PERFORMANCE EVALUATION OF A COLLECTOR WELL USING MODFLOW

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCES DEVELOPMENT (CIVIL)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the dissertation entitled **"PERFORMANCE EVALUATION OF A COLLECTOR WELL USING MODFLOW"** in partial fulfillment of the requirement for the award of degree of **Master of Technology in Water Resources Development (Civil)** in the Department of Water Resources Development and Management of Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during a period from July 2009 to June 2010 under the guidance of **Dr. M. L. Kansal,** Professor of Water Resources Development and Management, Indian Institute of Technology Roorkee, India.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

Dated : June 01, 2010
Place : Roorkee

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Candidate

CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Conventionally, water supplies for drinking purpose have been drawn from sub-surface and/or surface sources. The system of tapping sub-surface water have been tube wells (vertical well), infiltration galleries, and radial collector wells. Nowadays, radial collector wells have become quite popular as the ground water supply wells. A radial collector well consists of a number of horizontal perforated pipes laid in an aquifer and connected to a vertical cylindrical caisson, plugged at the bottom end. In case of multiple laterals in a radial collector well, the laterals interfere with each other, and hence it is important to provide non-perforated portion of pipes near the caisson. Performance of such collector wells is assessed by estimating the safe yield which depends on several factors like: location of the radial collector well, length, diameter, direction, number, and percentage perforation of laterals, aquifer parameters, and permissible drawdown, etc. In this study, performance of a radial collector well located under riverbed, near a straight reach of a river, and near meandering river has been studied through numerical modelling using MODFLOW. While modelling the geometry, opening slots, and percentage perforation, etc. a concept of equivalent conductivity is used. Various possible lay outs with different number of laterals are analysed and safe yield is estimated in terms of dimension less parameters. Relationship between the safe yield and ranges of various parameters is proposed on the basis of regression analysis.

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CONTENTS

NOTATIONS

a	: slot opening size, river width/width of the aquifer;
A	: cross sectional area;
b	: thickness of aquifer;
b_{av}	: average saturated thickness of the aquifer;
b"	: thickness of semi-confining layer;
B	: drainage factor;
$CC_{i-½,j,k}$	: conductance in column j and layer k between modes i-1,j,k and i,j,k;
$CR_{i,j-½,k}$	: conductance in row i and layer k between nodes i,j-1, k and i,j,k;
$CV_{i,j,k-½}$	: conductance in row i and column j between modes i,j,k-1 and i,j,k;
1/C	: leakage coefficient or leakance;
C	: hydraulic resistance;
d	: diameter of lateral;
D	: hydraulic difussity;
E	: efficiency;
g	: acceleration due to gravity;
h	: piezometric head;
hd	: head in lateral;
$h_{i,j,k}$	: the head in cell i,j,k;
$h_{i,j-1,k}$	: the head in cell i,j-1,k;
h_r	: head in the river;
h_w	: head in the caisson;
k	: hydraulic conductivity;
k'	: specific permeability;

k''	: vertical permeability of semi-confining layer permeability;
k_0	: conductivity of the slot;
k_c	: hydraulic conductivity in the cell of lateral;
K_e	: equivalent conductivity;
K_x, K_y, K_z	: hydraulic conductivity in x, y, z direction;
$KR_{i,j-1/2,k}$	: hydraulic conductivity along the row between nodes i,j,k and i,j-1,k;
l	: length of lateral;
l_b	: length of the blind part;
l_s	: perforated length of the lateral;
L	: leakage factor;
n	: porosity and number of laterals;
p	: percentage perforation;
$P_{i,j,k}$	: certain constant for cell i,j,k;
q_x, q_y, q_z	: specific discharge in x, y, z direction;
Q	: inflow to lateral;
$Q_{\Delta x \Delta y}$	: flow through area $\Delta x \Delta y$;
Q_i	: flow rate into the cell;
$Q_{i,j,k}$	: flow rate into cell i,j,k.;
$Q_{i,j-1/2,k}$	: volumetric fluid discharge through the face between cells i,j,k and i,j-1,k;
Q_x	: discharge in x direction;
$Q_{(l)}$	: discharge near the caisson;
$Q_{(x)}$	: discharge at a distance x;
r_c	: radius of the caisson;
r_e	: equivalent well radius;
r_w	: pipe/well radius;

R	: distance of a collector well from the riverbank;
s_c	:computed drawdown;
s_m	: measured drawdown;
S	: storativity;
Sr	: specific retention;
Ss	: specific storage of the porous material;
$SS_{i,j,k}$	: specific storage of cell i,j,k;
Sw	: storage coefficient;
Sy	: specific yield
t	: thickness of pipe;
T	: transmissivity of aquifer and thickness;
v_1	: entrance velocity;
v_2	: maximum axial velocity;
V_0	: total volume;
V_v	: volume of voids;
W	: volumetric flux per unit volume and represents sources and or sinks;
x	: distance from the tip of collector pipe;
z	: elevation of lateral;
z_i	: vertical position of lateral;
$\Delta c_i \Delta v_k$	: area of the cell faces normal to the row direction;
Δh	: the change in head;
$\Delta h_{i,j,k}$	: the finite different approximation for the derivative of head;
$\Delta r_{j-½}$	: distance between nodes i,j,k and i,j-1,k;
$\Delta r_j \Delta c_i \Delta v_k$	: volume of cell i,j,k is recent in time;

Δt	: time increment;
ΔV	: the volume of the cell;
Δx	: grid size in x direction;
Δy	: grid size in y direction;
Δz	: grid size in z direction;
$-1/\alpha$	: delay index;
μ	: co-efficient of viscosity;
γ	: specific weight;
υ	: fluid kinematic viscosity;

Other notations are locally defined wherever these appear.

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Water is a necessary requirement for human lives and is a precious resource. Water supplies for drinking, irrigation or industrial usage have been drawn from rivers, streams, reservoirs, or aquifers, and other natural or artificial sources. Rising demand due to increasing population, water pollution and climate change are a huge threat to fresh water supplies. Thus ensuring an adequate supply must be a priority. The water supplies specially for drinking purpose require costly treatment to make it turbidity-free and bacteriologically pure. Ground water can be an alternate sustainable source for drinking water as the largest available sources of fresh water lies underground and can be utilized, without or with marginal treatment.

The oldest method of groundwater tapping is digging a hole into the earth to a certain depth below the water table but a little water can be abstracted in this way. When a large quantity of water is required, the area of contact with the aquifer must be increased. This is carried out by increasing the horizontal or vertical dimension or both depending upon the local conditions; i.e. mainly the thickness of the aquifer and the depth of the water table below ground surface. The horizontal means of groundwater recovery are called infiltration galleries and the vertical means of groundwater recovery are called wells. In vertical wells, water is admitted from the sides as well as from the bottom of the wells, and in order to prevent sand from being blown into the well, the velocity of inflow is kept low. In order to increase the flow, these wells are generally connected to each other by means of porous pipes. Infiltration galleries also function on the same lines as that of vertical wells, except that they are narrow trenches sunk into the aquifer and then covered up with rubble, etc.

When the water bearing formation has a large thickness and the water table is at a short distance below ground level, both the horizontal and vertical means may be used for groundwater recovery but the real problem arise when water must be abstracted from an aquifer of small thickness situated at large depth below the ground level. Because of greater depth, the galleries can not be used and because of small saturated thickness of water bearing stratum the vertical well can not be proved a feasible solution. In some geological formations, the aquifer thickness may not be sufficient to supply the required volume of surface water body. In other situations, a thin layer of fresh water may overlie saline water, in such case the provision of deep vertical well will cause upcoming of the saltwater, thereby, destroying water quality.

Under these hydro geologic situations a different type of well for tapping groundwater is used, called Radial Collector Well. Radial collector wells are horizontal conduits that intercept and collect groundwater derived principally from surface water infiltration. Such supplies are found in sand and gravel deposits underlying and hydraulically connected with surface sources such as rivers, lakes, and ocean. For cities and industries located near rivers, the problem of obtaining a high quality, low temperature water at reasonable cost has become increasingly difficult. If located adjacent to a surface water supply, a collector well, lowers the water table and thereby induces seepage of surface water through the bed of the water body to the well. In this manner greater supplies of water can be obtained than would be available at the same location from an aquifer alone.

Radial collector wells are generally installed near a river as a part of Riverbank Filtration (RBF) system to increase the potential yield and the quality of the water as shown in

Figure 1.1. In humid regions, river water naturally percolates through the bank into aquifers (which are layers of sand and gravel those contain water underground) during high-flow conditions. In arid regions, most rivers lose flow, and the percolating water passes through soil and aquifer material until it reaches the water table. During these percolation processes, potential contaminants present in river water are filtered and attenuated. If there are no other contaminants present in the aquifer or if the respective contaminants are present at lower concentrations, the quality of water in the aquifer can be of higher quality than that found in the river. In RBF, production wells, which are placed near the banks of rivers, pump large quantities of water. The pumping action creates a pressure head difference between the river and aquifer, which induces the water from the river to flow downward through the porous media into pumping wells. The pumped water is a mixture of both groundwater originally present in the aquifer and infiltrated surface water from the river. Depending upon the ultimate use and the degree of filtering and contaminant attenuation, additional treatments may be provided to the pumped water prior to distribution. At a minimum, RBF acts as a pretreatment step in drinking-water production and, in some instances, can serve as the final treatment just before disinfection.

For more than 100 years, RBF has been used in Europe, most notably along the Rhine, Elbe, and Danube Rivers, to produce drinking water. Although RBF is not commonly utilized in the United States, interest is increasing in using RBF as a low-cost complement or alternative to filtration systems to remove pathogens from water. RBF has proven to be invaluable in treating drinking-water sources in Europe. Studies have shown that RBF generally removes a substantial percentage of organic compounds found in raw river water.

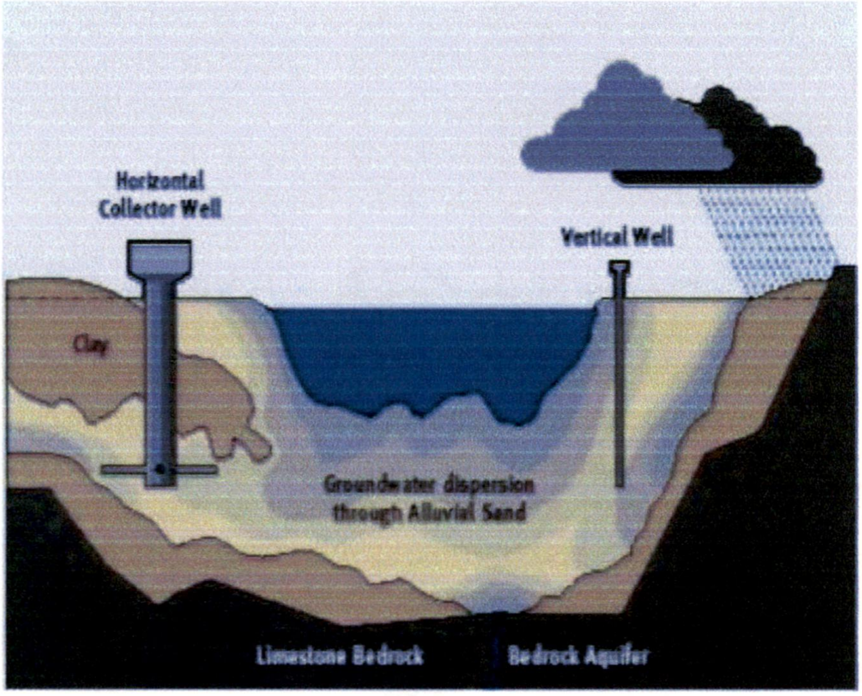


Figure 1.1: Riverbank Filtration

(http://www.bau.htw-dresden.de/bankfiltration/IRES/images/titlepic.jpg)

1.2 OBJECTIVES OF THE STUDY

The objective of this study is to evaluate the performance of a collector well using numerical method. Three specific cases are considered:

1. The collector well is laid under the riverbed
2. The collector well is located in the aquifer near a straight river reach
3. The collector well is located in the aquifer near a meandering river reach

The performance of collector well is evaluated by how much water can be drawn from the well which depends on several factors like: elevation, length, diameter, and number of laterals; distance from the river; percentage perforation; etc. Equivalent hydraulic conductivity has used to model the geometry of pipe, opening slot, and percentage perforation. The flow into collector well has been simulated by using MODFLOW and is presented in the form of dimensionless term for different parameters. Finally, the relationship of yield with various parameters has been established using regression analysis. The application of proposed relationships has been illustrated with the help of illustrative examples.

1.3 SCOPE AND LIMITATIONS

The scope of study includes the simulation using a computer program Processing Modflow for Windows version 5.3.0 software which was developed by Wen-Hsing Chiang and Wolfgang Kinzelbach with it's user's manual (Chiang (2005)). The simulation model only simulates a steady state flow to a collector well under a riverbed, besides flow to a single collector well having several laterals near a straight river reach as well as near a meandering river reach. The various parameters that have been used in the simulation are elevation, length, diameter, and number of laterals; distance of the well caisson from the river; percentage perforation. The type of aquifer for which simulation is done in this study is a confined aquifer.

1.4 ORGANIZATION OF DISERTATION

The dissertation is arranged in seven chapters as follows:

1. **Chapter I**: In this chapter, the background of the study has been described that the collector well can be an alternative as drinking water supply. The scope and objectives of the present study have been summarized and the organization of dissertation has been described.
2. **Chapter II**: This chapter covers the literature study related to the collector well. The importance of drinking water, a collector well as groundwater abstraction and the use of collector well have been described. It briefly discusses the highlights of the important studies on the flow, design and construction of a collector well.

3. **Chapter III**: The modeling of collector well using MODFLOW has been briefly described in this chapter and an example of the modeling steps details has been presented. The equivalent conductivity in the collector nodes for modeling the percentage of perforation has been introduced.
4. **Chapter IV:** In this chapter, the modeling of a collector well under a riverbed in comparison with Hantush solution has been carried out. The yield of a gallery (collector well with one co linear lateral has been compared with Hantush solution for different elevation of collector well.
5. **Chapter V:** In this chapter, the modeling of collector well adjacent to a straight river has been carried out. The modeling has been initiated by placing a single lateral of collector well parallel to the river. Further, collector well with multiple laterals has been modeled.
6. **Chapter VI**: In this chapter, the modeling of collector well adjacent to a meandering river has been carried out. Assuming the river and the aquifer system in hydrostatic state, the flow to a well near meandering reach of river has been conceptualized as a well at the centre of a circular island. The laterals are considered as partly screened and partly blind (non-perforated).
7. **Chapter VII**: This chapter presents the summary and important conclusions drawn from the study.

CHAPTER II

LITERATURE REVIEW

2.1 IMPORTANCE OF DRINKING WATER

Drinking water is crucial to the quality of life. Demand for water continues to grow. Safe, cost–effective, sustainable and environmentally friendly water sources are needed. The importance of drinking water is immeasurable and the health benefits of drinking water are innumerable.

Basically, one requires lot of fresh drinking water to stay healthy. Aside from aiding in digestion and the absorption of food, drinking water regulates body temperature, carries nutrients and oxygen to cells, and removes toxins and other wastes. This "body water," which is obtained by consuming plenty of drinking water, also cushions joints and protects tissues and organs, including the spinal cord, from shock and damage. Conversely, not in taking enough water or putting the body into a state of dehydration can be the cause of many ailments. Therefore, adequate quantity of drinking water source becomes important.

Besides quantity, one should also consider the quality of drinking water. The quality should be maintained with or without treatments to make sure that the water can be safely consumed by human being. Drinking water quality can be evaluated at many levels. To help with this drinking water evaluation process, some general guidelines have been established as a basis for the development of national drinking water standards for example Indian Standard Specification for Drinking Water (IS: 10500). If properly implemented, these national drinking water standards will ensure the safety of drinking water supplies through the elimination, or reduction to a minimum concentration, of constituents of drinking water that are known to be hazardous to health.

Regarding quality of drinking water source, one has to check the turbidity, presence of organic matter, organic and inorganic soil particles, animal and plant debris, fertilizers, pesticides, and pathogenic organisms. Municipal supplies require one or more treatment processes depending upon the impurities found in the water. Treatments which are commonly used in practice are sand filtration, chlorination, flocculation, sedimentation, aeration, etc.

2.1.1 Different Sources of Drinking Water

Drinking water or potable water is essential for survival, must be clean, safe and of sufficiently high quality that it can be consumed or used without risk of immediate or long term harm. Basically, drinking water resource is from fresh water which is a renewable resource, yet the world's supply of clean, fresh water is steadily decreasing. The distribution of earth's water can be shown in Figure 2.1. Water for drinking and domestic use may be obtained from natural sources like surface water, groundwater and rainwater. The sources of possible drinking water are highlighted as follows:

a. Surface Water: Streams, rivers and lakes are the major sources of surface waters. Usually these sources fulfill the requirements of municipal supplies. Water in these sources originates partly from groundwater outflows, snow melt, and partly from rainwater which flows over the terrestrial areas into the surface water bodies. Outflows from groundwater bring in the dissolved solids.
b. Groundwater: Wells and springs constitute groundwater supplies. Groundwater mostly originates from infiltrated rainwater after reaching the aquifer flows through the

underground. Groundwater provides water to meet the requirement of individual household supplies as well as municipal supplies.

c. Other Sources: Rainwater run off from roofs can be collected and stored for domestic use. Rainwater will be of high quality and the only possible source of contamination is airborne microorganisms that too will be present in very low numbers.

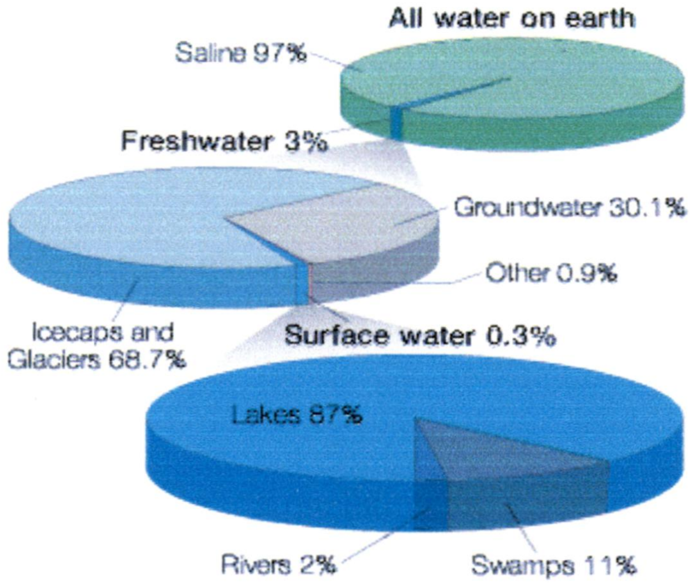


Figure2.1: Distribution of Earth's Water

(http://www.pacificwater.org/userfiles/image/WaterDemandManagement/earthswater.gif)

2.1.2 Sustainable Source of Drinking Water

Since the availability of water varies in space and time, a sustainable source of drinking water becomes important. Sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but also for future generations. The field of sustainable development can be conceptually broken into three constituent parts: environmental sustainability, economic sustainability and sociopolitical sustainability as shown in Figure 2.2.

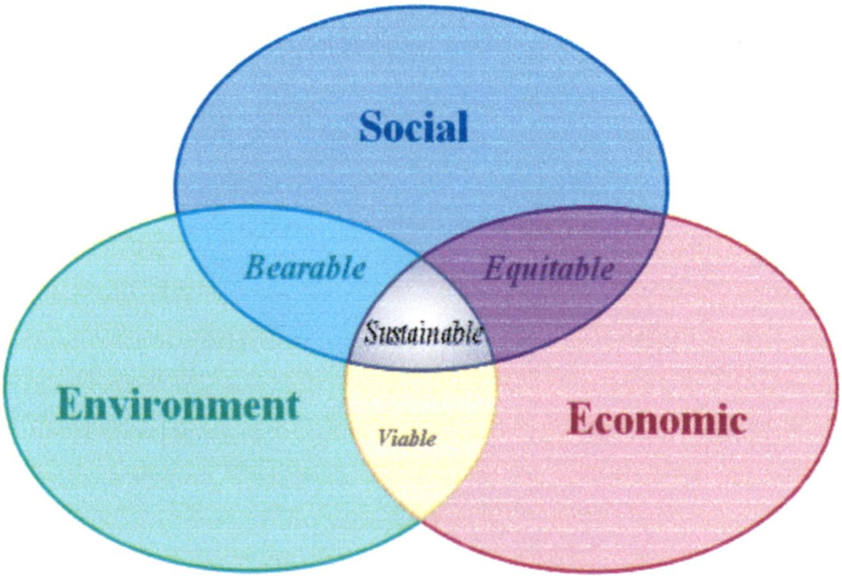


Figure 2.2: Scheme of sustainable development: at the confluence of three constituent parts (http://www.ac-nancy-metz.fr/enseign/anglais/Henry/Sustainable.png)

Sources of water can be a sustainable if they can meet the requirement of economically affordable in funding the infrastructure, the consumption is less than nature ability to replenish, and can improve the social life of human. Factors affecting sustainability of water sources are as follows:

1. The availability of freshwater supplies throughout periods of climatic change, extended drought, population growth and the needed supplies for the future generations.
2. The infrastructure to provide water supply for human consumption and food security, and to provide protection from water excess such as floods and other natural disasters, and the infrastructure for clean water and for treating water after it has been used by human before being returned to water bodies.
3. Adequate institutions to provide for both the water supply management and water excess management.

For ensuring sustainability of the systems, community participation in the implementation of drinking water supply schemes is important.

2.2 GROUNDWATER AS A SUSTAINABLE SOURCE OF DRINKING WATER

Ground water can be an alternate sustainable source for drinking water. In some countries artificial groundwater recharge is made to store water. Properly withdrawn groundwater will be free from turbidity and pathogenic microorganisms. It is important to select the location of groundwater supply at a safe distance from other sources of contamination like septic tanks. If done so, groundwater will be of high quality and can be used directly without any treatment.

The reasons for using groundwater as a sustainable source for drinking water are described as follows.

Quantitative aspect of the resource for using groundwater:

1. Provides large volume, which can be used over years. The supply can be increased to meet additional demands by drilling additional boreholes so far as the local groundwater resources permit this and the cost of borehole is relatively modest if water is at no great depth.
2. Seasonal fluctuations of precipitation are balanced.
3. In semi-arid regions, where groundwater and artificial/natural reservoirs are only reliable water resource, rivers may fall dry, unless fed by groundwater. With sufficient depth to the groundwater table, no direct evapotranspiration from groundwater takes place.
4. In some countries artificial groundwater recharge is made to store water.

Qualitative aspect for using groundwater:

1. Soils and aquifers are natural reactors, which can act as a system for filtration of particles, including bacteria and viruses, sufficient attenuation of pathogens after few days of residence time.

2. The wide area typically occupied by an aquifer makes it possible to procure water close to where it is required and many aquifers provide water that requires no treatment other than precautionary disinfection though in many developing countries even disinfection is not adopted.
3. Dampened fluctuation of temperature and stable hydro-geochemistry parameters (pH, major ions, DOC) is significant aspect of groundwater.

