0000220	.0000240	.0000260	.0000280	.0000290	7.0000000
.0000230	.0000250	.0000270	.0000290	.0000300	7.5000000
.0000240	.0000260	.0000280	.0000300	.0000310	8.0000000
.0000250	.0000270	.0000290	.0000300	.0000320	8.5000000
.0000260	.0000280	.0000300	.0000310	.0000330	9.0000000
.0000260	.0000280	.0000300	.0000320	.0000340	9.5000000
.0000270	.0000290	.0000310	.0000330	.0000350	10.0000000
.0000280	.0000300	.0000320	.0000340	.0000360	10.5000000
.0000280	.0000310	.0000330	.0000350	.0000370	11.0000000
.0000290	.0000310	.0000330	.0000360	.0000380	11.5000000
.0000300	.0000320	.0000340	.0000360	.0000380	12.0000000
.0000300	.0000330	.0000350	.0000370	.0000390	12.5000000
.0000310	.0000330	.0000360	.0000380	.0000400	13.0000000
.0000310	.0000340	.0000360	.0000390	.0000410	13.5000000
.0000320	.0000350	.0000370	.0000390	.0000410	14.0000000
.0000330	.0000350	.0000380	.0000400	.0000420	14.5000000
.0000330	.0000360	.0000380	.0000410	.0000430	15.0000000
.0000340	.0000360	.0000390	.0000410	.0000440	15.5000000
.0000340	.0000370	.0000400	.0000420	.0000440	16.0000000
.0000350	.0000380	.0000400	.0000430	.0000450	16.5000000
.0000350	.0000380	.0000410	.0000430	.0000460	17.0000000
.0000360	.0000390	.0000410	.0000440	.0000460	17.5000000
.0000360	.0000390	.0000420	.0000450	.0000470	18.0000000
.0000370	.0000400	.0000430	.0000450	.0000480	18.5000000
.0000370	.0000400	.0000430	.0000460	.0000480	19.0000000
.0000380	.0000410	.0000440	.0000460	.0000490	19.5000000
.0000380	.0000410	.0000440	.0000470	.0000500	20.0000000
.0000390	.0000420	.0000450	.0000480	.0000500	20.5000000
.0000390	.0000420	.0000450	.0000480	.0000510	21.0000000
.0000400	.0000430	.0000460	.0000490	.0000510	21.5000000
.0000400	.0000430	.0000470	.0000490	.0000520	22.0000000
.0000410	.0000440	.0000470	.0000500	.0000530	22.5000000
.0000410	.0000440	.0000480	.0000500	.0000530	23.0000000