While using groundwater following consideration should arise:

1. There are needs to apply measures to conserve and protect underground supplies.
2. Urban coverage may reduce the recharge of the aquifer and subsidence can result from over-pumping.

The occurrence and movement of groundwater depends on the geohydrological characteristics of the sub surface formation. These natural deposits vary greatly in their hydrological characteristics. The geological formations are classified into the following four types depending upon their hydrological properties:

1. ***Aquifer***: An aquifer is a formation or a geological structure which has good permeability to supply sufficient quantity of water to a well or spring. Unconsolidated sedimentary formations like gravel and sand form excellent aquifers. Fractured igneous and metamorphic rocks and carbonate rocks with solution cavities also form good aquifers.
2. ***Aquitard***: It is formation through which only seepage is possible and thus the yield is insignificant compared to an aquifer. It is partly permeable. A sandy clay unit is an example of aquitard. Through an aquitard appreciable quantities of water may leak to an aquifer below it.

3. ***Aquiclude***: It is a geological formation which is essentially impermeable to the flow of water. It may be considered as closed to water movement even though it may contain large amounts of water due to its high porosity. Clay is an example of an aquiclude.
4. ***Aquifuge***: It is a formation which is neither porous nor permeable e.g. massive igneous and metamorphic rocks.

2.2.1 Aquifer Types and Their Hydraulic Properties

The lateral continuity and vertical boundaries are often not well defined. The aquifers may be either of localized nature or may extend over distance of several hundred kilometers. Aquifer in Ganga basin India; Great Australian Artesian Basin and in Sahara (Nubian sandstone) have been traced over distances of several hundred kilometers. Based on the hydraulic characteristics, the aquifers can be classified into following four types:

1. ***Confined Aquifers***: These are also termed as artesian aquifers. A confined aquifer is overlain and underlain by a confining layer (aquiclude or aquifuge). Water in the confined aquifers occurs under pressure which is more than the atmospheric pressure. The piezometric surface which is an imaginary surface, to which the water will rise in wells penetrating the confined aquifer, should lie above the top of the aquifer, i.e. above the base of the overlying confining layer. A particular aquifer at one place may be a confined aquifer while at another place it may behave as an unconfined aquifer where the water level falls below the base of the overlying confining layer. Similarly, at one particular place an aquifer may change from confined to unconfined character with time.
2. ***Semi Confined Aquifers***: In nature, truly confined aquifers are rare because the confining layers are not exactly impervious. In semi confined or leaky confined aquifers, the aquifer is overlain or underlain by an aquitard or semi-pervious layer through which vertical

leakage takes place due to head difference. The permeability of the semi confining layer is small so that, any horizontal component of flow in it can be neglected.

3. ***Unconfined Aquifers***: An unconfined aquifer is not overlain by any confining layer but it has a confining layer at its bottom. It is normally partly saturated with water and the upper surface of saturation is termed as water table which is under atmospheric pressure. Water in an unconfined aquifer is called unconfined or phreatic water. In unconfined aquifer the gravity drainage is often not instantaneous and therefore there is some time lag in the lowering of water table and the drainage of the aquifer. The delay effect is more in fine grained aquifers as compared to coarse grained aquifers.
4. ***Semi Unconfined Aquifers***: These aquifers exhibit characters in between semi-confined and unconfined aquifers as the permeability of the fine grained overlying layers is more than in a semi confined aquifer and the horizontal flow component in it cannot be neglected.

The distinction between different types of aquifers is, at times, difficult. The subsurface lithology, water levels and other hydrological parameters of both the aquifers and confining layers should be studied carefully in order to ascertain the nature of the aquifers. The distinction between different types of aquifer as shown in Figure 2.3 is important because their capacity to release water from storage differs. This is also of relevance from the point of view, of groundwater balance and management studies.

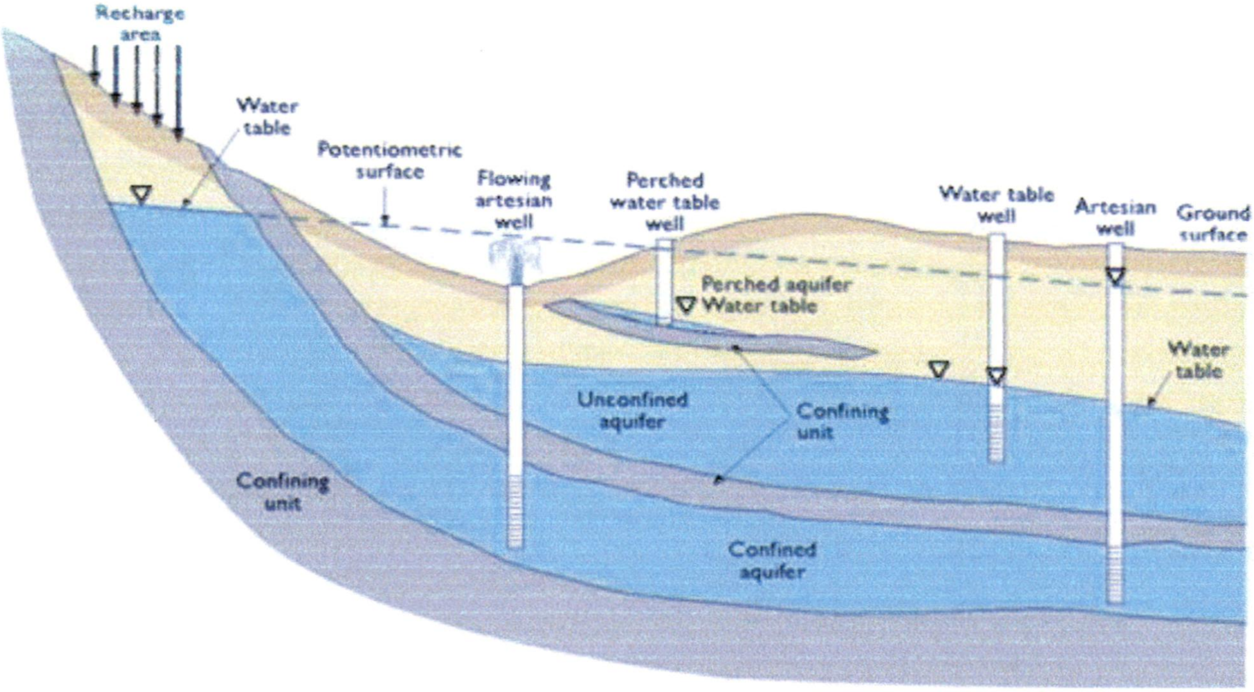


Figure 2.3: Type of Aquifers

(http://203.210.126.185/dsdweb/v4/apps/web/media/images/4103.jpg)

The important hydraulic properties of aquifers and confining layers are:

1. ***Porosity (n)***: It is an important hydrological characteristic of a formation. The porosity as shown in Figure 2.4 is the measure of the interstices present in a formation. It is defined as the ratio of the volume of voids (V_v) to its total volume (V_0) including volume of void and volume of solid and can be expressed either as a percentage or as decimal fraction.

   The porosity of an aquifer is the sum of specific retention (S_r) and specific yield (S_y). Specific retention is a measure of the volume of water which is retained by the aquifer material against gravity on account of cohesive and inter-granular forces. Specific yield is the water yielding capacity and is also termed as effective porosity. Specific yield is expressed quantitatively as the percentage of the total volume of rock occupied by the water which can be drained out by gravity. Specific yield increases with increase in -rain size and sorting while specific retention increases with decrease in grain size and assortment.

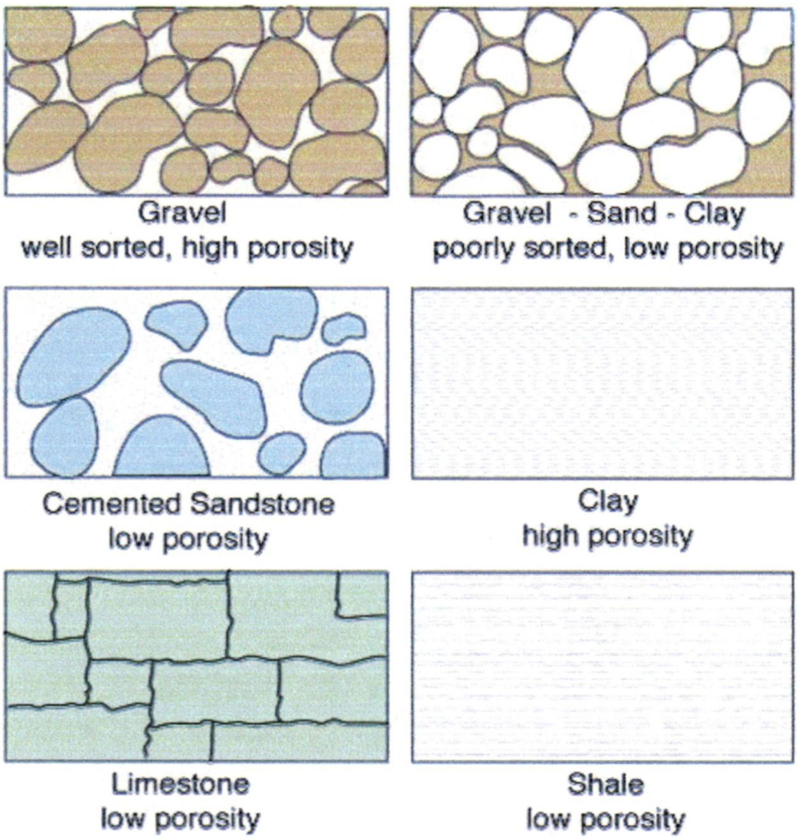


Figure 2.4: Porosity

(http://www.kgs.ku.edu/Publications/Bulletins/ED10/gifs/fig2.jpg)

2. ***Hydraulic conductivity (k)***: The hydraulic conductivity also known as permeability is a measure of the ease with which a fluid moves through a formation and is defined as the amount of flow per unit cross sectional area under the influence of a unit hydraulic gradient. It has the dimensions of velocity (LT^{-1}) and is usually expressed in m/day.

The hydraulic conductivity depends both upon the properties of the fluid as well as on the properties of the aquifer. The specific permeability, k' which is the permeability of the porous medium depends only on the property of the medium and is independent of the fluid properties. Specific permeability is related with hydraulic conductivity by the relation:

$$k = k'\frac{\gamma}{\mu}$$

where μ is the co-efficient of viscosity and γ is the specific weight of the fluid. Specific permeability has the dimensions of L^2 and is usually expressed in darcy units. The Darcy is defined as follows. A porous medium is said to have a permeability of one darcy if a single phase fluid of one centipose viscosity that completely fills the pore space of the medium will flow through it at a rate of 1 cm^3/sec per cm^2 of cross-sectional area under a pressure gradient of 1 atm. per cm. Substituting appropriate unit in the above definition, it can be determined that

1 darcy = 0.987×10^{-8} cm^2

For water at 20°C, medium of permeability of 1 darcy would have a hydraulic conductivity (k) of 9.613×10^{-4} cm/sec.

3. ***Transmissivity (T)***: Transmissivity or coefficient of transmissibility is a hydraulic characteristic of the aquifer which was first introduced in ground water literature by C.V. Theis in 1935. It is defined as the rate of flow of water at the prevailing field temperature under a unit hydraulic gradient through a vertical strip of aquifer of unit width and extending through the entire saturated thickness of the aquifer. It is, therefore, a product of the average permeability and the saturated thickness of the aquifer i.e. $T = kb$ where b is the thickness of the aquifer. Transmissivity has the dimensions of L^2T^{-1} and is usually expressed in m^2/day. The concept of transmissivity holds good in confined aquifer but in unconfined aquifer, as the saturated thickness of the aquifer changes with time, the T will also change accordingly.
4. ***Coefficient of Storage or Storativity (S)***: The storage coefficient of an aquifer is defined as the volume of water that a vertical column of the aquifer of unit cross-sectional area releases from storage or takes into storage as the average head within this column declines

or rises a unit distance. It is dimensionless. In artesian aquifers where water released from or taken into storage is entirely due to compressibility of aquifer and of water, the storage co-efficient S is given by S = bSs, where b is the thickness of the aquifer an Ss (specific storage) which has the dimensions of L^{-1} and is defined as the volume of water which a unit volume of the aquifer releases from storage because of expansion of water and compression of the aquifer under a unit decline in the average head within the unit volume of the aquifer. The storage coefficient in confined aquifers has the order of magnitude of 10^{-3} to 10^{-6}. The storage coefficient Sw for a water table aquifer is given by Sw = Sy + bSs where b is the height of water table above the base of the free aquifer, and Sy is the specific yield of the aquifer. Usually Sy $\geq$ bSs, thus Sw for all practical purposes be regarded as the specific yield. The specific yield is defined as the ratio of the volume of water that a rock or soil will yield by gravity to its own volume. In other words, it represents very closely the effective porosity. The storage coefficient in unconfined aquifers, Sw, ranges from 0.05 to 0.30. In confined aquifer the storage coefficient depends upon the compressibility of the aquifer and the expansion of water. Since an unconfined aquifer is not bounded by confining layers, the specific yield or storage coefficient does not depend upon the compressibility of either the aquifer or the fluid. The specific yield for all practical purposes is same as effective porosity or drainable porosity. Both S and Sy are important hydrological properties and their accurate determination is important for ground water balance studies.

5. ***Hydraulic Diffusivity (D)***: Hydraulic diffusivity is defined as the ratio of transmissivity (T) and storativity (S). Diffusivity has the dimensions of L^2T^{-1} and is generally expressed in m^2/day. For unconfined conditions, the hydraulic diffusivity term is directly proportional to the transmissivity of the aquifer, obtained as the product of the hydraulic conductivity of the water bearing material and the average saturated thickness b_{av} of the

aquifer and is inversely proportional to the storage coefficient. In unconfined aquifer, transmissivity can be expressed as $T = kb_{av}$, where b_{av}, is the average saturated thickness of the unconfined aquifer.

6. ***Leakage Coefficient or Leakance (1/C)***: It is the property of semi confining layer. It is the ratio of the vertical permeability of semi-confining layer to its thickness i.e. k"/b". It has dimensions of T^{-1}.
7. ***Hydraulic Resistance (C)***: It is also called reciprocal leakage coefficient or resistance against vertical flow and is a property or confining layers of leaky aquifers. It is equal to b"/k". It characterizes tile resistance of the semi-pervious layer to upward or downward leakage. It has the dimensions of time. If hydraulic resistance $C = \infty$, the aquifer is confined.
8. ***Leakage Factor (L)***: The leakage factor $L = \sqrt{T.C}$ determines the distribution of the leakage into the leaky (semi confined) aquifer. High value of L indicates a great resistance of semi pervious strata to flow. The factor L has the dimensions of length and is usually expressed in meters.
9. ***Delay Index (-1/α)***: It is a measure of the delayed drainage of an unconfined aquifer and has the dimension of time (T).
10. ***Drainage Factor (B)***: The drainage factor $B = \sqrt{kb / \alpha Sy}$ is a property of unconfined aquifer. Large values of B indicate a fast drainage. The drainage factor has the dimensions of length (L) and is expressed in meters.
11. ***Specific Capacity***: It is a measure of both the effectiveness of a well and also of the aquifer characteristics (T and S). It is defined as the ratio of the pumping rate and the drawdown and is usually expressed in liters per minute per meter of drawdown for a specific period of pumping.

12. ***Specific Capacity Index***: It is a measure of the formation characteristics. It is obtained by dividing the specific capacity by the saturated thickness of the aquifer. The specific capacity index values are of use in determining the relative productivity of different units in a multi unit aquifer and also in predicting well yield from a given thickness of aquifer. Unit area specific capacity values are obtained by dividing the specific capacity by the cross sectional area of the well. The specific capacity can also be divided by $2\pi r_w b$ (where r_w, is the radius of the well) to account for variation in the well radius and depth.

2.2.2 Wells as Groundwater Abstraction

Wells are holes sunk into the earth to obtain water from an aquifer. They are generally classified by type of construction as follows:

1. ***Dug wells***: They are dug by backhoe or by hand, usually shallow (9 m or less), and have large diameter casing (0.6 m to 1.2 m).They are made of concrete, rocks, bricks, or wood, easy to construct, have inexpensive initial cost and large casing provides storage. They may be used in poor-yielding aquifer. If shallow, water shortages are possible in dry periods. It is easy to seal properly, but it requires large volumes of material. Dug wells are vulnerable to near surface contamination. Water temperature in dug well may change seasonally.
2. ***Bore wells***: Same as dug wells except that they are constructed with boring machine. They are shallow or deep (15 m or less). Bore wells are more controlled hole than dug well.
3. ***Well Points (Driven, Jetted, Sand)***: Well points are driven in or jetted with water. They are shallow (15 m or less), have small-diameter casing (0.025 m to 0.05), generally simple and inexpensive to install, limited to permeable materials, and usually in shallow water table. The well points have limited yield, possible shortages in dry periods, and vulnerable to near-surface contamination

4. ***Drilled wells***: These wells are drilled with rotary or cable-tool water well drill and have the following features: shallow or deep (15 m to 60 m or more); small diameter casing (0.1 – 0.2 m), usually made of steel; can reach deeper aquifers, can be drilled into bedrock; less subject to contamination especially if deep; easier to seal; invariability maintain constant temperature; vulnerable to deep aquifer contaminants; poorer natural water quality from some deep aquifers may occur, e.g., from salt.

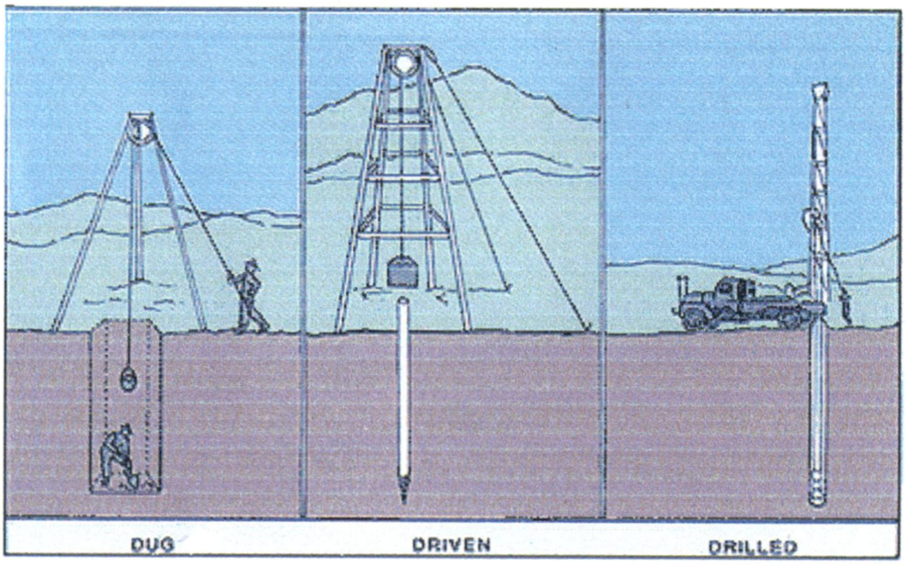


Figure 2.5: Type of wells

(http://pubs.usgs.gov/gip/gw_ruralhomeowner/images/fig9.gif)

Besides those types of wells as shown in Figure 2.5, there is a special well type named collector well which nowadays have become popular as a drinking water source. More explanation for this collector well is discussed in the next section of this chapter.

General rules for the design of groundwater abstraction in respect of:

1. Sustainable yield: The abstraction of groundwater should not exceed than it's recharged.
2. Determination of capture zone. Knowing from where the water comes is important to know the contamination from critical land use such as industry, cemetery, and agriculture with intensive use of agrochemicals in the capture zone

3. Estimation of drawdown with following consideration such as the abstraction will not dry the wetlands or spring flow, influence on other wells, and ground settlement.
4. Determination of travel times with consideration of critical land use in inner protection zone. Travel time from river to well also determine microbial contamination.
5. Use of a predictive flow and transport model.

Important things to be considered for flow to the well are as follow:

1. ***Well Diameter and Yield***: The yield of a well varies directly with logarithm of well radius other parameters remaining invariant. Well diameter in this case refers to the diameter of the hole that penetrates the aquifer.

2. ***Well Penetration and Yield***: The total depth of a well may be relatively unimportant as far as yield is concerned (Muskat, 1946). As noted previously, the important factor is the percentage of saturated thickness of the aquifer penetrated by and open to the well; that is, the percentage of open hole. In an artesian aquifer the specific capacity of a well will vary with the percentage of open hole and is maximize when the entire thickness of the aquifer is penetrated by a screen or open hole. A somewhat similar relationship exists in a free aquifer, but because of the thinning of the aquifer in the direction of flow to the well, the increase is limited somewhat depending on the amount of drawdown experienced and the desirability of limiting it to 60 to 65 percent of the aquifer thickness. But in either case, if sufficient additional aquifer thickness is available, the least expensive way to increase specific capacity and field is usually to increase either the depth of the well and the percentage of open hole or both, if possible (Bentall, 1963).

3. ***Entrance Velocity***: A generally acceptable principle of well design holds that the average entrance velocity (Q/A), based on the percentage of open area (A) of the screen and the desired yield Q, should be 0.1 foot per second or less. The hydraulic theory behind this criterion holds that at such low velocities flow is entirely laminar, thus turbulence will not contribute to well loss. However, the average entrance velocity concept may be misleading. Soliman (1965) and Li (1954) analyzed flow to a well and they showed that the entrance velocity in the upper 10 percent of a screen was about 70 times that of the lower 10 percent in an ideal aquifer. In every screened well, part of the entrance area is blocked by the screen and aquifer material or gravel pack. Depending upon the slot size and gradation of the grain in the aquifer, as much as 78 percent of the open area may be lost, although it is generally accepted that 50 percent is a more practical estimate. Furthermore, individual zones in an aquifer may have different permeabilities, and the volume of water delivered to the screen face, other factors being equal, is a function of the permeability of the adjacent aquifer. However, despite these many unknown and indeterminate variations from the average entrance velocity, the concept and practice has proved to be worthwhile in maintaining well efficiency and life. Where conditions and economics permit, the lowering of the entrance velocity to less than 0.1 foot per second, consistent with other criteria, would be advantageous.

4. ***Percentage of Open Area of Screen***: One of the major factors controlling head loss through a screen is the percentage of open area. Factors which control the percentage of open area include basic design, materials, fabrication processes, and strength requirements. In a screen of a given length and diameter, the head loss decreases rapidly with an increase in percentage of open area up to about 15 percent, less rapidly up to about 25 percent, and relatively slowly between about, 25 and 60 percent. Beyond an open

area of about 60 percent, practically no increase in efficiency is obtained. For practical purposes, a percentage of open area of about 15 percent is acceptable and easily obtained with many commercial screens, although not with perforated casing. If it is not, possible to obtain at least 15 percent of open area, other criteria may have to be modified to maintain the maximum 0.1 foot per second entrance velocity. This may be obtained by increasing the diameter or length of the screen or perforated casing used.

Peterson, et al. (1953) and Vaadia and Scott (1958) experimentally determined a relationship among the length, head loss, and diameter; percentage of open area; and the type of slot of a screen. Their findings, however, have limited usefulness under field conditions.

The percentage of open area in slotted pipe ranges from about, 1.0 percent for 0.020-inch slots to about 12 percent for 0.250-inch slots; in slotting patterns which do not seriously weaken the pipe. Punched or slotted screens have open areas between 4 and 18 percent depending upon pattern and size of slots. Open areas of louvered screens range from about 3 percent for 0.020-inch slots to about 33 percent for 0.200-inch slots. The open area of cage-type wire wound screens ranges from about 2 percent for 0.006-inch slots to as much as 62 percent for 0.150-inch slots.

5. ***Screen Slot Sizes and Patterns***: Uniform axial flow of water in a pipe is characterized by a stagnant zone at the wall of the pipe, and velocity and turbulence increase toward the center of the pipe. Conditions in a screen are different, however, because a screen performs as a header or collector in which each perforation operates as a radially directed jet. An illustration of screen slot size and pattern is shown in Figure 2.6.

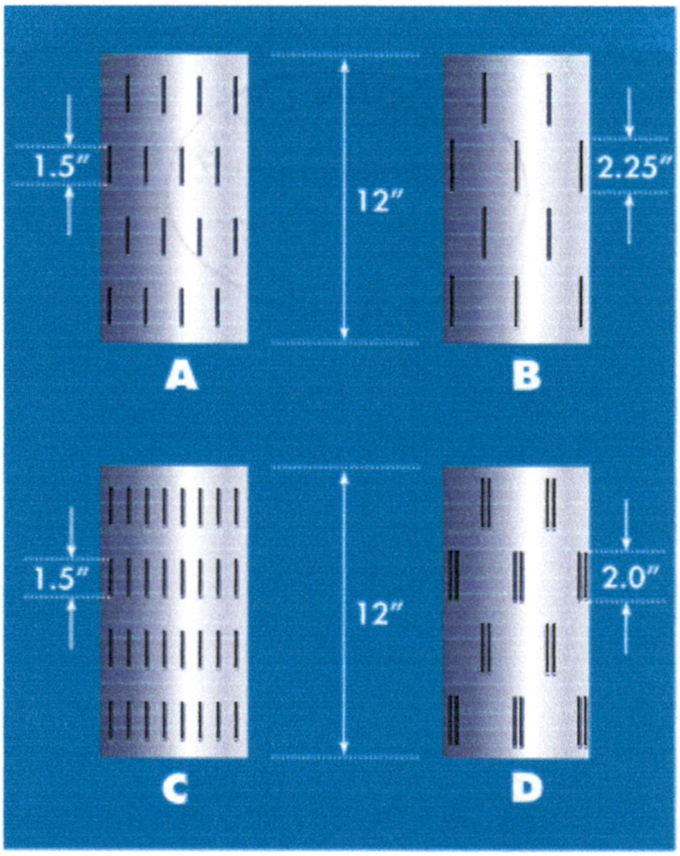


Figure 2.6: Screen Slot Size and Pattern

(http://www.gl-slotco.com/images/4slot_types.jpg)

As a result of this jet inflow, the stagnant layer is absent or only partially present and velocity of the axial flow is not uniform but, increases from the bottom of the screen to the top. This distribution of flow has not been studied thoroughly but it can be assumed that with screens of the same diameter and equal percentage of open area, the one with the smaller and more numerous slots would have lower velocity of flow through the slot and the smaller head loss. Parallel sided slots such as are found in many saw or machine perforated casings appear to be the least efficient type of orifice. In addition, they are more subject to clogging by sand grains. The thinner the edge, the more efficient the slot; thus, the V-shaped slot found in most wire-wound screens and on some perforated pipe has a small hydraulic advantage in addition to its self cleaning properties. Furthermore, a sharp, clean, smooth slot edge not only contributes to better hydraulic efficiency, but also may reduce the rate of corrosion and encrustation. The spacing of screen slots can add measurably to the convergence. With two screens having equal open area, the one with large widely spaced slots will require more convergence of flow lines and greater acceleration of the stream flow through the aquifer to the well, with a, consequent greater loss of head than would be experienced with the one having small closely spaced slots.

Use of very fine slots results in a small percentage of open area even in wire-wound screens. In addition, the small cross section of the slots results in high friction losses and may tend to promote encrustation. Slot sizes of 0.006 to 0.020 inch generally should be limited to use in small, low capacity wells. A gravel pack is advisable in large capacity wells if a slot size smaller than 0.030 inch would be required to stabilize the base material.

6. ***Gravel Packs***: The theory of gravel packs holds that surrounding the screen with a more permeable material than the aquifer as shown in Figure 2.7 increases the effective diameter of the well. Since the theoretical permeabilities of packs may be from 10 to 1,000 times as large as that of the aquifer, this is true. However, the benefit derived is questionable since tripling the effective diameter theoretically would increase the yield only about 20 percent. If the aquifer were sufficiently thick, a similar increase possibly could be obtained much more inexpensively by increasing the depth of the well. Where gravel packing is required, the grain size of the pack should be uniform and as large as possible commensurate with stabilization of the aquifer and ease of installation. The screen slot size should permit only a small percentage of the pack material to pass, and the pack should consist of firm, well rounded grains. All these factors together with a low entrance velocity contribute to better hydraulic efficiency.

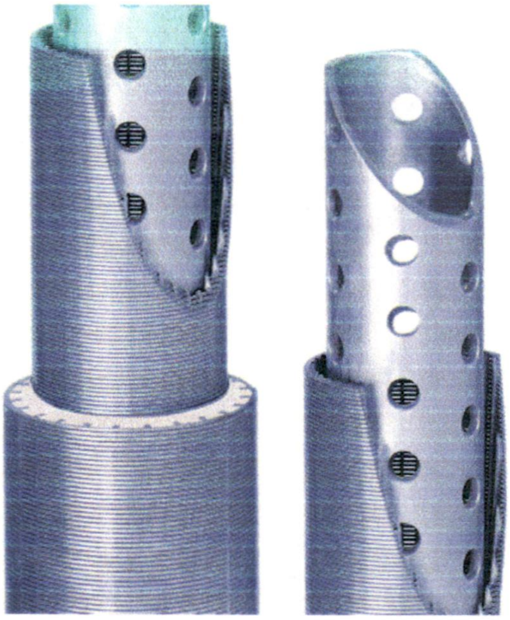


Figure 2.7: Gravel Pack

(http://www.euroslotkdss.com/images/tds-screens-attr.jpg)

7. ***Well Efficiency***: Well efficiency is a function of the loss of head resulting from flow through the screen and pack and axially in the well to the pump. Thus, in a 100 percent efficient well, all drawdown results from head losses in the aquifer and would be unrelated to the presence or design of the well. A reasonably accurate method is available for estimating the efficiency of a fully penetrating artesian well with 100 percent open holes if values of r_w and T and S of the aquifer are known. In such a well, values of the measurable drawdown s_m and t can be determined from a pumping test. By inserting the values of T, S, r_w, and t in the non equilibrium equation, the theoretical drawdown s_c can be computed. The efficiency then would be the computed drawdown, s_c, divided by the measured drawdown, s_m, times 100, or $E = (s_c/s_m) \times 100$.

If, however, the well does not have 100 percent open hole, the effects of partial penetration and anisotropy are difficult or even impossible to determine, but may have a major influence on the computed efficiency.

The problem is even greater for a well in a free aquifer. Not only is the result influenced by the value of r_w, but drawdown negates the effectiveness of 100 percent open hole even if used. Furthermore, anisotropy may have an adverse effect regardless of the percent of open hole and the effects may be compounded if the well does not fully penetrate the aquifer.

It appears, therefore, that any attempt to accurately determine well efficiency is futile unless conditions are ideal. The most practical procedure is to apply the theoretical and empirical factors accepted as being good design practice in conjunction with adequate well development and disregard theoretical well efficiency as a significant factor.

A step test analysis and determination of the apparent efficiency by the methods of Jacob (1947) and Rorabaugh (1953) may be useful in comparing variations in apparent efficiency of an individual well with time as an aid in recognizing deterioration and possible need of rehabilitation.

2.3 COLLECTOR WELL

Nowadays, collector wells have become a common abstraction to be proposed as an alternate drinking water source because one can have enough quantity and good quality of water. Radial wells are commonly used near the shore of a lake or near a river to obtain a large amount of relatively good quality water from adjacent sand or gravel beds. Radial wells also used in place of multiple vertical wells to obtain water from a relatively shallow aquifer. A radial well can be vertical central well. The central well or caisson, serves as the water collector for the water produced by the horizontal screened wells. The patented Ranney well (after the name of Leo Ranney) as shown in Figure 2.8 is an early form of collector well, usually made of cast iron and sunk in riverbank side gravels or alluvial deposits fed from the river with perforated collector tubes jacked into horizontally from the base in the most appropriate configuration, often parallel to the river.

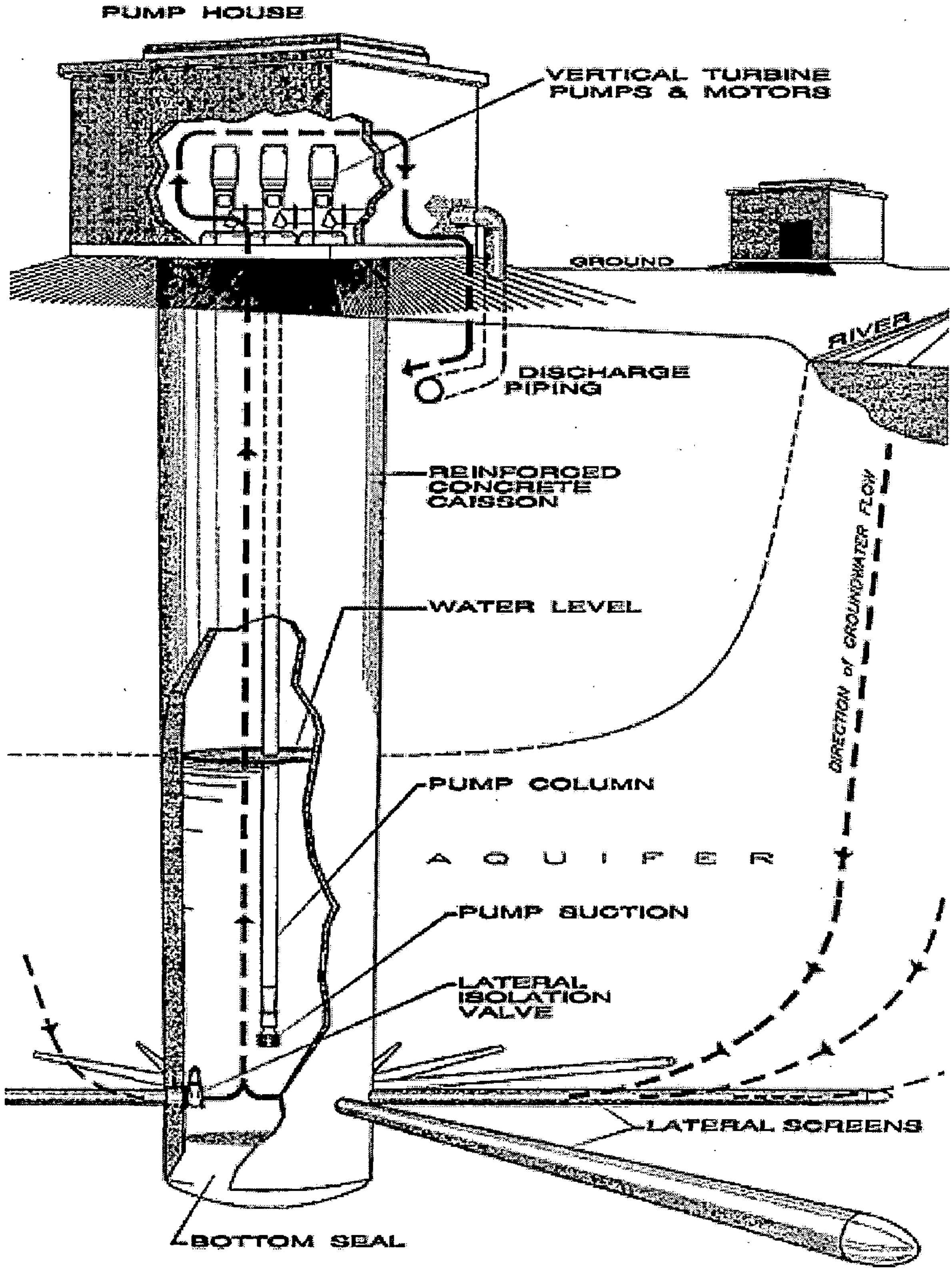


Figure 2.8: Ranney ® Collector Well

(http://www.ci.st-helens.or.us/Departments/WFF/Ranney_files/image002.gif)

Construction begins by sinking the central caisson, which is generally 5 to 6 m in diameter. The caisson is made by stacking poured in place reinforce concrete rings, each about 2 to 3 m high. The first section is formed with a cutting edge to facilitate the caisson's settling within the excavation. As soil is excavated from within the caisson, the concrete rings sink into place. Additional sections are then added and the excavation progresses. When the desired depth is reached, a concrete plug is poured to make a floor.

Horizontal wells are then constructed through wall sleeves near the bottom of the water bearing strata. The lateral may be constructed of slotted of perforated pipe or they may have conventional well screens. Each horizontal well is constructed with a gate valve located inside the caisson for subsequent dewatering or to discontinue use of individual collector wells. A super structure is erected on top of the caisson to house pumps, piping, and control.

The first RCW was installed at London, England, in 1933. Since then many municipalities throughout the world have successfully operated this type of groundwater collection system to obtain part of their water supply. If the site conditions do not restrict the use of a collector well (based upon first design of the wells or a feasibility evaluation), the capital, operation, and maintenance costs of both alternatives (a series of vertical wells versus a horizontal collector well) should be compared for resulting life-cycle costs. It is common for collector wells to have an advantage over vertical wells when operation and maintenance costs are compared for a specified period, and collector wells can also be found to be cost effective when total system costs are compared (a collector well versus a series of vertical wells that will produce the equivalent capacity with connecting pipelines, electrical service, etc).The advantages of the RCW over traditional vertical well are (Spirdonoff, 1964):

1. The horizontal perforated collector pipe (the configuration and length of which may vary) enables a large area of an aquifer to be exploited;
2. The removal of fine sand and gravel in the path of the projected collector pipe establishes an artificial aquifer of much higher permeability than the virgin soil;
3. After construction, the collector pipe simply serves as a sub drain in a filter surrounded by a circle of course gravel several feet in diameter;
4. The unrestricted access and independent control of each collector pipe permit easy regulation of flow into caisson and inspection and backwash of the collector pipe;
5. The large area of exposed perforations in the collector well causes low inflow velocities, which minimizes incrustation, clogging, and sand transport.

2.3.1 Collector Well Applications

The collector wells as ground water catchments of great capacity could be located on such places only where large quantities of withdrawn water could be restored. Preferably, they should be placed in the vicinity of a natural ground water recharge source, because it is very difficult to transfer the water a great distance through a duct filled with sand. Such places are usually adjacent to the banks of the rivers or other surface water bodies. If large quantities of ground water are required, a great number of such wells will be needed. Recharging of the underground storage with such quantities of water, amounting occasionally to several hundreds or thousand of litres per second, is possible almost exclusively from the surface streams possessing abundant discharges.

Where aquifer formations are relatively thin or limited extent, horizontal collector wells may be advantageous in maximizing the yield possible from available sites and in minimizing the number of pumping facilities needed. Obviously, where a suitable hydraulic interconnection exists between alluvial aquifer systems and an adjacent surface water source, yields can be maximized. When wells are over pumped (i.e., pumping water from the ground faster than it can be recharged), several problems arise. Over pumping results in higher infiltration velocities at the river/aquifer interface as well as amplified clogging of the interstitial space beneath the river bed, making it inaccessible for rehabilitation and restoration. These results adversely affect long-term infiltration capacities and lower the well yield.

Radial collector wells have been used for various applications through out the world. These applications are (Hunt, 2002b):

1. Riverbank Filtration (RBF)

   Radial collector wells are generally installed near a river as a part of Riverbank Filtration (RBF) system to increase the potential yield and the quality of the water. RBF is generally performed when the quality of water in the rivers not suitable for water supplies due to intermittent or chronic pollution. The riverbed sediments and aquifer materials provide 'slow-rate filtration' and the recovered water is of higher and more consistent quality than water drawn directly from the river. RBF provides passive exposure to various processes such as adsorption, reduction, physiochemical filtration, and biodegradation. It produces water that is relatively consistent in quality and easier to treat to higher levels of finished quality.

2. Seawater (beach) collector wells

   Seawater collector wells as shown in Figure 2.9 are used to produce filtered seawater for specialized purposes, such as reverse osmosis or cooling. The central pump station caisson can be installed some distance away from the beach, with the lateral well screens projected out horizontally into the beach deposits. In this way, suspended debris and surface-water organisms are typically filtered out before water reaches the pumps, providing pre-filtration of raw water to improve the quality of water entering the treatment plant or for point-of-use.

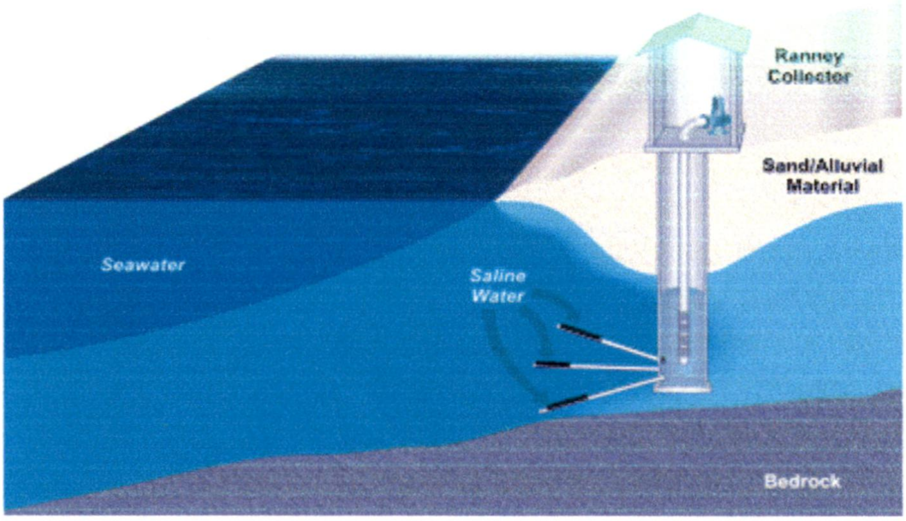


Figure 2.9: Seawater collector well

(http://www.scwd2desal.org/images/horizontal_well.gif)

3. Groundwater collector wells

   Groundwater collector wells consist of a central reinforced concrete caisson that serves as a well pump station. Well screens are projected out horizontally from within the caisson into the surrounding aquifer deposits, and are projected into the most hydraulically efficient zone within the aquifer to maximize yield. If more than one aquifer is identified, well screens can be projected into each zone. Where alluvial deposits exist adjacent to a surface-water source, such as a river, lake, or even the ocean, well screens can be projected into deposits that are hydraulically connected to the surface water to achieve natural filtration through RBF processes.

4. Artificial recharge wells/aquifer storage and recovery wells

   Horizontal collector wells have been used for the artificial recharge of aquifers as shown in Figure 2.10. Horizontal collector well can be used to recharge treated city water into the alluvial aquifer to replenish declining groundwater levels in the downtown area, which was caused by many years of over-pumping. In RBF, horizontal collector well can be used to recharge the water derived from a shallow surficial aquifer past a confining layer into a lower extensive aquifer for storage using passive recharging through two tiers of lateral well screens installed above and below the confining layer. Stored water was then pumped from the lower aquifer into the system. Lake water can be passively recharged into a local aquifer system using an intake-collector well combination unit to restore groundwater levels to support higher capacities for other wells installed in the local aquifer.

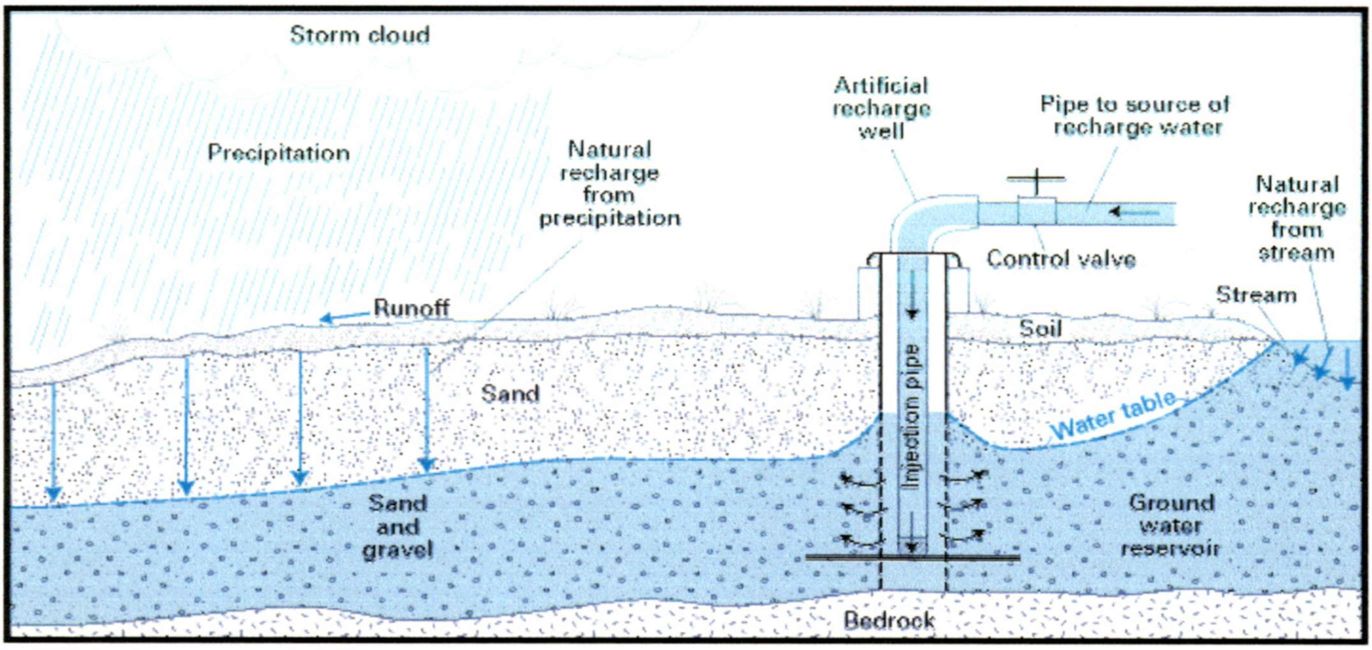


Figure 2.10: Artificial recharge well

(http://pubs.usgs.gov/gip/gw/recharge.html)

2.3.2 Collector Well Performance Parameters

The importance of collector wells is decided by evaluating the performance in terms of specific capacity of the well and the quality of water. The collector well can be placed under riverbed or adjacent to the river. For collector well located under riverbed, the yield will be more but the quality of water may not be sufficient. Inversely, the collector well placed adjacent to the river will have fewer yields but the quality of water is higher. Following are the parameters which influence the performance of a collector well:

a. Aquifer characteristics

Volume: The volume of the aquifer which is a function of the saturated thickness, width, and length of the aquifer, is important because it determines the quantity of water available for abstraction from a well in the absence of recharge. The length of the aquifer is not distinguishable in alluvial aquifers where the aquifer follows the river path. Therefore, the saturated thickness and width of the aquifer alone will be used to characterize the quantity of water available.