TABLE A4 CONTINUED

P	0·30	0·35	0·40	0·45	0·50	K(m/day)
	.0000420	.0000450	.0000480	.0000510	.0000540	23.5000000
	.0000420	.0000450	.0000490	.0000520	.0000540	24.0000000
	.0000420	.0000460	.0000490	.0000520	.0000550	24.5000000
	.0000430	.0000460	.0000500	.0000530	.0000560	25.0000000
	.0000430	.0000470	.0000500	.0000530	.0000560	25.5000000
	.0000440	.0000470	.0000510	.0000540	.0000570	26.0000000
	.0000440	.0000480	.0000510	.0000540	.0000570	26.5000000
	.0000450	.0000480	.0000520	.0000550	.0000580	27.0000000
	.0000450	.0000490	.0000520	.0000550	.0000580	27.5000000
	.0000450	.0000490	.0000530	.0000560	.0000590	28.0000000
	.0000460	.0000500	.0000530	.0000560	.0000590	28.5000000
	.0000460	.0000500	.0000530	.0000570	.0000600	29.0000000
	.0000470	.0000500	.0000540	.0000570	.0000600	29.5000000
	.0000470	.0000510	.0000540	.0000580	.0000610	30.0000000
	.0000470	.0000510	.0000550	.0000580	.0000610	30.5000000
	.0000480	.0000520	.0000550	.0000590	.0000620	31.0000000
	.0000480	.0000520	.0000560	.0000590	.0000620	31.5000000
	.0000490	.0000530	.0000560	.0000600	.0000630	32.0000000
	.0000490	.0000530	.0000570	.0000600	.0000630	32.5000000
	.0000490	.0000530	.0000570	.0000610	.0000640	33.0000000
	.0000500	.0000540	.0000580	.0000610	.0000640	33.5000000
	.0000500	.0000540	.0000580	.0000610	.0000650	34.0000000
	.0000500	.0000550	.0000580	.0000620	.0000650	34.5000000
	.0000510	.0000550	.0000590	.0000620	.0000660	35.0000000
	.0000510	.0000550	.0000590	.0000630	.0000660	35.5000000
	.0000520	.0000560	.0000600	.0000630	.0000670	36.0000000
	.0000520	.0000560	.0000600	.0000640	.0000670	36.5000000
	.0000520	.0000570	.0000600	.0000640	.0000680	37.0000000
	.0000530	.0000570	.0000610	.0000650	.0000680	37.5000000
	.0000530	.0000570	.0000610	.0000650	.0000690	38.0000000
	.0000530	.0000580	.0000620	.0000650	.0000690	38.5000000
	.0000540	.0000580	.0000620	.0000660	.0000690	39.0000000
	.0000540	.0000580	.0000620	.0000660	.0000700	39.5000000
	.0000540	.0000590	.0000630	.0000670	.0000700	40.0000000
	.0000550	.0000590	.0000630	.0000670	.0000710	40.5000000
	.0000550	.0000600	.0000640	.0000680	.0000710	41.0000000
	.0000550	.0000600	.0000640	.0000680	.0000720	41.5000000
	.0000560	.0000600	.0000640	.0000680	.0000720	42.0000000
	.0000560	.0000610	.0000650	.0000690	.0000730	42.5000000
	.0000560	.0000610	.0000650	.0000690	.0000730	43.0000000
	.0000570	.0000610	.0000660	.0000700	.0000730	43.5000000
	.0000570	.0000620	.0000660	.0000700	.0000740	44.0000000
	.0000570	.0000620	.0000660	.0000700	.0000740	44.5000000
	.0000580	.0000620	.0000670	.0000710	.0000750	45.0000000
	.0000580	.0000630	.0000670	.0000710	.0000750	45.5000000
	.0000580	.0000630	.0000670	.0000720	.0000760	46.0000000
	.0000590	.0000630	.0000680	.0000720	.0000760	46.5000000
	.0000590	.0000640	.0000680	.0000720	.0000760	47.0000000
	.0000590	.0000640	.0000690	.0000730	.0000770	47.5000000
	.0000600	.0000640	.0000690	.0000730	.0000770	48.0000000
	.0000600	.0000650	.0000690	.0000740	.0000780	48.5000000
	.0000600	.0000650	.0000700	.0000740	.0000780	49.0000000
	.0000610	.0000650	.0000700	.0000740	.0000780	49.5000000
	.0000610	.0000660	.0000700	.0000750	.0000790	50.0000000
	.0000610	.0000660	.0000710	.0000750	.0000790	50.5000000
	.0000610	.0000660	.0000710	.0000750	.0000800	51.0000000
	.0000620	.0000670	.0000710	.0000760	.0000800	51.5000000
	.0000620	.0000670	.0000720	.0000760	.0000800	52.0000000
	.0000620	.0000670	.0000720	.0000770	.0000810	52.5000000
	.0000630	.0000680	.0000720	.0000770	.0000810	53.0000000
	.0000630	.0000680	.0000730	.0000770	.0000810	53.5000000
	.0000630	.0000680	.0000730	.0000780	.0000820	54.0000000
	.0000640	.0000690	.0000730	.0000780	.0000820	54.5000000
	0000640	.0000690	.0000740	.0000780	.0000830	55.0000000