Transmissivity: The transmissivity is the rate of flow per unit width of aquifer through the entire thickness of the aquifer due to a unit hydraulic gradient and is a function of the conductivity of aquifer medium and the saturated thickness of the aquifer.

Storativity or Storage coefficient: The specific yield of an aquifer is the amount of water that is released per unit area for a unit drawdown in the phreatic surface in an unconfined aquifer. The storage coefficient is the amount of water released from a confined aquifer per unit area for a unit reduction in potentiometric level.

Porosity of the aquifer: The porosity is the ratio of the volume of voids to the total volume of the aquifer material. It influences the velocity at which water moves through an aquifer under a given hydraulic gradient.

b. Collector well location

The collector well can be located under riverbed or adjacent to the river. The production of collector well under riverbed is much higher than adjacent to the river but the quality of water may be poor. The scouring depth should be considered when placing the collector well under riverbed. In locating the collector well adjacent to a river or water body, it is needed to consider the river geometry, the width and depth of the river which impacts the ability of the river to recharge the aquifer and influences severity of clogging. Collector well can be placed in straight river sections or along the inside of the river bend as can be shown in Figure 2.11 below.

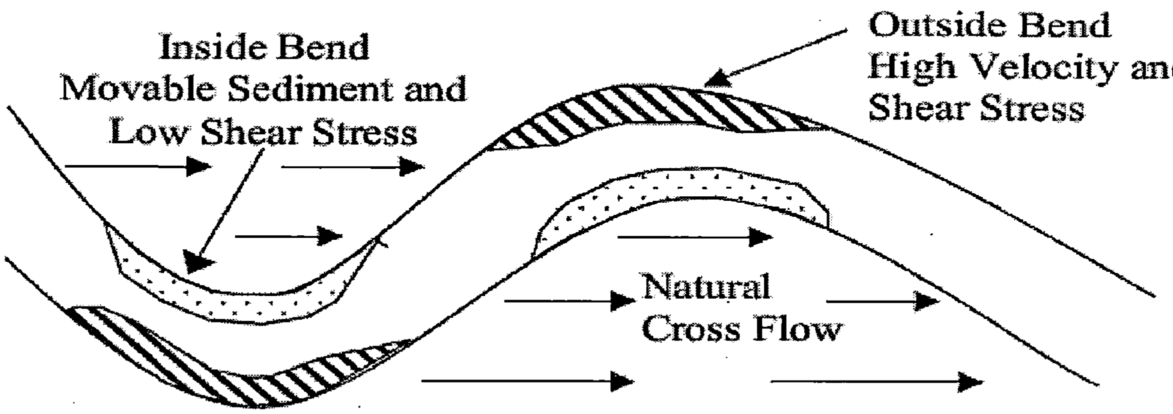


Figure 2.11: River Meander (Tiffany, 2006)

c. Riverbed Characteristics

The riverbed characteristics influence the ability of the river to recharge the aquifer. Riverbed hydraulic conductivity and grain size distribution should be considered especially when planning to locate a collector well under riverbed. Riverbed hydraulic conductivity is used to quantify the ease at which water can flow through the riverbed. The grain size distribution of the riverbed can be used when a direct measure of the hydraulic conductivity of the riverbed is not available. The grain size distribution can be quantified by estimating characteristic sizes such as the d_{10}, d_{50}, and d_{90}.

d. Collector well details

The parameters which are important in the collector well details are the permissible drawdown in the well, dimension of collector pipe in term of length and diameter, perforated portion of collector pipe corporate with the percentage of perforation, vertical location of the collector pipes, orientation and numbers of collector pipe.

e. Water quality

The quality of water of a collector well is affected by the quality of surface water and groundwater. The water quality has four characteristics, physical, chemical, biological, and radiological. The physical characteristics properties include temperature, turbidity, color, taste and odor. The chemical characteristics can be divided into inorganic (pH, hardness, dissolved oxygen, dissolved solids, and electrical conductivity) and organic. Biological characteristics correspond to the plants and animals, both dead and alive, which are found in water. They include viruses, bacteria, and other forms of aquatic life, as well as animal and plant contaminants. Radionuclides can occur in water supplies either from natural sources or as a result of human activities. Naturally occurring radionuclides include radium 226, radium 228, and radon.

2.3.3 Collector Well Casing and Screens

To keep loose sand and gravel from collapsing into the borehole, it is necessary to use well casing and screen. The screen supports the borehole walls while allowing water to enter the well. Unslotted casing is placed above the screen to keep the rest of the borehole open and serve as housing for pumping equipment. Well screens should have as large a percentage of non-clogging slots as possible, be resistant to corrosion, have sufficient strength to resist collapse, be easily developed and prevent sand pumping (Driscoll, 1986). These characteristics are best met in commercial continuous-slot (wire wrap) screens consisting of a triangular-shaped wire wrapped around an array of rods. If these screens are available, conduct a sieve analysis on samples on the water-bearing formation and select a slot size which will retain 40-60 percent of the material.

While wire wrap screen should be used whenever possible, it may be exorbitantly expensive and/or not available. Most wells are constructed using PVC casing and screen. Grey PVC pipe, which is available in most countries, is relatively cheap, corrosion resistant, lightweight, easy to work with and chemically inert.

Important design criteria for collector well include the following (Driscoll, 1986; Ray, 2002):

1) Entrance velocity through the screen slot openings should be 0.03 m/ sec or less.
2) Axial velocity inside the screen should be 0.9 m/sec or less, so that the head loss in a collector tube will be less than 0.3 m.
3) Screen slot size is predicated on the grain-size distribution of the filter pack; and should always retain 100 percent of the filter pack.

There are three standard methods for installing lateral well screens (Hunt, 2002a), original method using perforated pipe sections, projection pipe method (developed by Dr. Hans Fehlmann), and German method for installing an artificial gravel-pack filter around well screens. This multi-design capability allows the lateral well screens to be matched most efficiently with the formation materials to be screened. Figure 2.12 below shows the three methods (Hunt, 1985).

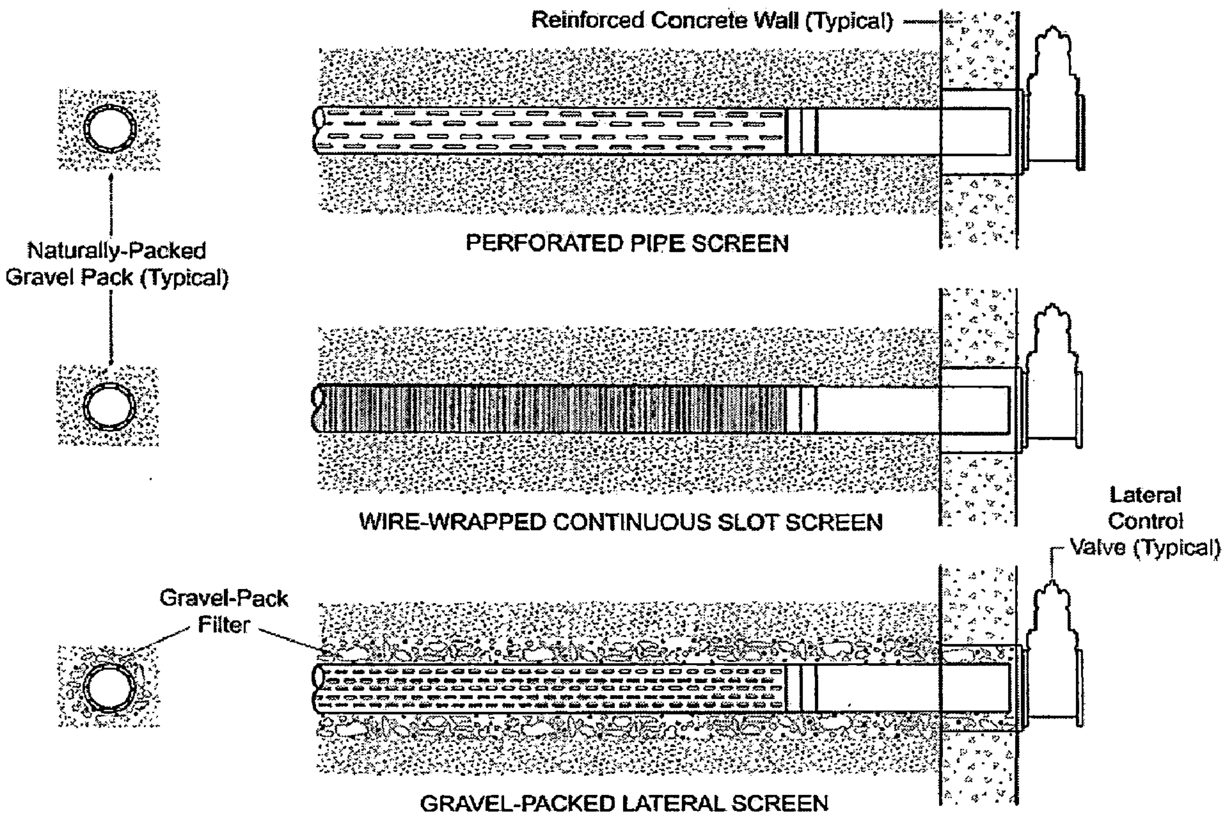


Figure 2.12: Different types of well screen completion

2.4 FLOW TO A COLLECTOR WELL

Estimation of flow to a collector well is a complex problem. Even under simplified conditions, its estimation is more complex than in case of a vertical well. Since, the water enters through a number of horizontal screened pipes (laterals), analytical solutions of flow to a collector well are base don the theory of flow to a horizontal pipe. Estimations of flow to a lateral can be based on two fundamental assumptions, i.e., (i) the total discharge through a lateral is uniformly distributed along its entire length, i.e., the uniform flux boundary exist along the laterals, and (ii) that the head along the lateral is uniform, i.e., Dirichelt type boundary condition exist along the laterals.

For simplification, the analytical studies generally analyse 2D groundwater flow to a collector well. The flow domain of a collector well in a thin aquifer near a stream can be consider as

2.5 CONCLUSIONS

From the literature review on the subject, it is clear that water is very important for human life specially for drinking purpose. The importance of drinking water is immeasurable and the health benefits of drinking water are innumerable, therefore, sustainable drinking water sources are needed. Groundwater can provide adequate quantity and high quality of water, thus can be used as a sustainable source of drinking water. Groundwater conventionally is abstracted by using vertical well. Nowadays, collector wells have become a common abstraction structure as one can have enough quantity and good quality of water. Collector wells are commonly used near the shore of a lake or near a river to obtain a large amount of relatively good quality water from adjacent sand or gravel beds. Radial collector wells are also used in place of multiple vertical wells to obtain water from a relatively shallow aquifer. It is observed that little analytical works have been carried out on the flow to a radial collector well located near a river. A radial collector well consists of group of horizontal pipe, hence from theory of flow to a horizontal pipe, total flow to a radial collector well can be estimated. From the literature review, it is clear that there are two basic approaches to find solution of flow to a horizontal well. These two approaches are: either constant flux or constant head boundary condition persists along the horizontal well. Hence, it is desirable to investigate the performance of a collector well. In the next chapter, the modeling of collector well using popular software MODFLOW has been discussed.

CHAPTER III

COLLECTOR WELL MODELING USING MODFLOW

3.1 INTRODUCTION

Groundwater distribution and flow can be studied by means of analytic, field, and model techniques. Model studies and numerical analysis methods may have useful applications when direct analysis and adequate field investigation are not possible.

Groundwater models can be grouped into four general types: sand, electrical, viscous fluid, and membrane. Of these, only the sand model represents a true model in that both aquifer and model involve flow through porous media. The other models are analogies of groundwater flow. Sizes and shapes of ground water models are determined by the particular purpose and type of model. Models of hydrologic interest are designed to represent aquifers and their boundaries.

Numerical models can also be considered to study groundwater flow and with the computer assistance, then the methods are very helpful. The finite difference method (FDM) is a numerical method that is quite versatile, relatively simple, and currently the most widely used method for flow modeling. The current standard FDM program is MODFLOW, thus, it is desired to evaluate the performance of a collector well using MODFLOW.

3.2 MODFLOW

The performance of a collector well can be evaluated by using software like MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996) that was first published in 1984. MODFLOW simulates steady and unsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated.

In MODFLOW, the ground water flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. In plan view the blocks are made from grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is written for each block, called a cell. Several solvers are provided for solving the resulting matrix problem. In this software the user can choose the best solver for particular problem. Flow rate and cumulative volume balances from each type of inflow and outflow are computed for each time step.

In this study, Processing Modflow for Windows version 5.3.0, which was developed by Wen-Hsing Chiang and Wolfgang Kinzelbach, and the user's manual (Chiang (2005)) is used. This software is available on http://www.pmwin.net/pmwin5.htm. This software offers a totally integrated simulation system for modeling groundwater flow and transport processes with MODFLOW-88, MODFLOW-96, PMPATH, MT3D, MT3DMS, MOC3D, PEST and UCODE.

Processing Modflow comes with a professional graphical user-interface, the supported models and programs and several other useful modeling tools. The graphical user-interface allows user to create and simulate models with ease and fun. It can import DXF- and raster graphics and handle models with up to 1,000 stress periods, 80 layers and 250,000 cells in each model layer.

3.2.1 Model Formulation

Flow to a collector well can be estimated by using mathematical model. For developing a mathematical model of a collector well flow system one should formulate the general flow equations through porous media. General flow equations are the differential equations that are driven from the physical principles governing the flow process through the collector well. In groundwater flow, Darcy's law and mass balance equations are the two fundamental equations. For an isotropic, steady state of one-dimensional saturated flow, Darcy's Law can be expressed as follows:

$$Q_x = -K_x \frac{dh}{dx} A; q_x = \frac{Q_x}{A}; q_x = -K_x \frac{dh}{dx} \tag{3.1}$$

Groundwater is not constrained to flow only in one direction, but may flow in complex three-dimensions. Therefore, Darcy's Law for three-dimensional flow is

$$q_x = -K_x \frac{\partial h}{\partial x}; q_y = -K_y \frac{\partial h}{\partial y}; q_z = -K_z \frac{\partial h}{\partial z} \tag{3.2}$$

The *x, y, z* coordinate system can have any orientation, but as a convention *z* is represented as vertical and *x* and *y* as horizontal axes in this study.

In a typical mass balance or continuity analysis, the net flux of mass through the boundary of an element is equated to the rate of change of mass within the element. For steady state, the mass flux into the element is same as that of the mass flux out, which means there is no change in the mass of water stored within the element. Hence, the continuity condition for one dimensional flow can be simplified as:

$$\frac{\partial q_x}{\partial x} = 0 \tag{3.3}$$

Substituting the q_x as given by Darcy's law, the general equation of steady state three-dimensional flow in isotropic domain is:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (3.4)$$

Development of the groundwater flow equation in the finite difference form follows the application of continuity equation: the sum of all flows into and out the cell must be equal to the rate of change in storage within the cell (McDonald and Harbaugh, 1988). Under the assumption that the density of groundwater is constant, the continuity equation expressing the balance of flow for a cell is:

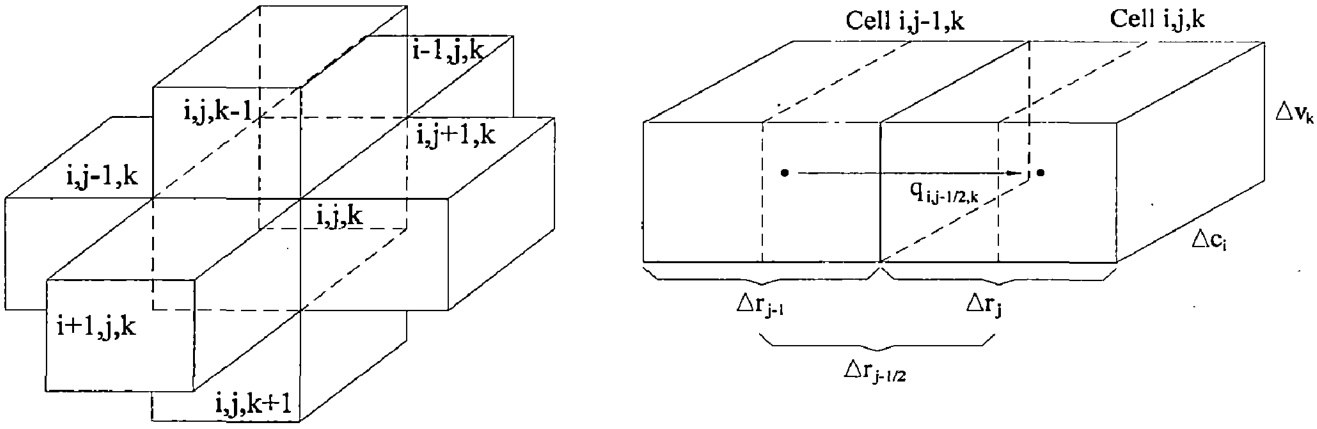
$$\sum Q_i = S_S \frac{\Delta h}{\Delta t} \Delta V \qquad (3.5)$$

where Q_i is a flow rate into the cell (L^3T^{-1}), S_s is the specific storage of the porous material (L^{-1}); ΔV is the volume of the cell (L^3); and Δh is the change in head (L) over a time interval of the length Δt (T).

Figure 3.1a depicts a cell i, j, k and six adjacent aquifer cells i-1, j, k; i+1, j, k; i, j-1, k; i, j-+, k; i, j, k-1; and i, j, k+1. To simplify the following development, flows are considered positive if they are entering cell i, j, k; and the negative sign usually incorporated in Darcy's law has been dropped from all terms. Following these convention, flow into cell i, j, k in the row direction from cell i,j-1,k as shown in Figure 3.1b, is given by Darcy's law as shown in Equation (3.1) as:

$$Q_{i,j-\frac{1}{2},k} = KR_{i,j-\frac{1}{2},k} \Delta c_i \Delta v_k \frac{\left(h_{i,j-1,k} - h_{i,j,k}\right)}{\Delta r_{j-\frac{1}{2}}} \qquad (3.6)$$

where $h_{i,j,k}$ is the head at node i,j,k and $h_{i,j-1,k}$ that at node i,j-1,k (L); $Q_{i,j-1/2,k}$ is the volumetric fluid discharge through the face between cells i,j,k and i,j-1,k (L^3T^{-1}); $KR_{i,j-1/2,k}$ is the hydraulic conductivity along the row between nodes i.j.k and i,j-1,k (LT^{-1}); $\Delta c_i \Delta v_k$ is the area of the cell faces normal to the row direction (L^2); and $\Delta r_{j-½}$ is the distance between nodes i,j,k and i,j-1,k (L).



(a) (b)

Figure 3.1: (a) Cell i,j,k and indices for the six adjacent cells, (b) Flow into cell i,j,k from cell i,j-1,k (McDonald and Harbaugh, 1988)

The finite difference approximation for any cell (i,j,k) in the grid may be obtained as:

$$CR_{i,j-½,k}(h_{i,j-1,k} - h_{i,j,k}) + CR_{i,j+½,k}(h_{i,j+1,k} - h_{i,j,k}) + CC_{i-½,j,k}(h_{i-1,j,k} - h_{i,j,k}) + CC_{i+½,j,k}(h_{i+1,j,k} - h_{i,j,k}) + CV_{i,j,k-½}(h_{i,j,k-1} - h_{i,j,k}) + CV_{i,j,k+½}(h_{i,j,k+1} - h_{i,j,k}) + P_{i,j,k}\,h_{i,j,k} + Q_{i,j,k} = SS_{i,j,k}(\Delta r_j\ \Delta c_i\ \Delta v_k)\ \Delta h_{i,j,k} / \Delta t \qquad (3.7)$$

where $CC_{i-½,j,k}$ is conductance in column j and layer k between modes i-1,j,k and i,j,k; $CR_{i,j-½,k}$ conductance in row i and layer k between nodes i,j-1, k and i,j,k; $CV_{i,j,k-½}$ conductance in row i and column j between modes i,j,k-1 and i,j,k (L^2T^{-1}); $h_{i,j,k}$ the head in cell i,j,k (L); $P_{i,j,k}$ certain constant for cell i,j,k (L^2T^{-1}); $Q_{i,j,k}$ flow rate into cell i,j,k (L^3T^{-1}); $SS_{i,j,k}$

specific storage of cell i,j,k (L^{-1}); $\Delta r_j \Delta c_i \Delta v_k$ volume of cell i,j,k is recent in time (L^3); $\Delta h_{i,j,k}$ the finite different approximation for the derivative of head with respect to time Δt (LT^{-1}).

3.2.2 Model Simulation

By using the help of groundwater software, MODFLOW, the simulation for evaluating the performance of a collector well can be done. In MODFLOW, the parameters which are being considered are the grid size, layer type, boundary condition, layer thickness, initial head, hydraulic conductivity, and effective porosity. The multilayer approach by discretizing the aquifer vertically in a number of layers is used to simulate ground water flow to a collector well. At the level of the collector pipes/ laterals of the collector well, the thickness of the layer is considered as that of the diameter of the lateral and the lateral is modeled with constant head. For modeling number of laterals, use of lay out map in the form of AUTOCAD file (*.dfx) is very helpful as there is limitation in the number of grid and memory usage will be high during the simulation. As the map is used in the model, assigning the grid for laterals can be carried out by using zone input type. The flow is computed with a standard finite-difference scheme by using MODFLOW.

For estimating the flow into a collector well the flowchart as shown in Figure 3.2 is followed. For more detail, following are the steps in modeling a collector well using MODFLOW:

1. Create a new model

To create a new model, choose **New Model** from the **File** menu. A **New Model** dialog box appears. Select a folder for saving the model data, such as C:\PM5DATA\SAMPLE, and type the file name WELL for the model then click **OK** as shown in Figure 3.3. PMWIN takes a few seconds to create the new model. The name of the new model name is shown in the title bar.

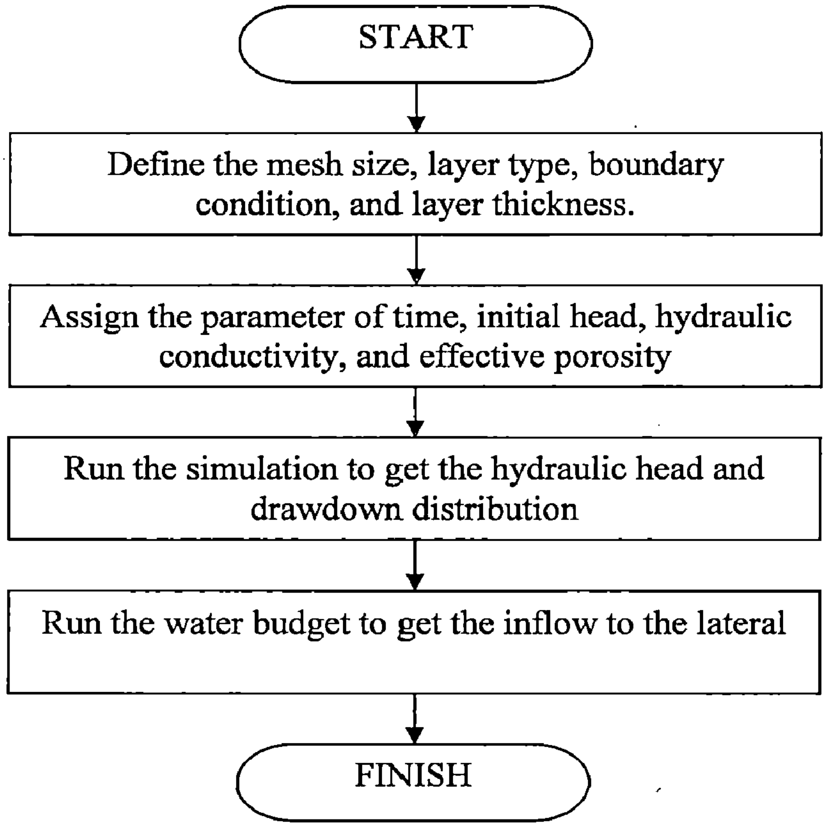


Figure 3.2: Flowchart

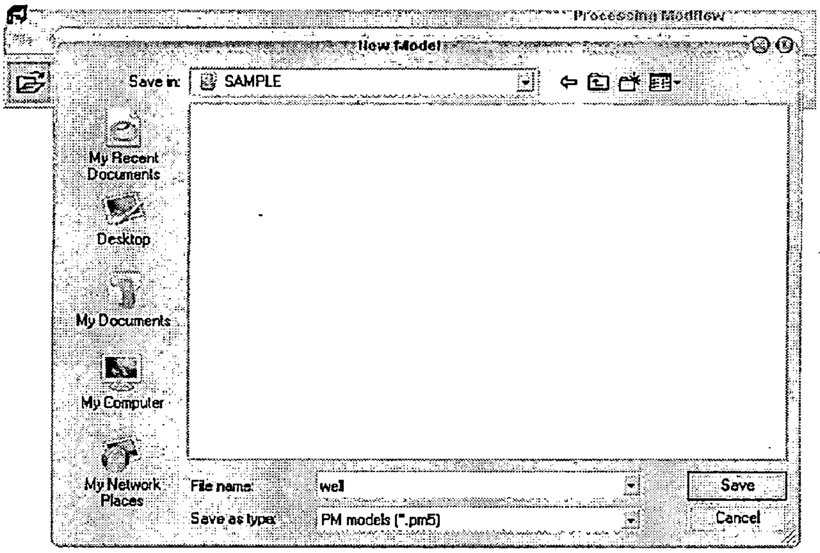


Figure 3.3: A New Model dialog box

2. Assign model data

The second step in running a flow simulation is to generate the model grid (mesh), specify boundary conditions, and assign model parameters to the model grid. To generate the model grid choose **Mesh Size** from the **Grid** menu. Enter respective data in The **Model Dimension** dialog box which consists of number of layers, number of columns and rows, and size of columns and rows. The radius on an island R is 50 m, then takes R+10 m as constraint boundary of the mesh size to be considered as a model area and at least 5 layers are assigned as shown in Figure 3.4. Click **OK** and the model can be shown in Figure 3.5, then choose **Leave Editor** from the **File** menu. Decretise the model grid into variable grid size so that the cells which are considered as a collector well is similar with the diameter of collector pipe d = 0.5 m. This can be done with the help of .DFX map from AUTOCAD. To load the map choose **Option** < **Maps** or Ctrl+M.

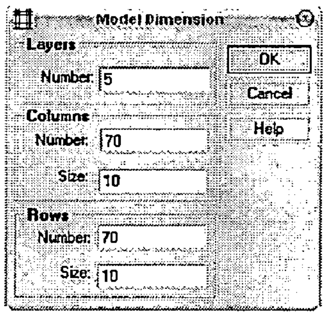


Figure 3.4: The Model Dimension dialog box

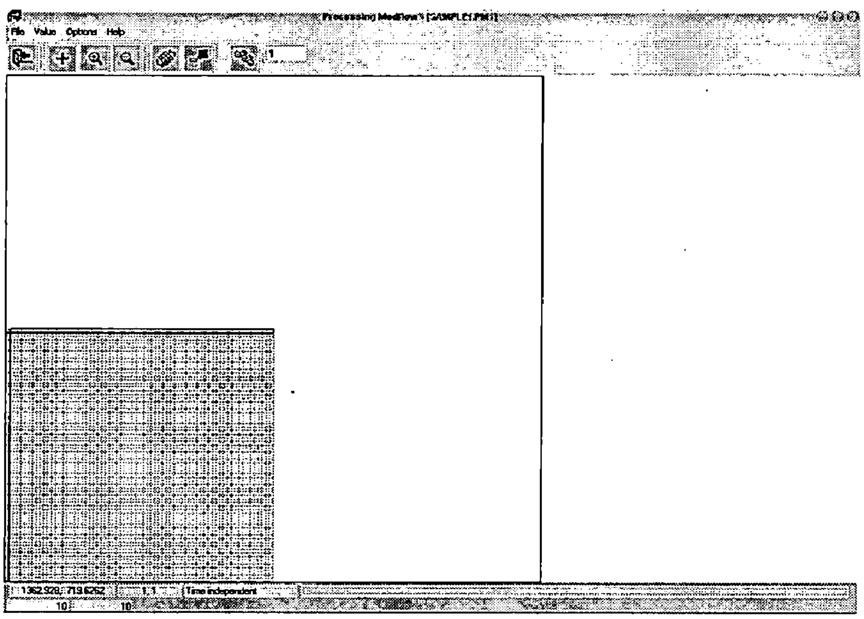


Figure 3.5: The generated model grid

To assign the type of layers choose **Layer Type** from the **Grid** menu. Assign the layer type to be confined aquifer and for the other parameter we take the default as shown in Figure 3.6. Click **OK.**

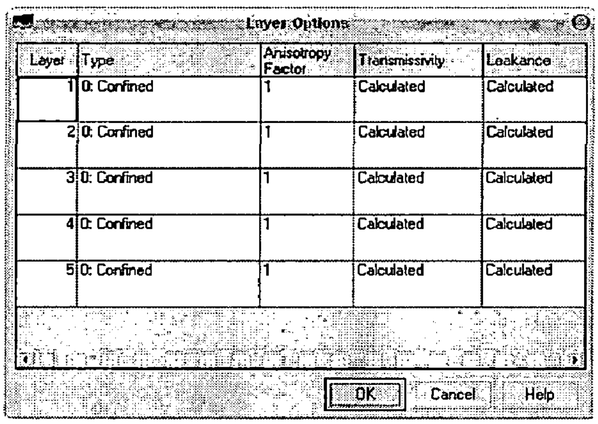


Figure 3.6: The Layer Option dialog box

To assign the boundary condition to the flow model choose **Boundary Condition** < **IBOUND (Modflow)** from the **Grid** Menu. Use 1 for an active cell, -1 for a constant-head cell, and 0 for an inactive cell. Assign the river as a constant head of (h_r) for all the layers, the lateral in layer 3 as a constant head of (h_w), and the blind portion in the lateral as an inactive cell as can be shown in Figure 3.7. Choose **Leave Editor** from the **File** menu.

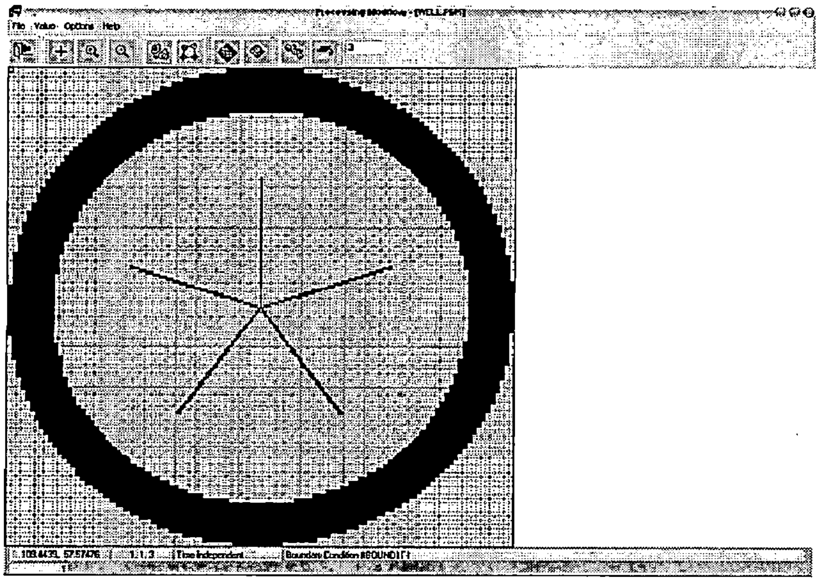


Figure 3.7: The Boundary Condition plan view

To specify the elevation of the top of model layers choose **Top of Layers (TOP)** from the **Grid** menu. The elevation of the first layer is the thickness of the aquifer and the elevation of other layers are determined by the diameter and vertical location of collector pipe. Choose **Leave Editor** from the **File** menu. To specify the elevation of the bottom of model layers choose **Bottom of Layers (BOT)** from the **Grid** menu. As the elevation of the aquifer top has been specified, it can be used for the elevation of the aquifer bottom by click **Yes.** Choose **Leave Editor** from the **File** menu.

To specify the temporal parameters choose **Time...** from the **Parameters** menu. Enter the time of **Length** of the first period. Consider this model into steady state condition with unit of time in day. Click **OK** to accept the other default values.
To specify the initial hydraulic head choose **Initial Hydraulic Heads** from the **Parameters** menu. We assign the value of (h_r) for all the cells and (h_w) for the cells which are determined as collector well. Choose **Leave Editor** from the **File** menu.

To specify the horizontal hydraulic conductivity choose **Horizontal Hydraulic Conductivity** from the **Parameters** menu, assign the aquifer conductivity (k) for all cell, and equivalent conductivity (K_e) for the cells which are assigned as collector well. Choose **Leave Editor** from the **File** menu. To specify the vertical hydraulic conductivity choose **Vertical Hydraulic Conductivity** from the **Parameters** menu. Follow the same way as horizontal conductivity. Choose **Leave Editor** from the **File** menu. To specify the effective porosity choose **Effective Porosity** from the **Parameters** menu. Choose **Leave Editor** from the **File** menu.

3. Perform the flow simulation

To perform the flow simulation choose **MODFLOW<Run...** from the **Models** menu. Select the **Modflow version** as MODFLOW96 + INTERFACE TO MT3D96 AND LATER. Check all in the **Generate** column as can be shown in Figure 3.8. Click **OK**.

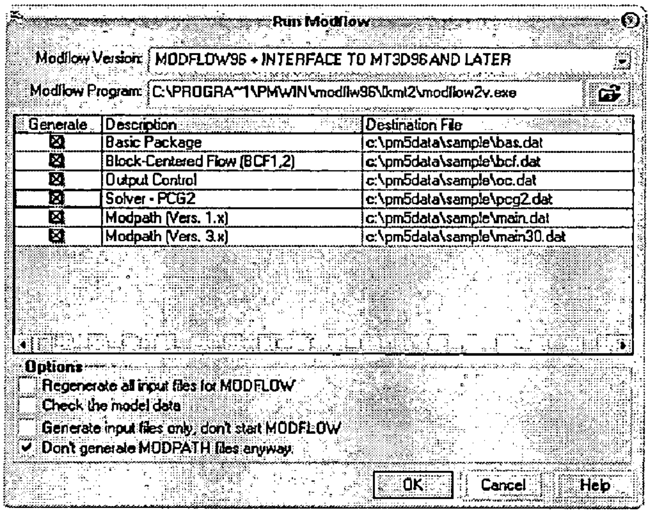


Figure 3.8: The Run Modflow dialog box

4. Check simulation results

During a flow simulation, MODFLOW writes a detailed run record to the listing file *path*\OUTPUT.DAT, where *path* is the folder in which your model data are saved. If a flow simulation is successfully completed, MODFLOW saves the simulation results in various unformatted (binary) files. Prior to running MODFLOW, the user may control the output of these unformatted (binary) files by choosing **Modflow<Output Control** from the **Models** menu

5. Calculate subregional water budget

To calculate subregional water budgets Choose **Water Budget** from the **Tools** menu. Click **Zones** as can be shown in Figure 3.9. Assign the cells which are desired to quantify the flow, for example, the entire cell in zone 0 and the collector well cells as zone 1.

Choose **Leave Editor** from the **File** menu. Click **OK** in the **Water Budget** dialog box. Run the file **WATERBDG.DAT** in the model directory to find the flow to the collector well.

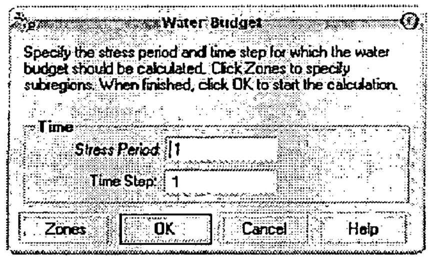


Figure 3.9: The Water Budget dialog box

6. Produce output

   To produce the outputs choose **Results Extractor...** from the **Tools** menu. To generate a contour map of the calculated hydraulic heads choose **Presentation** from the **Tools** menu. Choose **Value** < **Result Extractor** < **Read** < **Apply** to assign the hydraulic head at layer 3 (location of collector well) as can be shown in Figure 3.10. Choose **Leave Editor** from the **File** menu.

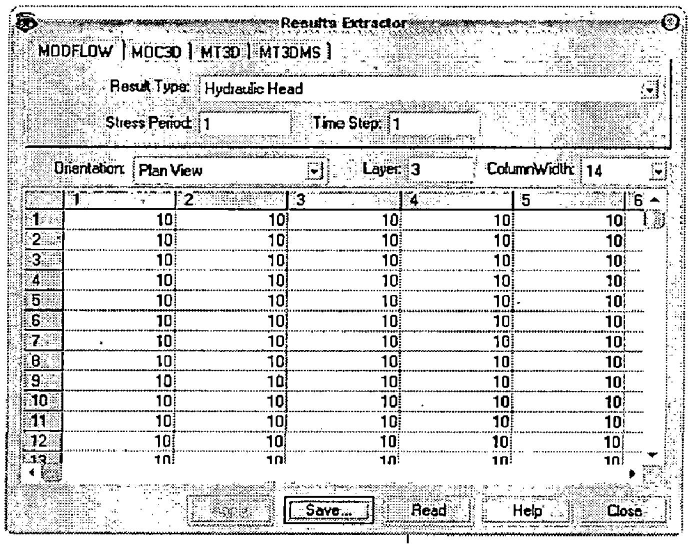


Figure 3.10: The Result Extractor dialog box

To delineate flow lines choose **PMPATH (Pathlines and Contours)** from the **Models** menu. PMWIN calls the advective transport model PMPATH and the current model will be loaded into PMPATH automatically. PMPATH uses a "grid cursor" to define the column and row for which the cross-sectional plots should be displayed. One can move the grid cursor by holding down the Ctrl-key and click the left mouse button on the desired position. To make the flow line, click Set Particle [+], then place the particle at the desire cell, in this case along the collector well. Click Run Particle to show the flow line. To show the hydraulic head and flow line Click Option < Environment or Ctrl+E, choose contours. The flow line and hydraulic head can be shown as presented in Figure 3.11.

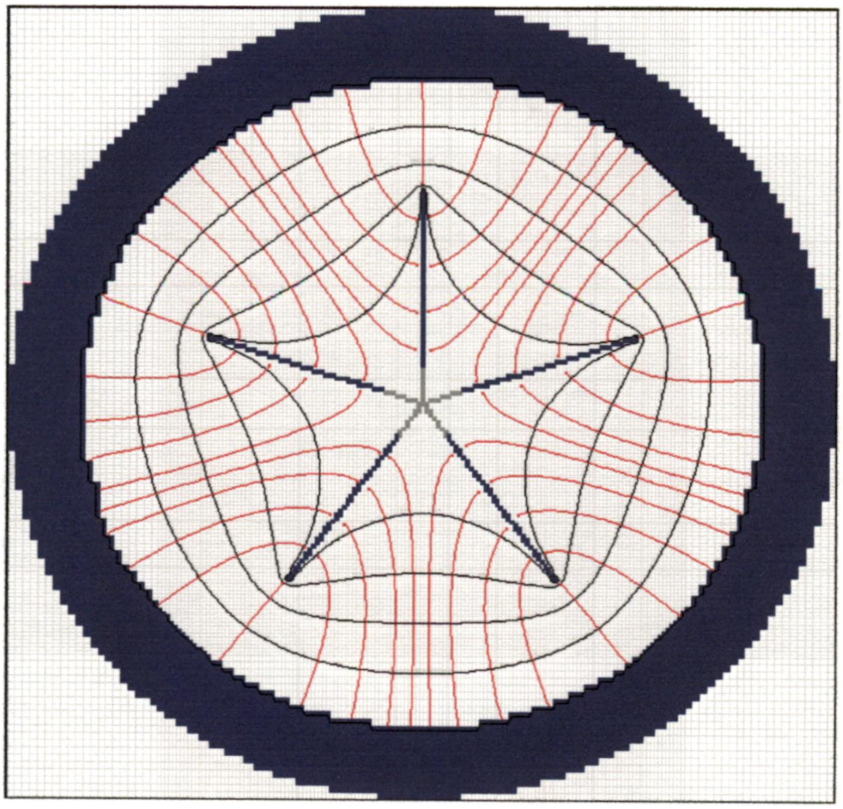


Figure 3.11: The hydraulic head and flow line

3.3 EQUIVALENT CONDUCTIVITY

Geometric configuration of the collector pipe with its given opening (defined by slot size and perforation percentage) is considered as a parameter that affects the performance of collector well. Following conditions which have been illustrated in Figure 3.12 is considered to model these parameters:

i) Flow through porous media without pipe:

In this condition, the conductivity in the cell (k_c) of lateral is same as the conductivity of aquifer (k), inflow to the lateral is calculated by following the Darcy's law as:

$$Q = k\frac{h_{(i,j,k+1)} - h_{(i,j,k)}}{\Delta z} \times \Delta x \times \Delta y \tag{3.8}$$

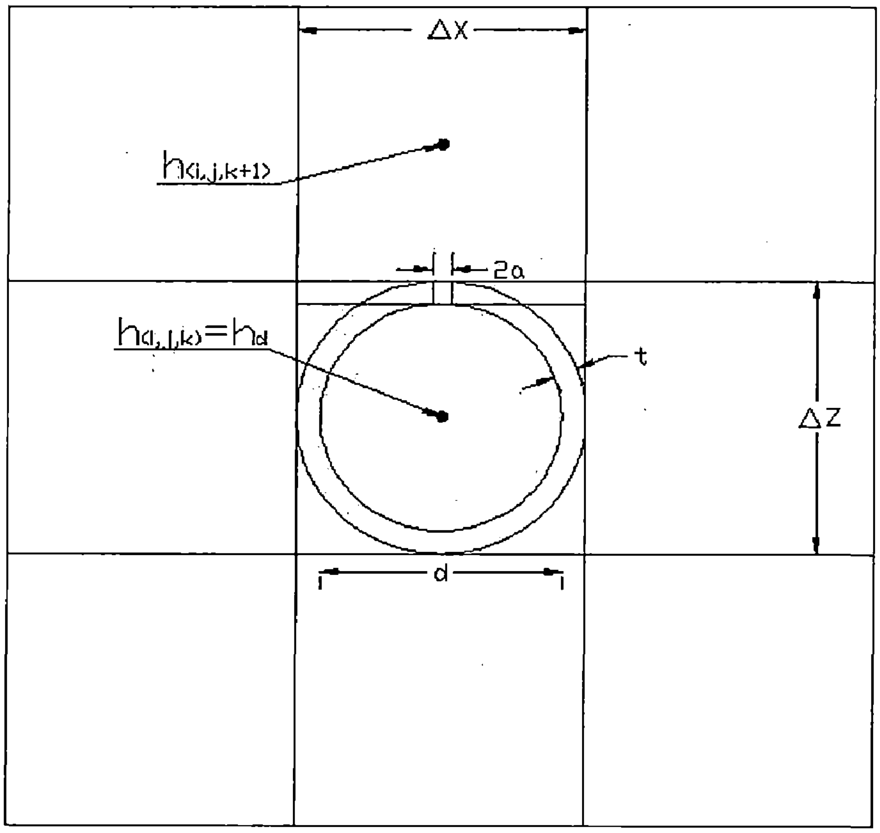


Figure 3.12: Layout of pipe/lateral

ii) Flow through porous media with pipe:

In this condition, the conductivity in the cell of lateral is governed by the thickness of pipe (t), the slot opening size (a), and the percentage perforation (p), and can be written as

$$k_c = \left[\frac{(0.5 \times \Delta z) + t}{\frac{(0.5 \times \Delta z)}{k} + \frac{t}{k_0}} \right] \tag{3.9}$$

where, slot conductivity (k_0) for steady flow with the Dupuit assumptions, can be written as :

$$k_0 = \frac{a^2 g}{3\upsilon} \tag{3.10}$$

where, g is acceleration due to gravity, and υ is fluid kinematic viscosity.

In this model, circular pipe has been used but MODFLOW allows a rectangular discretisation, so flow through area ΔxΔy ($Q_{\Delta x \Delta y}$) to lateral is calculated as:

$$Q_{\Delta x \Delta y} = p \times \left[\frac{(0.5 \times \Delta z) + t}{\frac{(0.5 \times \Delta z)}{k} + \frac{t}{k_0}} \right] \times \left[\frac{h_{(i,j,k+1)} - h_d}{\frac{\Delta z}{2} + t} \right] \times \frac{\pi \times d}{4 \times \Delta x} \times \Delta x \times \Delta y \tag{3.11}$$

The value of t will be small in comparison to Δz/2. Hence, Δz/2 + t $\simeq$ Δz/2. After rearranging the equation (3.11), the inflow through area ΔxΔy to lateral will be:

$$Q_{\Delta x \Delta y} = \underbrace{p \times \left[\frac{(0.5 \times \Delta z) + t}{\frac{(0.5 \times \Delta z)}{k} + \frac{t}{k_0}} \right] \times 2 \times \frac{\pi \times d}{4 \times \Delta x}}_{\text{conductivity}} \times \underbrace{\left[\frac{h_{(i,j,k+1)} - h_d}{\Delta z} \right]}_{\text{gradient}} \times \underbrace{\Delta x \times \Delta y}_{\text{area}} \tag{3.12}$$

Comparing with the inflow equation for condition without pipe (3.8), the equivalent conductivity for the cell of lateral (K_e) can be estimated as

$$K_e = p \times \left[\frac{(0.5 \times \Delta z) + t}{\frac{(0.5 \times \Delta z)}{k} + \frac{t}{k_0}} \right] \times \frac{2 \times \pi \times d}{4 \times \Delta x} \tag{3.13}$$

Once the equivalent conductivity is estimated, this value is applied to the cells which are assigned as a collector well, thus the flow into the lateral can be estimated using MODFLOW. The entrance velocity (v_1) to the collector well can be calculated by

$$v_1 = \frac{Q}{n \pi d l_s p} \tag{3.14}$$

Where, d is the diameter of the perforated pipe and p is the percentage of perforations of the lateral, Q is the total flow to the collector, l_s is the perforated length of the lateral.