TABLE 11.4 CONTINUED

P 0·30	0·35	0·40	0·45	0·50	K (m/day)
~~.0000640~~	~~.0000690~~	~~.0000740~~	~~.0000790~~	~~.0000830~~	~~55.5000000~~
.0000640	.0000700	.0000750	.0000790	.0000830	56.0000000
.0000650	.0000700	.0000750	.0000790	.0000840	56.5000000
.0000650	.0000700	.0000750	.0000800	.0000840	57.0000000
.0000650	.0000710	.0000760	.0000800	.0000840	57.5000000
.0000660	.0000710	.0000760	.0000800	.0000850	58.0000000
.0000660	.0000710	.0000760	.0000810	.0000850	58.5000000
.0000660	.0000720	.0000760	.0000810	.0000860	59.0000000
.0000660	.0000720	.0000770	.0000820	.0000860	59.5000000
.0000670	.0000720	.0000770	.0000820	.0000860	60.0000000
.0000670	.0000720	.0000770	.0000820	.0000870	60.5000000
.0000670	.0000730	.0000780	.0000830	.0000870	61.0000000
.0000680	.0000730	.0000780	.0000830	.0000870	61.5000000
.0000680	.0000730	.0000780	.0000830	.0000880	62.0000000
.0000680	.0000740	.0000790	.0000840	.0000880	62.5000000
.0000680	.0000740	.0000790	.0000840	.0000880	63.0000000
.0000690	.0000740	.0000790	.0000840	.0000890	63.5000000
.0000690	.0000750	.0000800	.0000850	.0000890	64.0000000
.0000690	.0000750	.0000800	.0000850	.0000900	64.5000000
.0000690	.0000750	.0000800	.0000850	.0000900	65.000000
.0000700	.0000750	.0000810	.0000860	.0000900	65.500000
.0000700	.0000760	.0000810	.0000860	.0000910	66.000000
.0000700	.0000760	.0000810	.0000860	.0000910	66.500000
.0000710	.0000760	.0000820	.0000870	.0000910	67.000000
.0000710	.0000770	.0000820	.0000870	.0000920	67.500000
.0000710	.0000770	.0000820	.0000870	.0000920	68.000000
.0000710	.0000770	.0000820	.0000870	.0000920	68.500000
.0000720	.0000770	.0000830	.0000880	.0000930	69.000000
.0000720	.0000780	.0000830	.0000880	.0000930	69.500000
.0000720	.0000780	.0000830	.0000880	.0000930	70.000000
.0000720	.0000780	.0000840	.0000890	.0000940	70.500000
.0000730	.0000790	.0000840	.0000890	.0000940	71.000000
.0000730	.0000790	.0000840	.0000890	.0000940	71.500000
.0000730	.0000790	.0000850	.0000900	.0000950	72.000000
.0000730	.0000790	.0000850	.0000900	.0000950	72.500000
.0000740	.0000800	.0000850	.0000900	.0000950	73.000000
.0000740	.0000800	.0000850	.0000910	.0000960	73.500000
.0000740	.0000800	.0000860	.0000910	.0000960	74.000000
.0000740	.0000800	.0000860	.0000910	.0000960	74.500000
.0000750	.0000810	.0000860	.0000920	.0000970	75.000000
.0000750	.0000810	.0000870	.0000920	.0000970	75.500000
.0000750	.0000810	.0000870	.0000920	.0000970	76.000000
.0000750	.0000820	.0000870	.0000920	.0000980	76.500000
.0000760	.0000820	.0000870	.0000930	.0000980	77.000000
.0000760	.0000820	.0000880	.0000930	.0000980	77.500000
.0000760	.0000820	.0000880	.0000930	.0000980	78.000000
.0000760	.0000830	.0000880	.0000940	.0000990	78.500000
.0000770	.0000830	.0000890	.0000940	.0000990	79.000000
.0000770	.0000830	.0000890	.0000940	.0000990	79.500000
.0000770	.0000830	.0000890	.0000950	.0001000	80.000000
.0000770	.0000840	.0000890	.0000950	.0001000	80.500000
.0000780	.0000840	.0000900	.0000950	.0001000	81.000000
.0000780	.0000840	.0000900	.0000950	.0001010	81.500000
.0000780	.0000840	.0000900	.0000960	.0001010	82.000000
.0000780	.0000850	.0000910	.0000960	.0001010	82.500000
.0000790	.0000850	.0000910	.0000960	.0001020	83.000000
.0000790	.0000850	.0000910	.0000970	.0001020	83.500000
.0000790	.0000850	.0000910	.0000970	.0001020	84.000000
.0000790	.0000860	.0000920	.0000970	.0001030	84.500000
.0000800	.0000860	.0000920	.0000980	.0001030	85.000000
.0000800	.0000860	.0000920	.0000980	.0001030	85.500000
.0000800	.0000860	.0000920	.0000980	.0001030	86.000000
.0000800	.0000870	.0000930	.0000980	.0001040	86.500000
.0000800	.0000870	.0000930	.0000990	.0001040	87.000000