The maximum axial velocity (v_2) in the lateral is

$$v_2 = \frac{4 Q}{n \pi d^2} \tag{3.15}$$

3.4 CONCLUSIONS

Flow to a collector well is a case of three dimensional flows. It is complicated to develop an analytical works. Hence, using appropriate computer software can be very helpful. Popular software MODFLOW can be used to model the flow to a collector well. In this study Processing Modflow for Windows version 5.3.0 is used. In MODFLOW, the parameters which are being considered are the grid size, layer type, boundary condition, layer thickness, initial head, hydraulic conductivity, and effective porosity. The multilayer approach by discretizing the aquifer vertically in a number of layers is used to simulate ground water flow to a collector well. At the level of the collector pipes/laterals of the collector well, the thickness of the layer is considered as that of the diameter of the lateral and the lateral is modeled with constant head. The equivalent hydraulic conductivity which is governed by percentage of pipe, pipe thickness, slot size and diameter of the pipe has been derived. In the next chapter, the modeling of collector well under riverbed has been discussed.

CHAPTER IV

COLLECTOR WELL UNDER RIVER BED

4.1 INTRODUCTION

In some groundwater basin, the alluvial deposit in the vicinity of a river may contain boulders. Pushing horizontal radials into such deposits is very difficult. In such aquifers, infiltration galleries are laid at a shallow depth after making an open excavation. A gallery may be laid under the riverbed or in the vicinity of the riverbank. A significant quantity of water can be pumped from an infiltration gallery because the hydraulic conductivity of the natural material and the filter pack surrounding the screens is so high that recharge is sufficient to meet required pumping rate with permissible drawdown. A gallery laid near a river bank is oriented perpendicular to the ground water flow direction. The galleries located adjacent to a water body usually receive water that has lower turbidity and fewer bacteria than bed-mounted galleries, because water gets filtered more extensively (Ray et. al, 2002). Moreover a gallery placed under river bed is to be safeguarded against scour problem.

The large area of exposed perforations in a collector well causes low inflow velocities, which minimize incrustation, clogging, and sand transport. Polluted river water is filtered by its passage through the unconsolidated aquifer to the well. The initial cost of a collector well exceeds that of a vertical well; however, advantages of large yield, reduced pumping heads, and low maintenance cost are factors to be considered.

Hantush and Papadopulos (1962) have derived analytical solutions for drawdown distribution around a collector well with several horizontally laid laterals in confined and unconfined aquifers, located near or under a stream channel, satisfying uniform-flux boundary condition along the laterals. The uniform flux rate is equal to the pumping rate per unit screen length of the collector system. The extreme point of a screen being singular points, and the hydraulic gradient being infinite at these points, there is influx concentration at these locations. So, uniform flux condition along the collector theoretically is not applicable. Hantush has stated that rather uniform head condition along a collector is applicable. The equivalent hydraulic conductivity for the collector pipe is not implicitly considered in Hantush and Papadopulos's flow model. In case of collector with large diameter (> 0.3 m) and small length (< 30 m), the friction loss and turbulent loss along the collector pipe are small. Therefore, for such collectors uniform head condition (equal to head at the caisson) is applicable. The tip of the collector pipe is being a singular point and the entry gradient being infinite. There is flux concentration at the tip, so uniform flux condition is not applicable.

Recently, Kim et al. (2008) have conducted experimental study on flow to a collector pipe. Using a sand tank, Kim et al. (2008) have analyzed flow to a collector pipe of very small length (l = 1.8 m), and very small diameter (d = 20 mm), for high hydraulic conductivity (k = 0.44 mm/s = 38.02 m/day) applying a drawdown, (h_r-h_w) = 0.34 m at the well (corresponding to water level of 0.15 in the well). The collector pipe is laid close to the tank base (0.1 above the base). The ratio of width of the tank to radius of the pipe is 10. Overlooking this limitation in the experimental set up, the dimensionless flow to the tank is computed using Hantush and Papadopulos' equation (Hantush and Papadopulos, 1962, Eq.(37); Hantush, 1964, page 407, Eq.(130a)); the computed dimensionless yield, $Q/kl(h_r-h_w)$ = 1.2438, where Q is the axial flow in the collector near the caisson, and the corresponding production rate, Q = 0.0003349 m^3/s. The production rate measured by Kim et al. is 0.000114 m^3/s. The two production rates have the same order of magnitude. However, the experimental value is less than that computed by Hantush and Papadopulos's equation. This is due to the fact that:

1. Hantush and Papadopulos's equation is derived for infinite length of aquifer across the pipe (i.e. for a large width to diameter ratio).
2. In the experimental set up, small width of the tank restricts the flux rate.
3. The measured hydraulic conductivity and actual hydraulic conductivity of the sand when placed in the thank can differ
4. The equivalent hydraulic conductivity of the collector pipe may become smaller than the high hydraulic conductivity of the filter sand under the high turbulent condition.

In this chapter, a comparison between Hantush solution with MODFLOW has been carried out for collector pipe laid below the riverbed and analyzing the flow concentration along the collector pipe.

4.2 STATEMENT OF THE PROBLEM

Consider a river with width a, which is also width of the aquifer as shown in Figure 4.1. The thickness of the aquifer below the riverbed is b. A horizontal collector well laid under the riverbed intersects the river flow; l = length of the collector pipe; d = diameter of the collector pipe; z_i = the vertical position of collector pipe. The water level in the river is at level h_r measured from the middle of collector pipe. The caisson is located at the bank of the river. The collector well is pumped at a constant rate Q. A steady state flow condition is attained. In the steady state condition, the water level in the caisson is at height h_w. It is required to quantify the specific capacity of the collector pipe for specified a, b, l, d and z_i.

The following assumptions are made in the analysis:

1. The aquifer is homogenous and isotropic;
2. The flow is in steady state;
3. Interference of the caisson on the flow characteristic is negligible.

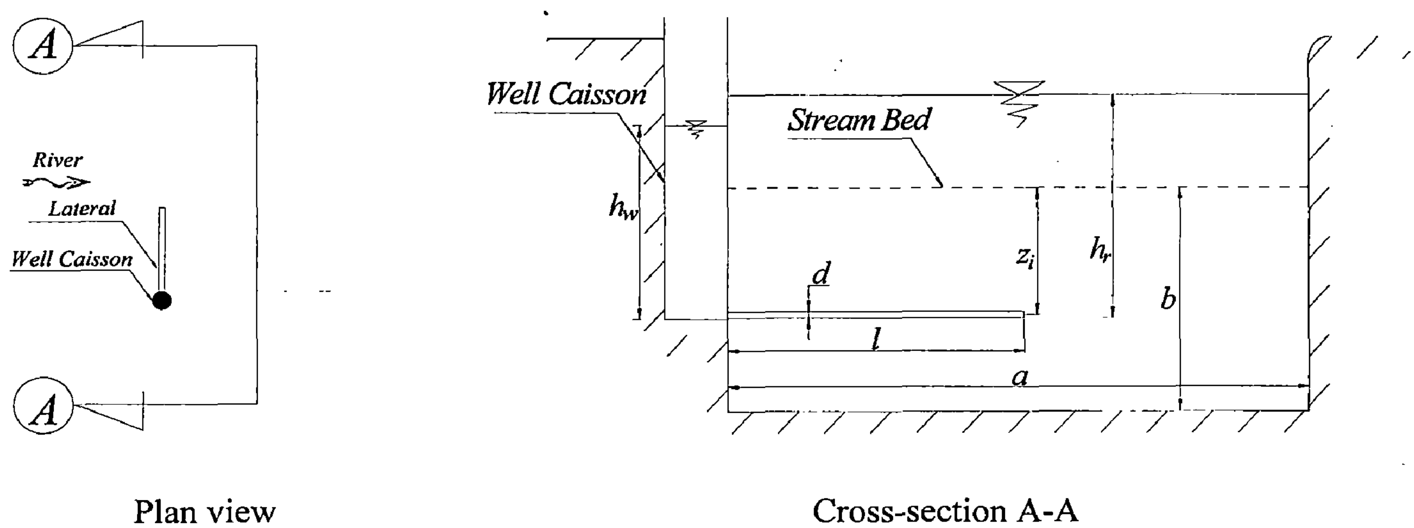


Figure 4.1: Plan and cross-sectional view of the model

Following parameters have been taken for modeling the collector well using MODFLOW: Initial depth of saturation in a water table aquifer (b) = 10 m, hydraulic conductivity (k) = 10 m/day, hydraulic head in the river (h_r) = 15 m, hydraulic head in the lateral (h_w) = 14 m, and therefore the drawdown (h_r-h_w) = 1 m, width of the aquifer (a) = 100 m, length of collector pipe (l) = 40 m, and diameter of collector pipe (d) = 1 m, 0.5 m, 0.3 m, and 0.2 m. The yield of the collector well has been computed for (z_i/b): 0.35, 0.45, 0.55, 0.65, and 0.75 using MODFLOW.

The modelling of collector well laid under river bed is same as already mentioned in section 3.2.2. The differents are only in defining the mesh size and assigning the constant head boudary of the river. The results obtained from MODFLOW are compared with that of

Hantush and Papadopolous (1962) for single collector pipe located below streambed. The Hantush and Papadopolous equation can be shown below. This equation is for a steady state, $d/2 \leq b/\pi$; $l > b$; and $a > 0.5\ (b + r_c + l')$; $l' = l + r_c$;.

$$\frac{Q}{kl(h_r - h_w)} \leq 4\pi \frac{1}{\ln\left\{\left(\frac{4b}{\pi r_w}\right)^2 \bullet \frac{\left[1-\cos\frac{\pi}{2b}(2z_i + r_w)\right]}{\left[1+\cos\frac{\pi}{2b}(2z_i + r_w)\right]}\right\}} \qquad (4.1)$$

where Q is discharge of a collector well (L^3T^{-1}), k is hydraulic conductivity (LT^{-1}), a is width of the aquifer (L), l is the length of lateral (L), (h_r-h_w) is drawdown (L), b is Initial depth of saturation in a water table aquifer (L), r_w = radius of the lateral (L), r_c is radius of the caisson (L), and z_i = vertical position of lateral (L).

4.3 RESULTS AND DISCUSSIONS

The flow to a collector pipe laid under a riverbed has been modeled for steady state flow condition using MODFLOW. The hydraulic head distribution, flow path, and quantity of inflow to the lateral (Q) are obtained. The hydraulic head distribution and flow line are shown in Figure 4.2. The complete result tables are given in Appendix A.

The variations of dimensionless inflow to the lateral, $Q/[kl(h_r-h_w)]$ with z_i/b is presented in Figure 4.3. The results obtained using Hantush solution is shown in the figure. The numerical results correspond to k = 10 m/day; drawdown = 1m; l = 40m; b = 10m; d = 1m; a = 100m. Confirming that $d/2 \leq b/\pi$; $l > b$; and $a > 0.5\ (b + r_c + l')$ Hantush's equation has been used. From the graph, it is seen that the MODFLOW value is less than that computed by Hantush and Papadopulos's equation. This is due to the fact that Hantush and Papadopulos's equation is derived for infinite length of aquifer across the pipe (i.e. for a large width to diameter ratio). MODFLOW results correspond to aquifer length = 100 m.

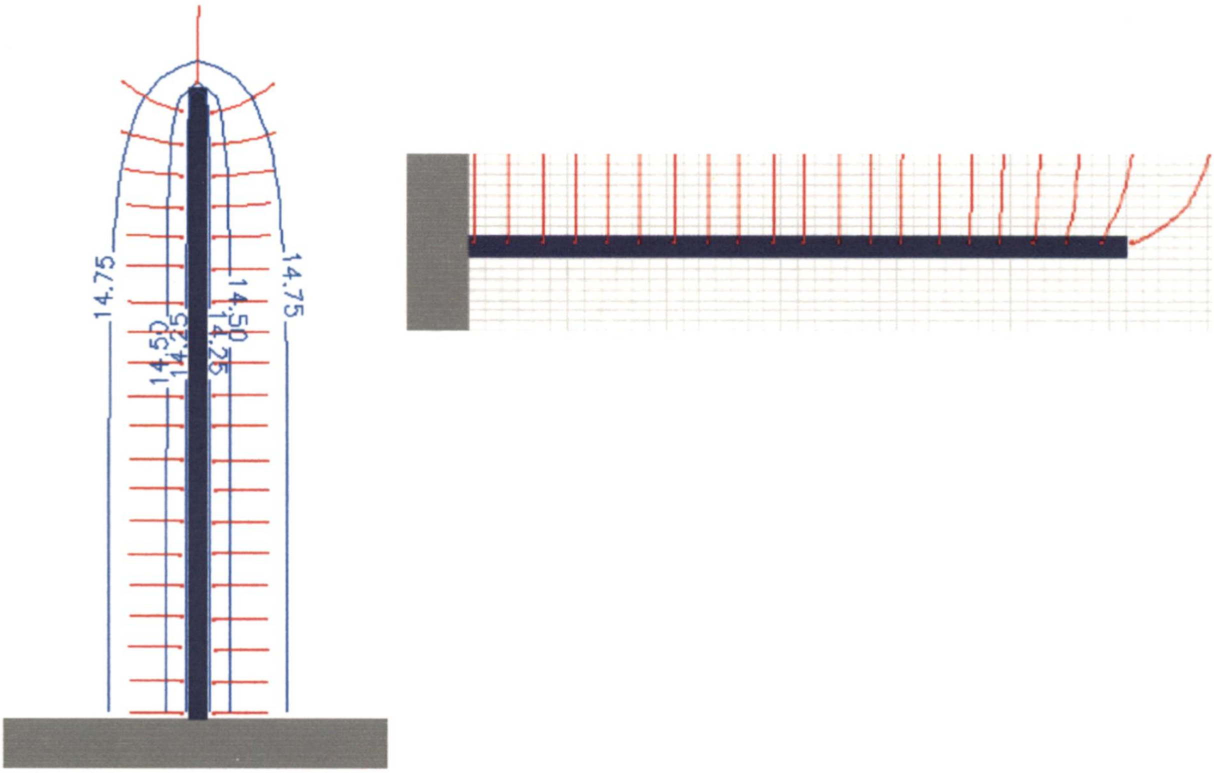


Figure 4.2: Hydraulic head and flow lines of collector well under riverbed

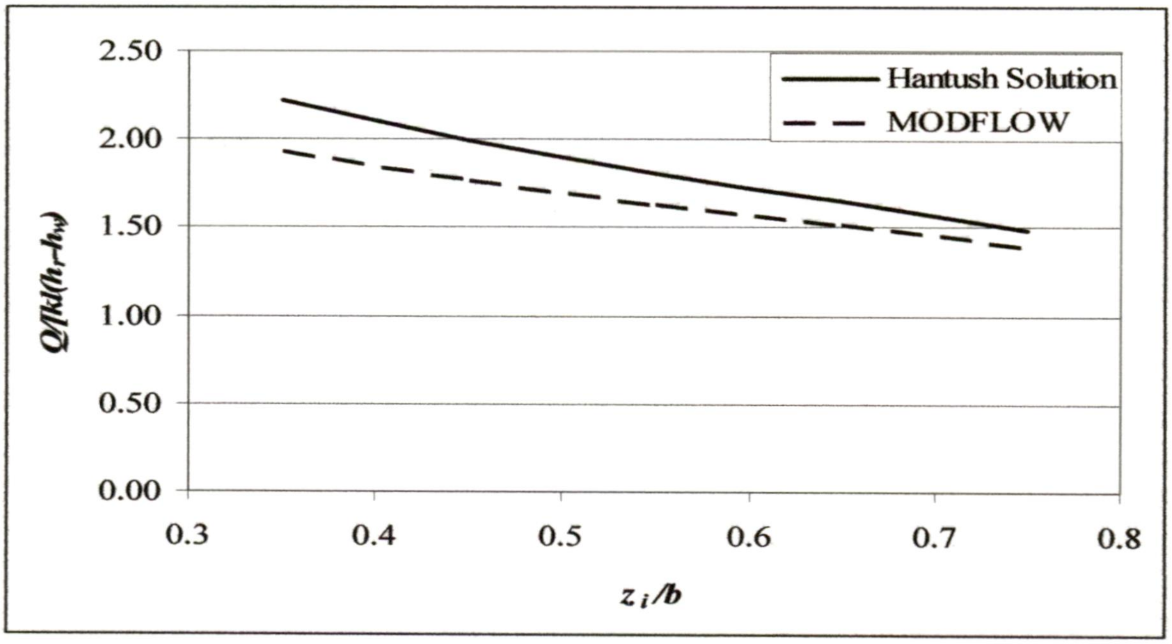


Figure 4.3: $Q/[kl(h_r-h_w)]$ versus z_i/b

It has been observed that the dimensionless flow of $Q/kl(h_r-h_w)$ is governed by the diameter of the pipe, and the vertical location of the pipe. The relationship between the parameters which influence the performance of collector well placed under riverbed of large width can be written as:

$$\frac{Q}{kl(h_r - h_w)} = f\left(\frac{d}{b};\frac{z_i}{b}\right) = C\left(\frac{d}{b}\right)^{\alpha}\left(\frac{z_i}{b}\right)^{\beta} \tag{4.2}$$

where α, β, and C are dimensionless parameters. These parameters are obtained using regression analysis. The relation is given by:

$$\frac{Q}{kl(h_r - h_w)} = 2.48\frac{\left(\frac{d}{b}\right)^{0.28}}{\left(\frac{z_i}{b}\right)^{0.33}} \tag{4.3}$$

The observed dimensionless parameter $Q/[kl(h_r-h_w)]$ using MODFLOW and calculated values using equation (4.3) are plotted to analyse the error. The error was found to fall within a band width of $\pm$ 6% as shown in Figure 4.4.

The variation of influx to the collector along its length is investigated using MODFLOW and the result is presented in Figure 4.5 and 4.6. Near the bank of the river, the aquifer boundary being treated as impervious, there is no flow contribution to the collector pipe from the bank side. The flow lines lie in a vertical plane through the collector axis near the caisson. Therefore, the flow to the collector pipe is minimum at x = l, i.e. near the caisson. At x = 0. i.e. at the tip of the collector as seen from the figure is maximum. This is because the flow domain beyond the tip of the collector pipe also contributes to the influx.. The flow concentration decreases with increasing length of the collector. The results have been presented for two elevation of the collector pipe.

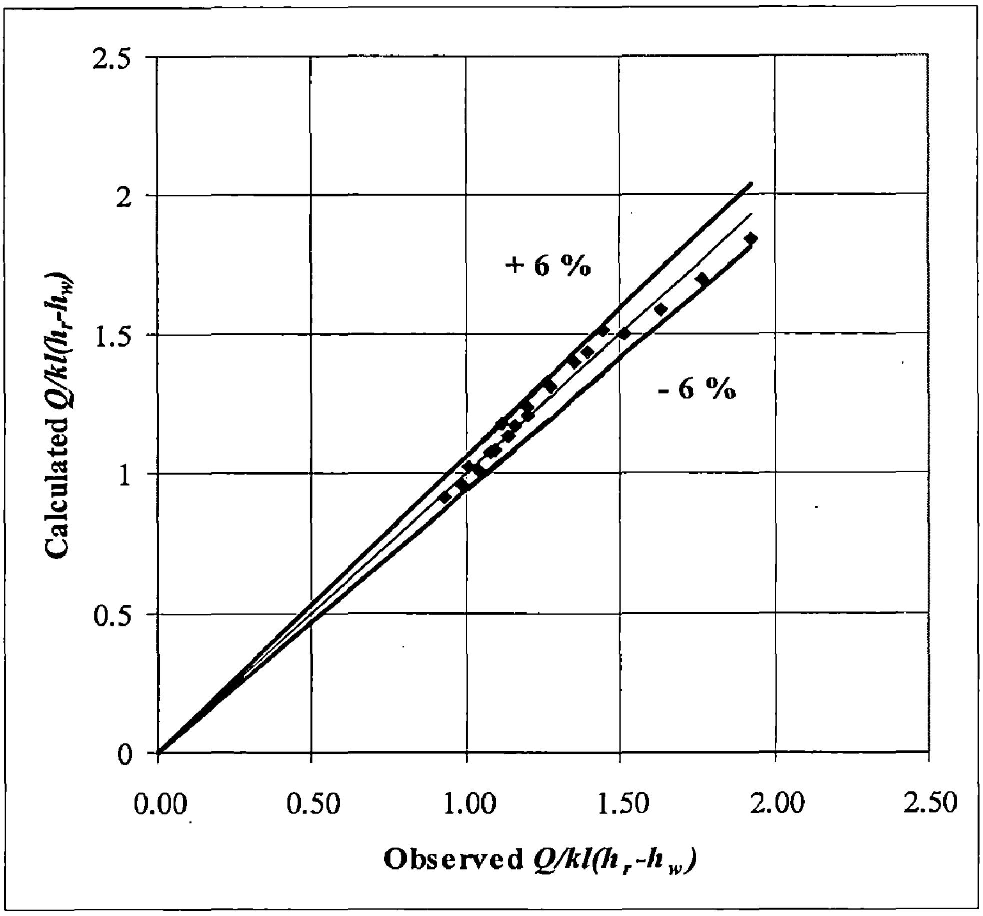
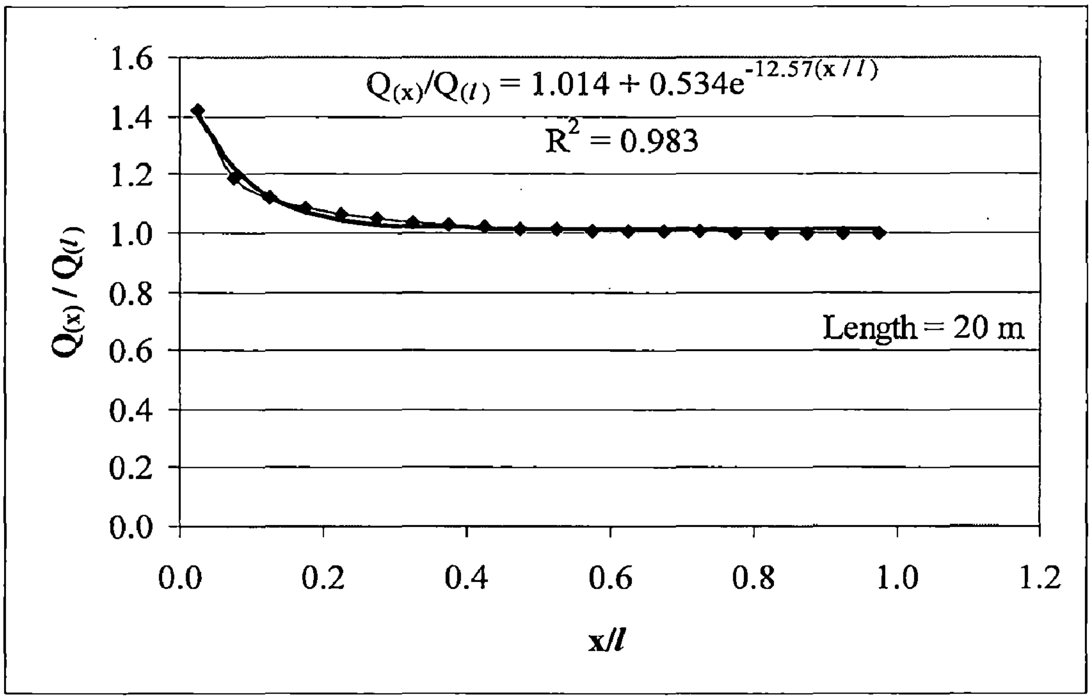
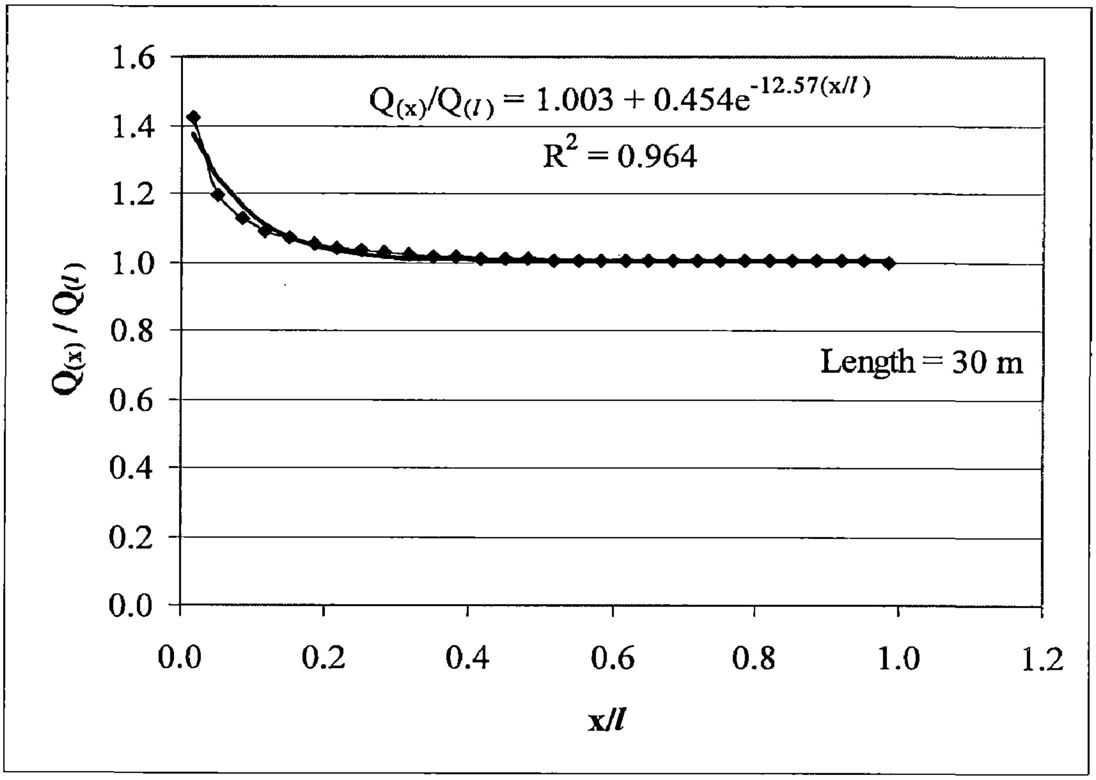