TABLE A4 CONTINUED

P	0·30	0·35	0·40	0·45	0·50	K(m/day)
	.0000810	.0000870	.0000930	.0000990	.0001040	87.500000
	.0000810	.0000870	.0000940	.0000990	.0001050	88.000000
	.0000810	.0000880	.0000940	.0001000	.0001050	88.500000
	.0000810	.0000880	.0000940	.0001000	.0001050	89.000000
	.0000820	.0000880	.0000940	.0001000	.0001060	89.500000
	.0000820	.0000880	.0000950	.0001000	.0001060	90.000000
	.0000820	.0000890	.0000950	.0001010	.0001060	90.500000
	.0000820	.0000890	.0000950	.0001010	.0001060	91.000000
	.0000830	.0000890	.0000950	.0001010	.0001070	91.500000
	.0000830	.0000890	.0000960	.0001010	.0001070	92.000000
	.0000830	.0000900	.0000960	.0001020	.0001070	92.500006
	.0000830	.0000900	.0000960	.0001020	.0001080	93.000000
	.0000830	.0000900	.0000960	.0001020	.0001080	93.500000
	.0000840	.0000900	.0000970	.0001030	.0001080	94.000000
	.0000840	.0000910	.0000970	.0001030	.0001080	94.500000
	.0000840	.0000910	.0000970	.0001030	.0001090	95.000000
	.0000840	.0000910	.0000970	.0001030	.0001090	95.500000
	.0000850	.0000910	.0000980	.0001040	.0001090	96.000000
	.0000850	.0000920	.0000980	.0001040	.0001100	96.500000
	.0000850	.0000920	.0000980	.0001040	.0001100	97.000000
	.0000850	.0000920	.0000980	.0001040	.0001100	97.500000
	.0000850	.0000920	.0000990	.0001050	.0001100	98.000000
	.0000860	.0000930	.0000990	.0001050	.0001110	98.500000
	.0000860	.0000930	.0000990	.0001050	.0001110	99.000000
	.0000860	.0000930	.0000990	.0001060	.0001110	99.500000
	.0000860	.0000930	.0001000	.0001060	.0001120	100.000000

TABLE A5-WIDTH OF INFILTRATION BASINS (m)

p					K (m/day)
0.30	0.35	0.40	0.45	0.50	
2.66	2.88	3.08	3.26	3.44	.50
3.77	4.07	4.35	4.62	4.87	1.00
4.62	4.99	5.33	5.66	5.96	1.50
5.33	5.76	6.16	6.53	6.89	2.00
5.96	6.44	6.89	7.30	7.70	2.50
6.53	7.06	7.54	8.00	8.43	3.00
7.06	7.62	8.15	8.64	9.11	3.50
7.54	8.15	8.71	9.24	9.74	4.00
8.00	8.64	9.24	9.80	10.33	4.50
8.43	9.11	9.74	10.33	10.89	5.00
8.85	9.56	10.22	10.84	11.42	5.50
9.24	9.98	10.67	11.32	11.93	6.00
9.62	10.39	11.11	11.78	12.42	6.50
9.98	10.78	11.53	12.22	12.89	7.00
10.33	11.16	11.93	12.65	13.34	7.50
10.67	11.53	12.32	13.07	13.78	8.00
11.00	11.88	12.70	13.47	14.20	8.50
11.32	12.22	13.07	13.86	14.61	9.00
11.63	12.56	13.43	14.24	15.01	9.50
11.93	12.89	13.78	14.61	15.40	10.00
12.22	13.20	14.12	14.97	15.78	10.50
12.51	13.52	14.45	15.33	16.15	11.00
12.79	13.82	14.77	15.67	16.52	11:50
13.07	14.12	15.09	16.01	16.87	12.00
13.34	14.41	15.40	16.34	17.22	12.50
13.60	14.69	15.71	16.66	17.56	13.00
13.86	14.97	16.01	16.98	17.90	13.50
14.12	15.25	16.30	17.29	18.23	14.00
14.37	15.52	16.59	17.60	18.55	14.50
14.61	15.78	16.87	17.90	18.87	15.00
14.85	16.04	17.15	18.19	19.18	15.50
15.09	16.30	17.43	18.48	19.48	16.00
15.33	16.55	17.70	18.77	19.79	16.50
15.56	16.80	17.96	19.05	20.08	17.00
15.78	17.05	18.23	19.33	20.38	17.50
16.01	17.29	18.48	19.61	20.67	18.00
16.23	17.53	18.74	19.88	20.95	18.50
16.45	17.76	18.99	20.14	21.23	19.00
16.66	18.00	19.24	20.41	21.51	19.50
16.87	18.23	19.48	20.67	21.79	20.00
17.08	18.45	19.73	20.92	22.06	20.50
17.29	18.68	19.97	21.18	22.32	21.00
17.50	18.90	20.20	21.43	22.59	21.50
17.70	19.12	20.44	21.68	22.85	22.00
17.90	19.33	20.67	21.92	23.11	22.50