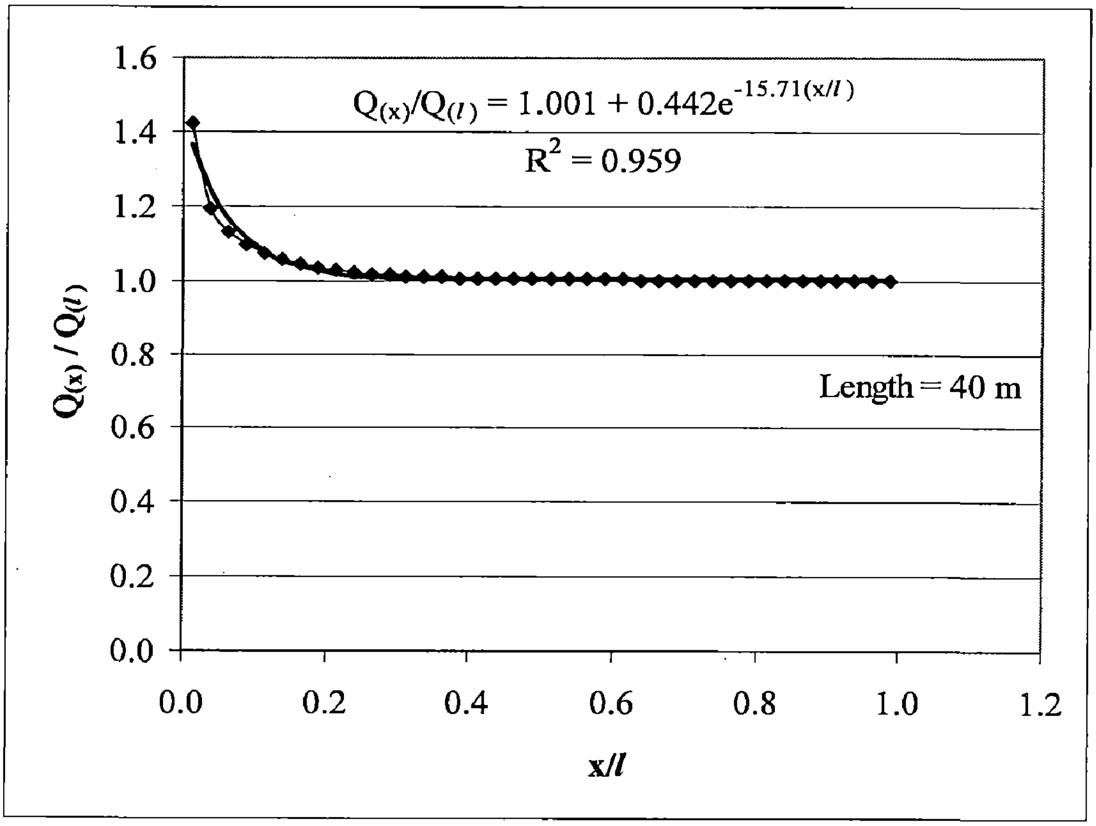
Figure 4.4: Observed versus Calculated $Q/kl(h_r-h_w)$



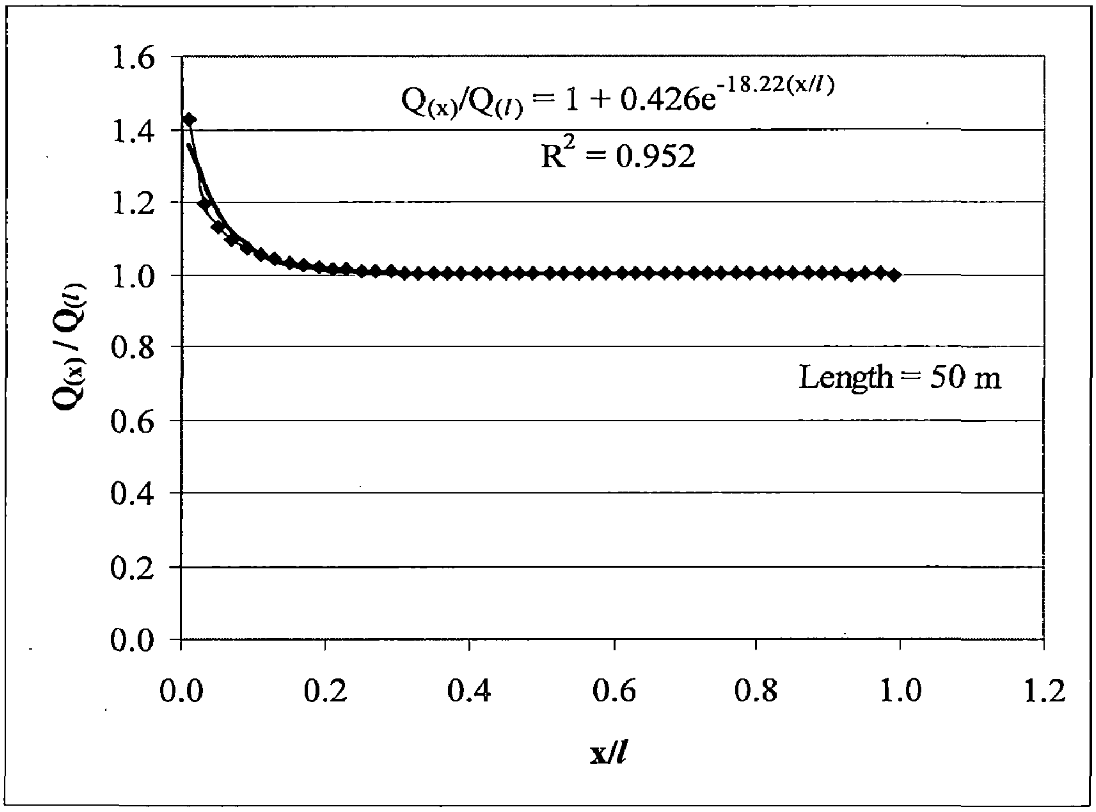
(a)


$Q_{(x)}/Q_{(l)} = 1.003 + 0.454e^{-12.57(x/l)}$
$R^2 = 0.964$
Length = 30 m
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$Q_{(x)} / Q_{(l)}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
x/l

(b)

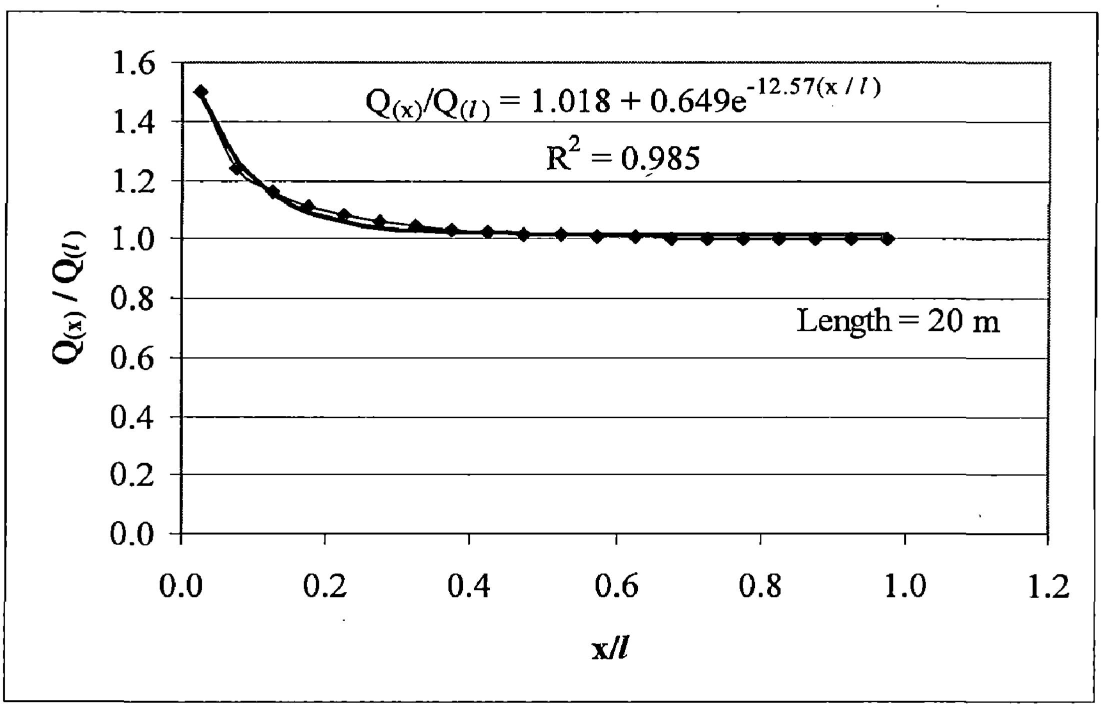

$Q_{(x)}/Q_{(l)} = 1.001 + 0.442e^{-15.71(x/l)}$
$R^2 = 0.959$
Length = 40 m
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$Q_{(x)} / Q_{(l)}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
x/l

(c)

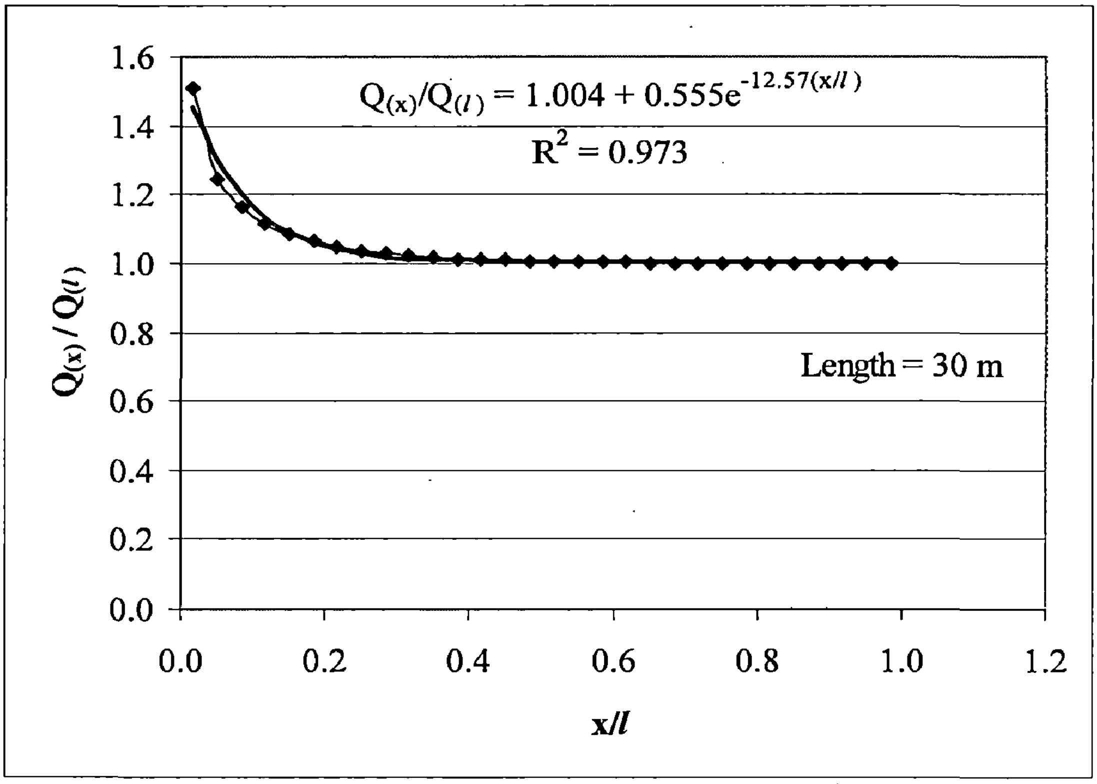


(d)

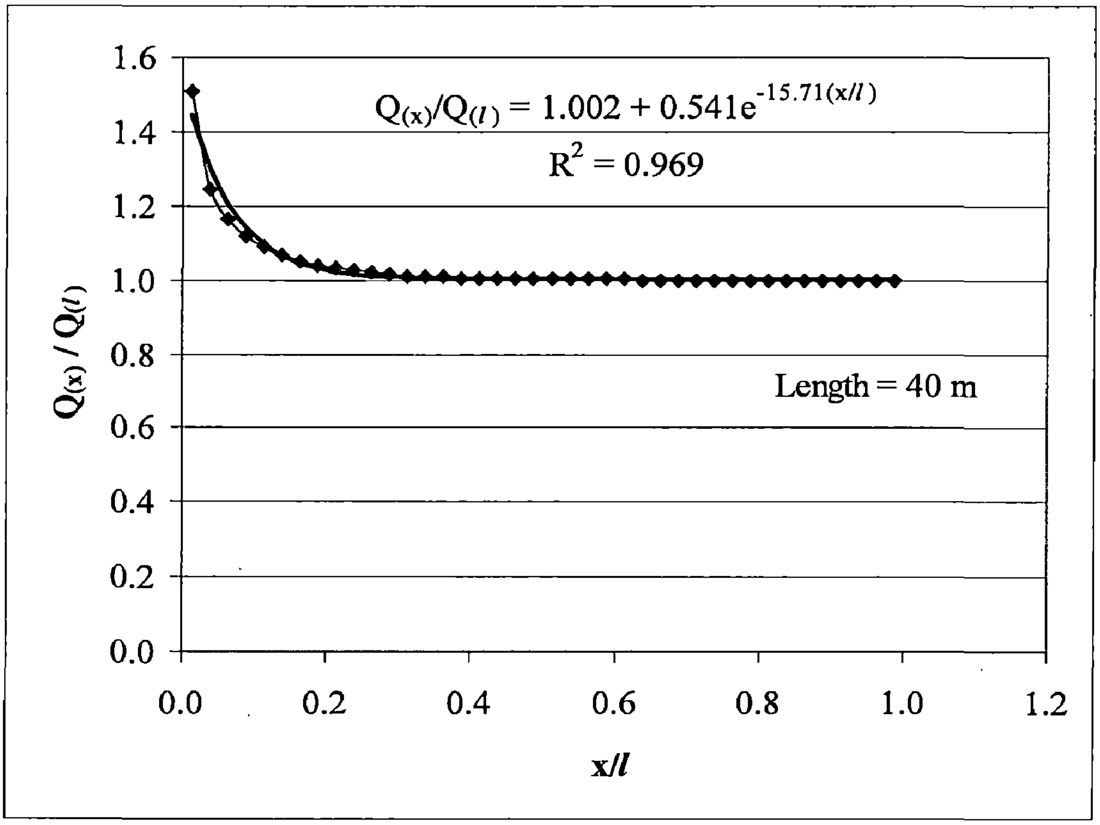
Figure 4.5: Variation of $Q_{(x)}/Q_{(l)}$ versus x/l for d= 0.3 m and z_i =5 m



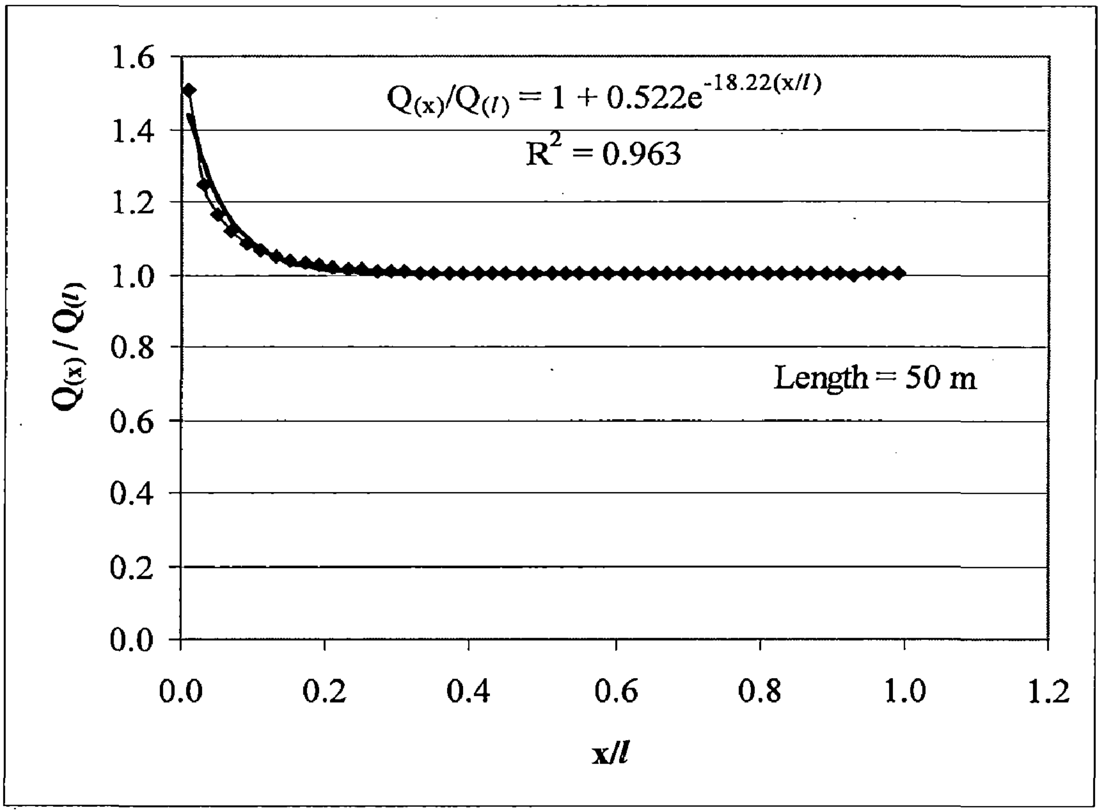
(a)


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
$Q_{(x)}/Q_{(l)} = 1.004 + 0.555e^{-12.57(x/l)}$
$R^2 = 0.973$
Length = 30 m
$Q_{(x)} / Q_{(l)}$
x/l

(b)


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
$Q_{(x)}/Q_{(l)} = 1.002 + 0.541e^{-15.71(x/l)}$
$R^2 = 0.969$
Length = 40 m
$Q_{(x)} / Q_{(l)}$
x/l

(c)



(d)

Figure 4.6: Variation of $Q_{(x)}/Q_{(l)}$ versus x/l for d= 0.3 m and z_i =2.5 m

4.4 CONCLUSIONS

Hantush and Papadopulos 1962 have been formulated the equation for quantifying the production rate of a horizontal collector well which is laid under a riverbed. The production rate estimation using MODFLOW for the same collector well has been carried out alternate vertical location of collector well pipe for different collector lengths. The yield per unit length of collector well is influenced by diameter of the pipe and the vertical location of the pipe. MODFLOW under estimates the production rate as compared to Hantush's solution. The difference may occur mainly because of Hantush and Papadopulos's equation is derived for larger width to diameter ratio than that considered in MODFLOW. The flow concentration near the tip of the collector pipe decreases with increasing length. The collector pipe should not be considered as uniform sink.

CHAPTER V

COLLECTOR WELL ADJACENT TO A STRAIGHT RIVER REACH

5.1 INTRODUCTION

A radial collector well constructed close to a stream induces recharge from surface water bodies. In some cases, the laterals are extended beneath the streambed to increase groundwater production. The yield of a collector well increases with increasing length and diameter of collector pipe, and proximity of the lateral screens to the river. The quality of the water gets improved as the distance of the perforated pipe from the riverbank increases. Therefore, a radial collector well should be located at an appropriate distance from the effective line of infiltration.

Analytical study of flow to a radial collector well or horizontal collector wells in hydrological science can be dated back to Hantush and Papadopulos (1962), who investigated flow to a collector well consisting of a series of horizontal wells. Milojevic (1963) has conducted experiments using electrical analog model to analyze yield of a radial collector well near a river. Bakker, et al. (2005) have applied multilayer analytic element modelling to estimate steady flow to two tier radial collector well with several laterals. Recently, Fahimuddin (2007) have applied conformal mapping to asses the performance of radial collector well near a stream.

The objective of the present chapter is to analyse the performance of a collector well loacated near a stream under steady state flow conditions. Using MODFLOW, yield of a collector well located near a straight river reach is quantified for various orientations of laterals and distance of the collector well from the river.