TABLE A5 CONTINUED

p	0·30	0·35	0·40	0·45	0·50	k(m/day)
	18.10	19.55	20.90	22.16	23.36	23.00
	18.29	19.76	21.12	22.40	23.61	23.50
	18.48	19.97	21.34	22.64	23.86	24.00
	18.68	20.17	21.57	22.87	24.11	24.50
	18.87	20.38	21.79	23.11	24.36	25.00
	19.05	20.58	22.00	23.34	24.60	25.50
	19.24	20.78	22.22	23.56	24.84	26.00
	19.42	20.98	22.43	23.79	25.08	26.50
	19.61	21.18	22.64	24.01	25.31	27.00
	19.79	21.37	22.85	24.23	25.55	27.50
	19.97	21.57	23.06	24.45	25.78	28.00
	20.14	21.76	23.26	24.67	26.01	28.50
	20.32	21.95	23.46	24.89	26.23	29.00
	20.49	22.14	23.67	25.10	26.46	29.50
	20.67	22.32	23.86	25.31	26.68	30.00
	20.84	22.51	24.06	25.52	26.90	30.50
	21.01	22.69	24.26	25.73	27.12	31.00
	21.18	22.87	24.45	25.94	27.34	31.50
	21.34	23.06	24.65	26.14	27.56	32.00
	21.51	23.23	24.84	26.35	27.77	32.50
	21.68	23.41	25.03	26.55	27.98	33.00
	21.84	23.59	25.22	26.75	28.20	33.50
	22.00	23.77	25.41	26.95	28.41	34.00
	22.16	23.94	25.59	27.15	28.61	34.50
	22.32	24.11	25.78	27.34	28.82	35.00
	22.48	24.28	25.96	27.54	29.03	35.50
	22.64	24.45	26.14	27.73	29.23	36.00
	22.80	24.62	26.32	27.92	29.43	36.50
	22.95	24.79	26.50	28.11	29.63	37.00
	23.11	24.96	26.68	28.30	29.83	37.50
	23.26	25.12	26.86	28.49	30.03	38.00
	23.41	25.29	27.04	28.68	30.23	38.50
	23.56	25.45	27.21	28.86	30.42	39.00
	23.72	25.62	27.38	29.05	30.62	39.50
	23.86	25.78	27.56	29.23	30.81	40.00
	24.01	25.94	27.73	29.41	31.00	40.50
	24.16	26.10	27.90	29.59	31.19	41.00
	24.31	26.26	28.07	29.77	31.38	41.50
	24.45	26.41	28.24	29.95	31.57	42.00
	24.60	26.57	28.41	30.13	31.76	42.50
	24.74	26.73	28.57	30.31	31.95	43.00
	24.89	26.88	28.74	30.48	32.13	43.50
	25.03	27.04	28.90	30.66	32.31	44.00
	25.17	27.19	29.07	30.83	32.50	44.50
	25.31	27.34	29.23	31.00	32.68	45.00
	25.45	27.49	29.39	31.17	32.86	45.50
	25.59	27.64	29.55	31.35	33.04	46.00
	25.73	27.79	29.71	31.52	33.22	46.50
	25.87	27.94	29.87	31.68	33.40	47.00
	26.01	28.09	30.03	31.85	33.58	47.50
	26.14	28.24	30.19	32.02	33.75	48.00
	26.28	28.38	30.35	32.19	33.93	48.50
	26.41	28.53	30.50	32.35	34.10	49.00
	26.55	28.68	30.66	32.52	34.28	49.50
	26.68	28.82	30.81	32.68	34.45	50.00
	26.82	28.96	30.96	32.84	34.62	50.50
	26.95	29.11	31.12	33.01	34.79	51.00
	27.08	29.25	31.27	33.17	34.96	51.50
	27.21	29.39	31.42	33.33	35.13	52.00
	27.34	29.53	31.57	33.49	35.30	52.50
	27.47	29.67	31.72	33.65	35.47	53.00
	27.60	29.81	31.87	33.80	35.63	53.50
	27.73	29.95	32.02	33.96	35.80	54.00

TABLE A5 CONTINUED

p	0·30	0·35	0·40	0·45	0·50	k(m/day)
	27.86	30.09	32.17	34.12	35.97	54.50
	27.98	30.23	32.31	34.28	36.13	55.00
	28.11	30.36	32.46	34.43	36.29	55.50
	28.24	30.50	32.61	34.59	36.46	56.00
	28.36	30.64	32.75	34.74	36.62	56.50
	28.49	30.77	32.90	34.89	36.78	57.00
	28.61	30.91	33.04	35.05	36.94	57.50
	28.74	31.04	33.18	35.20	37.10	58.00
	28.86	31.17	33.33	35.35	37.26	58.50
	28.98	31.31	33.47	35.50	37.42	59.00
	29.11	31.44	33.61	35.65	37.58	59.50
	29.23	31.57	33.75	35.80	37.74	60.00
	29.35	31.70	33.89	35.95	37.89	60.50
	29.47	31.83	34.03	36.10	38.05	61.00
	29.59	31.96	34.17	36.24	38.21	61.50
	29.71	32.09	34.31	36.39	38.36	62.00
	29.83	32.22	34.45	36.54	38.51	62.50
	29.95	32.35	34.59	36.68	38.67	63.00
	30.07	32.48	34.72	36.83	38.82	63.50
	30.19	32.61	34.86	36.97	38.97	64.00
	30.31	32.73	35.00	37.12	39.13	64.50
	30.42	32.86	35.13	37.26	39.28	65.00
	30.54	32.99	35.27	37.40	39.43	65.50
	30.66	33.11	35.40	37.55	39.58	66.00
	30.77	33.24	35.53	37.69	39.73	66.50
	30.89	33.36	35.67	37.83	39.88	67.00
	31.00	33.49	35.80	37.97	40.03	67.50
	31.12	33.61	35.93	38.11	40.17	68.00
	31.23	33.73	36.06	38.25	40.32	68.50
	31.35	33.86	36.20	38.39	40.47	69.00
	31.46	33.98	36.33	38.53	40.61	69.50
	31.57	34.10	36.46	38.67	40.76	70.00
	31.68	34.22	36.59	38.81	40.91	70.50
	31.80	34.34	36.72	38.94	41.05	71.00
	31.91	34.47	36.85	39.08	41.19	71.50
	32.02	34.59	36.97	39.22	41.34	72.00
	32.13	34.71	37.10	39.35	41.48	72.50
	32.24	34.83	37.23	39.49	41.62	73.00
	32.35	34.94	37.36	39.62	41.77	73.50
	32.46	35.06	37.48	39.76	41.91	74.00
	32.57	35.18	37.61	39.89	42.05	74.50
	32.68	35.30	37.74	40.03	42.19	75.00
	32.79	35.42	37.86	40.16	42.33	75.50
	32.90	35.53	37.99	40.29	42.47	76.00
	33.01	35.65	38.11	40.42	42.61	76.50
	33.11	35.77	38.24	40.56	42.75	77.00
	33.22	35.88	38.36	40.69	42.89	77.50
	33.33	36.00	38.48	40.82	43.03	78.00
	33.43	36.11	38.61	40.95	43.16	78.50
	33.54	36.23	38.73	41.08	43.30	79.00
	33.65	36.34	38.85	41.21	43.44	79.50
	33.75	36.46	38.97	41.34	43.58	80.00
	33.86	36.57	39.10	41.47	43.71	80.50
	33.96	36.68	39.22	41.60	43.85	81.00
	34.07	36.80	39.34	41.72	43.98	81.50
	34.17	36.91	39.46	41.85	44.12	82.00
	34.28	37.02	39.58	41.98	44.25	82.50
	34.38	37.13	39.70	42.11	44.38	83.00
	34.48	37.25	39.82	42.23	44.52	83.50
	34.59	37.36	39.94	42.36	44.65	84.00
	34.69	37.47	40.06	42.49	44.78	84.50
	34.79	37.58	40.17	42.61	44.92	85.00
	34.89	37.69	40.29	42.74	45.05	85.50

TABLE #5 CONTINUED

P	0·30	0·35	0·40	0·45	0·50	K(m/day)
	35.00	37.80	40.41	42.86	45.18	86.00
	35.10	37.91	40.53	42.99	45.31	86.50
	35.20	38.02	40.64	43.11	45.44	87.00
	35.30	38.13	40.76	43.23	45.57	87.50
	35.40	38.24	40.88	43.36	45.70	88.00
	35.50	38.34	40.99	43.48	45.83	88.50
	35.60	38.45	41.11	43.60	45.96	89.00
	35.70	38.56	41.22	43.72	46.09	89.50
	35.80	38.67	41.34	43.85	46.22	90.00
	35.90	38.78	41.45	43.97	46.35	90.50
	36.00	38.88	41.57	44.09	46.47	91.00
	36.10	38.99	41.68	44.21	46.60	91.50
	36.20	39.10	41.80	44.33	46.73	92.00
	36.29	39.20	41.91	44.45	46.86	92.50
	36.39	39.31	42.02	44.57	46.98	93.00
	36.49	39.41	42.14	44.69	47.11	93.50
	36.59	39.52	42.25	44.81	47.23	94.00
	36.68	39.62	42.36	44.93	47.36	94.50
	36.78	39.73	42.47	45.05	47.49	95.00
	36.88	39.83	42.58	45.17	47.61	95.50
	36.97	39.94	42.69	45.28	47.73	96.00
	37.07	40.04	42.81	45.40	47.86	96.50
	37.17	40.14	42.92	45.52	47.98	97.00
	37.26	40.25	43.03	45.64	48.11	97.50
	37.36	40.35	43.14	45.75	48.23	98.00
	37.45	40.45	43.25	45.87	48.35	98.50
	37.55	40.56	43.36	45.99	48.47	99.00
	37.64	40.66	43.47	46.10	48.60	99.50
	37.74	40.76	43.58	46.22	48.72	100·00

Appendix B

Computer programs for design tables

TABLE A1.

```
1 OPEN1.4
10 PEM PROGPAM FOR INDUCED INFILTRATION TO GALLEPIES
20 PRINT#1."TABLE A1-DISTANCE BETWEEN GALLERY AND RIVER"
25 PRINT#1:PRINT#1
30 DATA 6912000.1.5
40 READ T.S
60 REM PEPEAT ON NEW LINE FOR K=0.50 TO 100.00
70 FOR K=0.50 TO 100.00 STEP 0.50
90 REM PRINT ON ONE LINE FOR POROSITIES 0.30TO 0.50
100 FOP P=0.30 TO 0.55 STEP 0.05
110 L=0.9*SQR(K/(86400*P)*S*T)
120 X=L*100
130 Y=INT(X)
140 Z4=Y/100
150 GOSUB210
160 NEXT P
163 Z4=K
165 GOSUB210
167 PRINT#1.
170 NEXT K
180 END
190 STOP
210 Z1=Z4
220 V1=3:V2=2:V=Z1:GOSUB230:PRINT#1.V$;"  ";
230 REM 'USING' ARRANGE IN COLUMNS
240 PEM V IS VALUE; V1.V2 PRINTS
250 V4=INT(V*10↑V2+.5)
260 V$=RIGHT$("          "+STP$(V4).V1+V2+1):O$=V$
270 IF V2<1 GOTO310
280 FOPV5=V1+2TOV1+V2+1:IF ASC(MID$(V$.V5))<48THENNEXTV5
290 V6=V5-V1-1
300 V$=MID$(V$.V6.V1+1)+LEFT$(".00000".V6)+MID$(V$.V5)
310 IF ASC(V$)>47 THEN V$=LEFT$("**********".V1+V2+2+(V2=0))
320 RETURN
```

TABLE A2

```
1 OPEN2,4:CMD2:LIST
2 PRINT#2,"TABLE A2-DISTANCE BETWEEN RIVEP AND WELL"
4 INPUTQ1
6 OPEN2,4
8 CMD2
10 PEM INDUCED INFILTRATION DISTANCE BETWEEN PIVER AND WELL
12 DATA 0.40,30.00,6912000
14 PRINT#2,Q1
16 READ P,H,T
18 FOR Q=0.0000579 TO .0059 STEP .00011622 PEM G=INITIAL GUESS FOR A
24 LET G=1.01
26 PEM F=FUNCTION OF A
28 REM B=IMPROVED GUESS
30 LET F=(1/(SQR(G-1))*(ATN(1/(SQR(G-1))))-(1/G)-(3.142*Q1*Q1*T)/(P*H*
32 LET B=G+0.1
34 IF F<0.01 THEN 40
36 LET G=B
38 GO TO 30
40 LET A=B
42 LET L=Q/(A*3.142*Q1)
44 X=L*100
46 Y=INT(X)
48 Z=Y/100
50 PRINT#2,Z
52 IF Q>0.0059 GO TO 4
54 IF Q<0.0059 GO TO 56
56 NEXT Q
58 CLOSE2
60 GO TO 4
62 END
```

TABLE A3.

```
1 OPEN1.4
10 REM PROGRAM(1) FOR DESIGN OF INFILTRATION BASINS
20 PRINT#1."TABLE A3-DISTANCE BETWEEN BASIN AND GALLERY"
25 PRINT#1:PRINT#1
30 DATA 6912000.1.5
40 READ T,S
60 REM REPEAT ON NEW LINE FOR K=0.50 TO 100.00
70 FOR K=0.50 TO 100.00 STEP 0.50
90 REM PRINT ON ONE LINE FOR POROSITIES0.30 TO 0.50
100 FOR P=0.30 TO 0.55 STEP 0.05
110 L=SQR(K/(86400*P)*S*T)
120 X=L*100
130 Y=INT(X)
140 Z4=Y/100
150 GOSUB210
160 NEXT P
163 Z4=K
165 GOSUB210
167 PRINT#1,
170 NEXT K
180 END
190 STOP
210 Z1=Z4
220 V1=3:V2=2:V=Z1:GOSUB230:PRINT#1.V$;"  ";
230 REM 'USING' ARRANGE IN COLUMNS
240 REM V IS VALUE: V1.V2 PRINTS
250 V4=INT(V*10↑V2+.5)
260 V$=RIGHT$("            "+STR$(V4).V1+V2+1):Q$=V$
270 IF V2<1 GOTO310
280 FORV5=V1+2TOV1+V2+1:IF ASC(MID$(V$.V5))<48THENNEXTV5
290 V6=V5-V1-1
300 V$=MID$(V$.V6.V1+1)+LEFT$(".00000".V6)+MID$(V$,V5)
310 IF ASC(V$)>47 THEN V$=LEFT$("**********".V1+V2+2+(V2=0))
320 RETURN
```

TABLE A4.

```
1 OPEN1,4
10 REM PROGRAM FOP INDUCED INFILTRATION TO GALLERIES
20 PRINT#1,"TABLE A4-FLOW PER UNIT AQUIFEP WIDTH
25 PRINT#1:PRINT#1
30 DATA 6912000.1.5.10.00
40 PEAD T.S.H
60 REM REPEAT ON NEW LINE FOR K=0.50 TO 100.00
70 FOR K=0.50 TO 100.00 STEP 0.50
90 REM PRINT ON ONE LINE FOR POPOSITIES0.30 TO 0.50
100 FOP P=0.30 TO 0.55 STEP 0.05
110 Q=H*SQR(K*S*P/(T*86400))
120 X=Q*1000000
130 Y=INT(X)
140 Z4=Y/1000000
150 GOSUB210
160 NEXT P
165 Z4=K
167 GOSUB210
169 PRINT#1,
170 NEXT K
180 END
190 STOP
210 Z1=Z4
220 V1=2:V2=7:V=Z1:GOSUB230:PFINT#1,V$;"  ";
230 REM 'USING' ARPANGE IN COLUMNS
240 REM V IS VALUE; V1.V2 PRINTS
250 V4=INT(V*10↑V2+.5)
260 V$=R1GHT$("       "+STR$(V4),V1+V2+1):O$=V$
270 IF V2<1 GOTO310
280 FORV5=V1+2TOV1+V2+1:IF ASC(MID$(V$,V5))<48THENNEXTV5
290 V6=V5-V1-1
300 V$=MID$(V$,V6,V1+1)+LEFT$(".00000",V6)+MID$(V$,V5)
310 IF ASC(V$)>47 THEN V$=LEFT$("+++++++++++",V1+V2+2+(V2=0))
320 RETURN
```

TABLE A5.

```
1 OPEN1,4
10 PEM PPOGPAM(2) FOP DESIGN
20 PRINT#1,"TABLE A5-WIDTH OF INFILTRATION BASINS"
25 PPINT#1:PRINT#1
30 DATA 6912000,1.50,10.00,0.0000046
40 PEAD T,S,H,V9
60 REM REPEAT ON NEW LINE FOR K-=0.50 TO 100.00
70 FOP K=0.50 TO 100.00 STEP 0.5
90 REM PRINT ON ONE LINE FOR POPOSITIES 0.30 TO 0.50
100 FOP P=0.30 TO 0.55 STEP 0.05
110 Q=H*SQR(K*S*P/(T*86400))
115 W=Q/V9
120 X=(W*2)*100
130 Y=INT(X)
140 REM Z IS WIDTH OF INFILTRATION BASIN
145 Z4=Y/100
150 GOSUB210
160 NEXT P
163 Z4=K
165 GOSUB210
167 PRINT#1,
170 NEXT K
180 END
190 STOP
210 Z1=Z4
220 V1=2:V2=2:V=Z1:GOSUB230:PRINT#1,V$;"  ";
230 REM 'USING' APRANGE IN COLUMNS
240 REM V IS VALUE; V1,V2 PRINTS
250 V4=INT(V*10↑V2+.5)
260 V$=RIGHT$("          "+STR$(V4),V1+V2+1):O$=V$
270 IF V2<1 GOTO310
280 FORV5=V1+2TOV1+V2+1:IF ASC(MID$(V$,V5))<48THENNEXTV5
290 V6=V5-V1-1
300 V$=MID$(V$,V6,V1+1)+LEFT$(".00000",V6)+MID$(V$,V5)
310 IF ASC(V$)<47 THEN V$=LEFT$("**********",V1+V2+2+(V2=0))
320 RETURN
60826 X
52144 ASCY
```