5.2 STATEMENT OF THE PROBLEM

A collector pipe well is located at a distance R from the riverbank. The diameter of the pipe is d; length of each lateral is l, which is laid parallel to the river axis. The confined aquifer has thickness T. The layout of the collector well is as shown in Figure 5.1. The water level in the river is at level h_r measured from the middle of collector pipe. The collector well is pumped at a constant rate Q. A steady state flow condition has been attained. In the steady state condition, the water level in the caisson is at height h_w. It is required to quantify the specific capacity (discharge of the well per unit drawdown) of the collector pipe for specified R, d, and l.

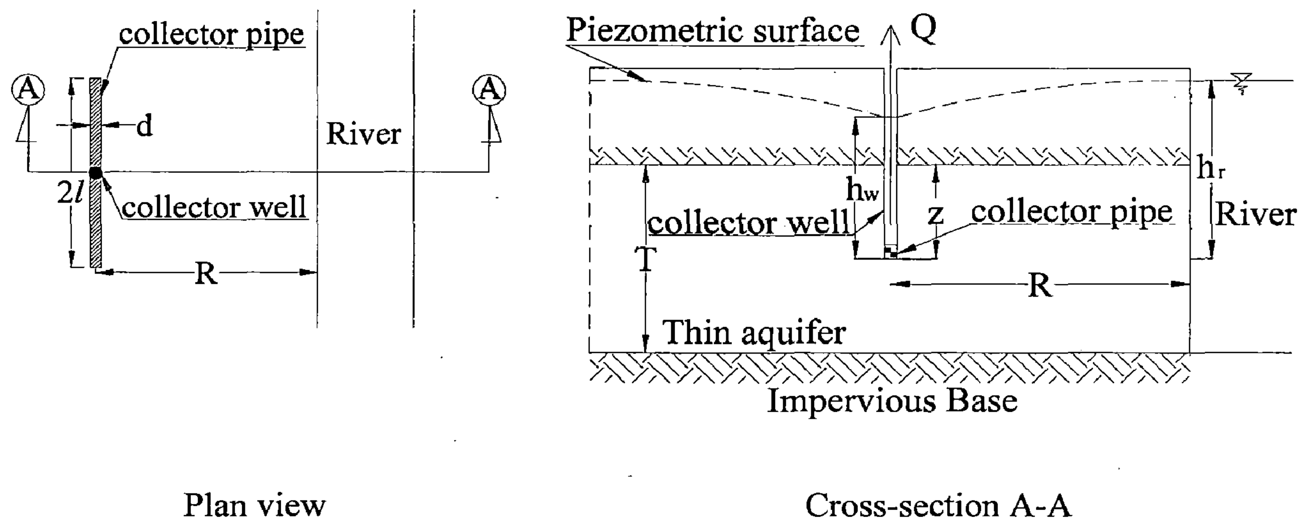


Figure5.1: Plan and cross-sectional view of the model

In order to illustrate the influence of length and diameter of the collector pipe, distance of the well from riverbank, and elevation of collector axis on performance of the well, specific capacities of the well are computed for the following ranges of parameter:

- elevation of lateral (z): z/T = 1/3, 2/5, 1/2, 3/5, 2/3;
- distance of the well (R): R/T = 1, 2, 3, 4, 5;
- length of lateral (l): l/T = 1, 2, 3, 4, 5;
- diameter of lateral (d): d/T = 0.03, 0.04, 0.05, 0.08, 0.1;

The following aquifer parameters are assumed for illustration purpose:

Aquifer thickness (T) = 10 m, hydraulic conductivity (k) = 10 m/day, hydraulic head in the river (h_r) = 10 m, hydraulic head in the collector pipe (h_w) = 9 m, and therefore the drawdown (h_r-h_w) = 1 m.

In order to carry out the analysis, following assumptions are made:

- The aquifer is homogenous and isotropic,
- The flow is in steady state,
- Interference of the caisson on the flow characteristic is negligible,
- Equivalent conductivity for collector pipe geometry and percentage perforation is not considered.

Further, different configurations of multiple collector pipes (laterals) spreading out from the central caisson have been considered. The different layouts used for modeling purpose are shown in Figure 5.2.

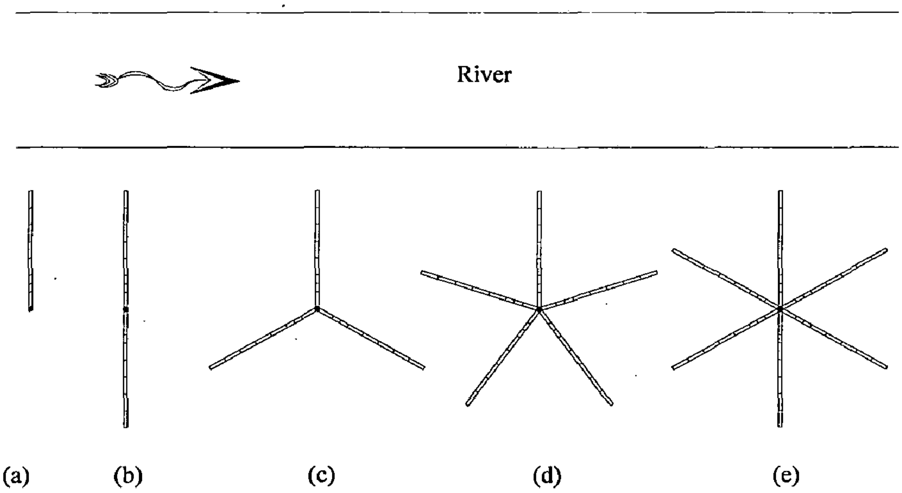


Figure 5.2: Collector well with different number of collector pipes/laterals

The modelling of collector well located in the aquifer near a straight river reach is same as already mentioned in section 3.2.2. The differents are only in defining the mesh size and assigning the constant head boudary of the river.

5.3 RESULTS AND DISCUSSIONS

Flow to the collector well considering the above-mentioned details has been modeled using MODFLOW, and the hydraulic head distribution, flow path, and quantity of inflow to the lateral (Q) are obtained. The hydraulic head distribution and flow line are shown in Figure 5.3 for different cases of the laterals as mentioned in Figure 5.2.

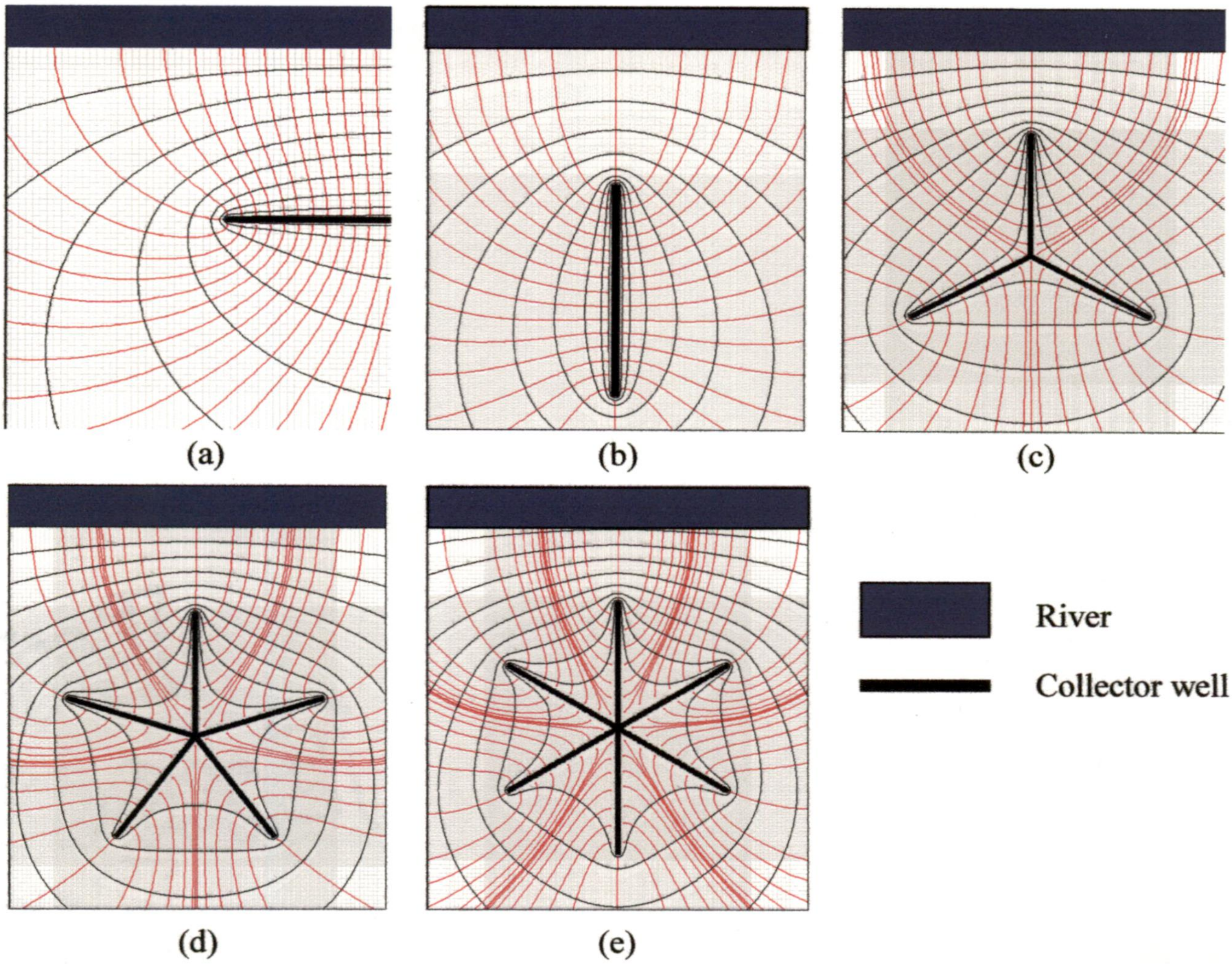


Figure 5.3: Hydraulic head and flow lines for different lay outs of Figure 5.2 on a horizontal plane through collector pipe

The inflow to the lateral is presented by a dimensionless term, $Q/[kT(h_r-h_w)]$. The complete result tables are given in Appendix A. This dimensionless parameter is plotted against z/T and is shown in Figure 5.4. It may be noticed from the graph that the maximum inflow occurs if the lateral is placed at z/T = 0.5 and as the flow domain is symmetrical about a horizontal plane through collector pipe axis the inflow will remain same if the lateral is placed at an elevation which is at equal distance either from the top or bottom of the aquifer.

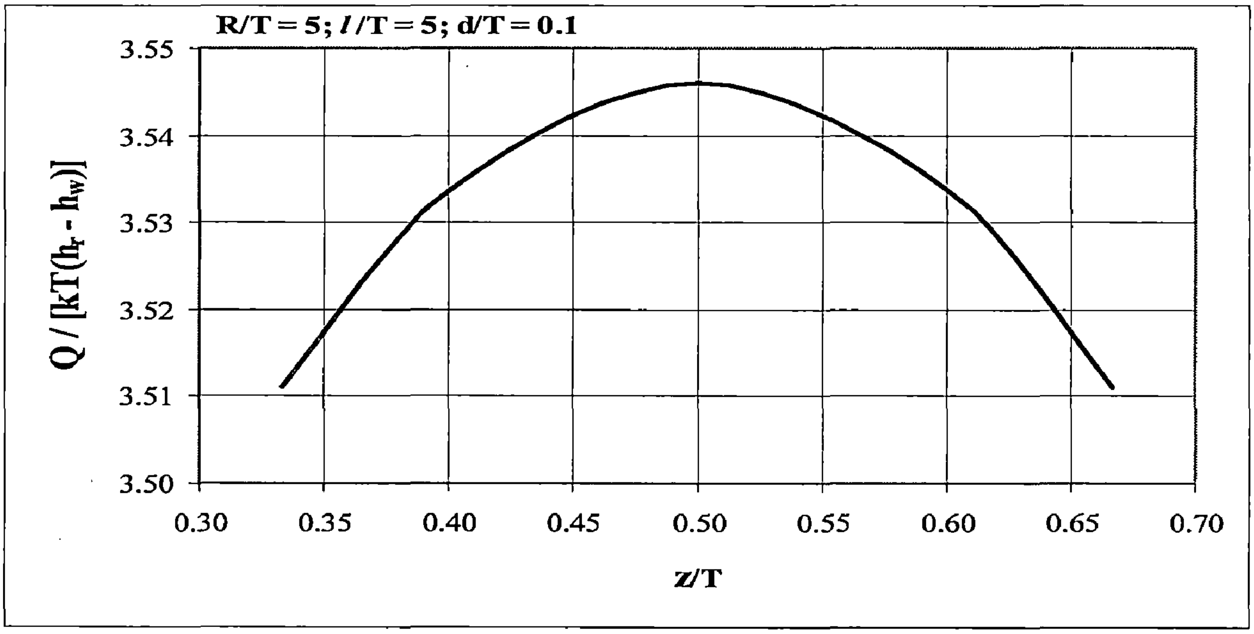


Figure 5.4: $Q/[kT(h_r-h_w)]$ versus z/T

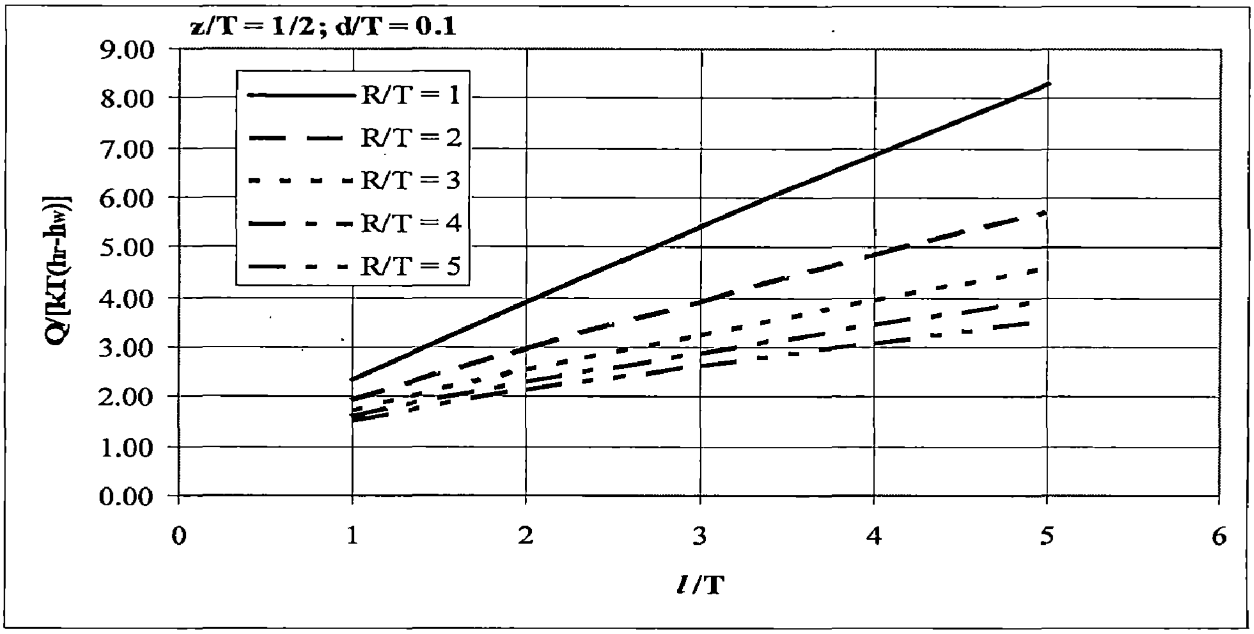


Figure 5.5 : $Q/[kT(h_r-h_w)]$ versus l/T for different R/T

The variations of $Q/[kT(h_r-h_w)]$ with l/T for different values of R/T and d/T are presented in Figure 5.5 and 5.6 respectively. From these figures, it is noticed that the inflow into the lateral increases quasi linearly with the increase of length and diameter of lateral as it increases the flow area. The flow decreases with the increase in distance from the river.

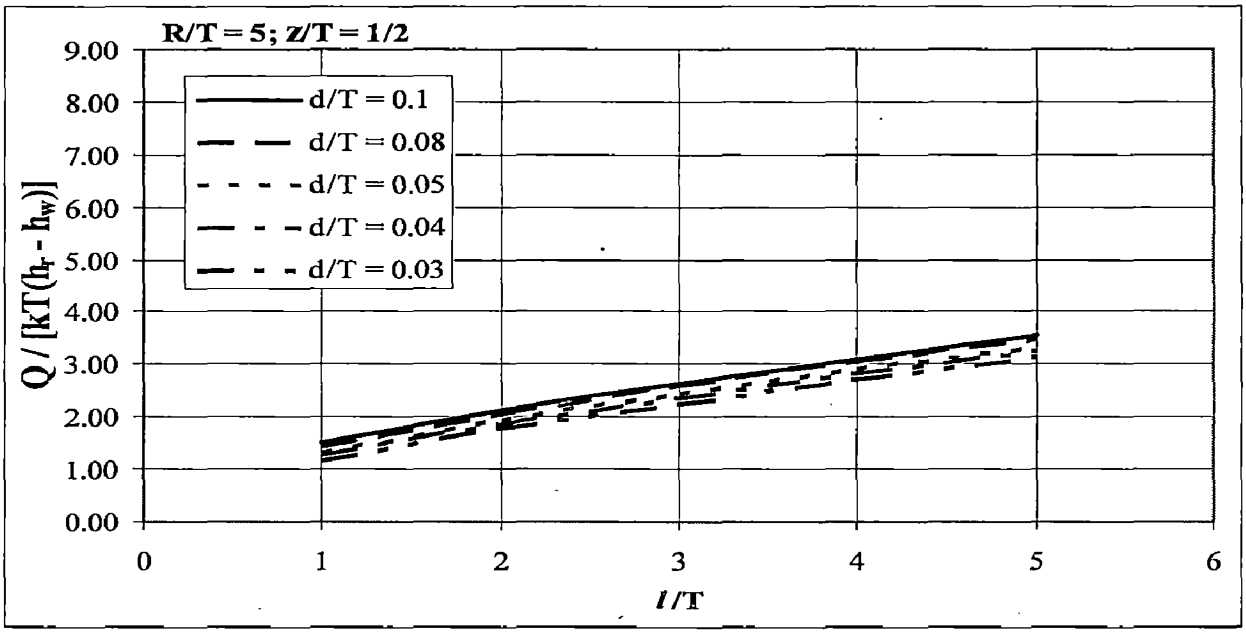


Figure 5.6 : $Q/[kT(h_r-h_w)]$ versus l/T for different values of d/T

Thus, the inflow to the collector pipe is governed by the distance from the river, length of collector pipe, and diameter of collector pipe as well as the elevation of the pipe. The relationship of dimensionless flow with well geometry of collector well parallel to straight river reach can be written as:

$$\frac{Q}{kT(h_r - h_w)} = f\left(\frac{R}{T};\frac{l}{T};\frac{d}{T}\right) = \eta\frac{\left(\frac{l}{T}\right)^a\left(\frac{d}{T}\right)^b}{\left(\frac{R}{T}\right)^c} \qquad (5.1)$$

where η, a, b, c are dimensionless parameters which are determined from regression analysis making use of the inflow values obtained from MODFLOW for different geometry of the collector well. The following relationship is found to be applicable.

$$\frac{Q}{kT(h_r - h_w)} = 3.73 \times \frac{\left(\frac{l}{T}\right)^{0.64}\left(\frac{d}{T}\right)^{0.17}}{\left(\frac{R}{T}\right)^{0.37}} \tag{5.2}$$

The observed dimensionless parameter $Q/[kT(h_r-h_w)]$ using MODFLOW and calculated values using equation (5.2) are plotted to analyse the error. The error was found to fall within a band width of $\pm$ 30% as shown in Figure 5.7.

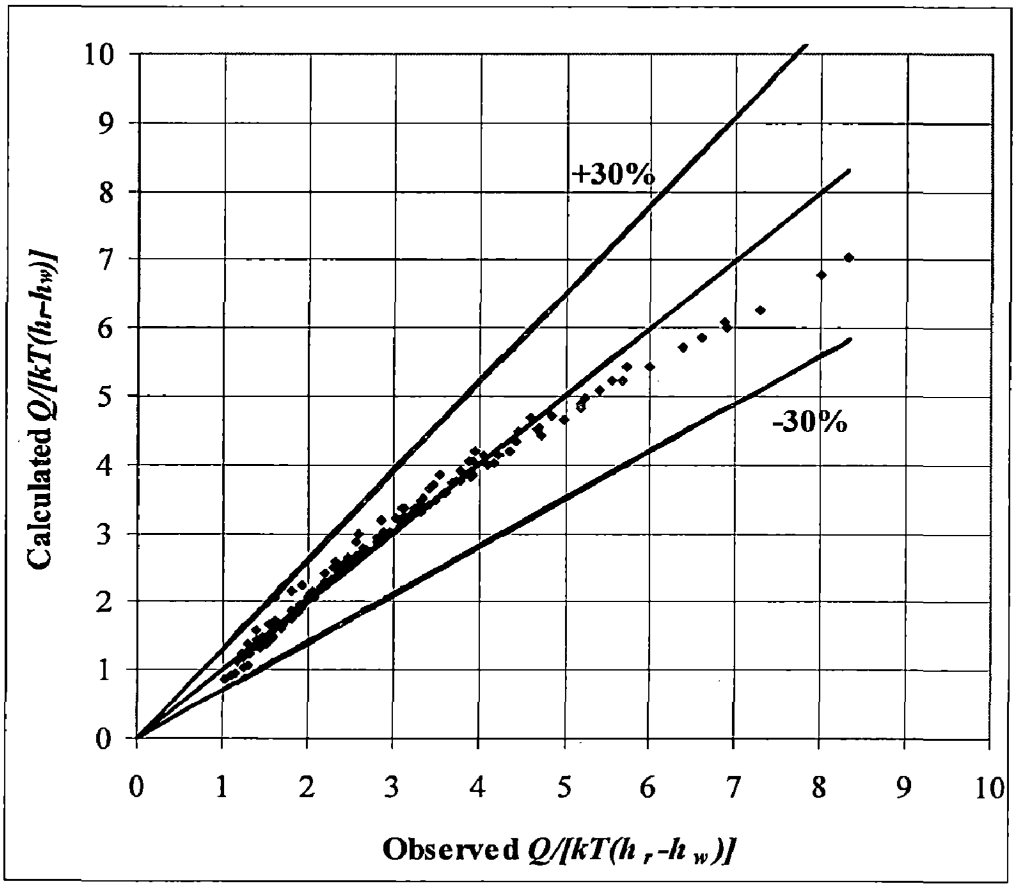


Figure 5.7: Observed versus calculated $Q/[kT(h_r-h_w)]$

Further, in order to reduce the band width of error, different relationships for various ranges of R/T values are obtained using regression analysis. Following three ranges were tried:

$\frac{R}{T} = 1$; $\quad 2 \le \frac{R}{T} \le 4$; $\quad$ and $\quad \frac{R}{T} \ge 5$.

The values of η, a, b, and c for these ranges were estimated using the regression analysis, and were found to be as follows:

R/T	η	*a*	*b*	*c*
1	4	0.82	0.25	0
2 – 4	3.67	0.65	0.17	0.34
$\geq$ 5	3.46	0.52	0.13	0.33

Using these parameters, the percentage error is within $\pm$ 10% as shown in Figure 5.8.

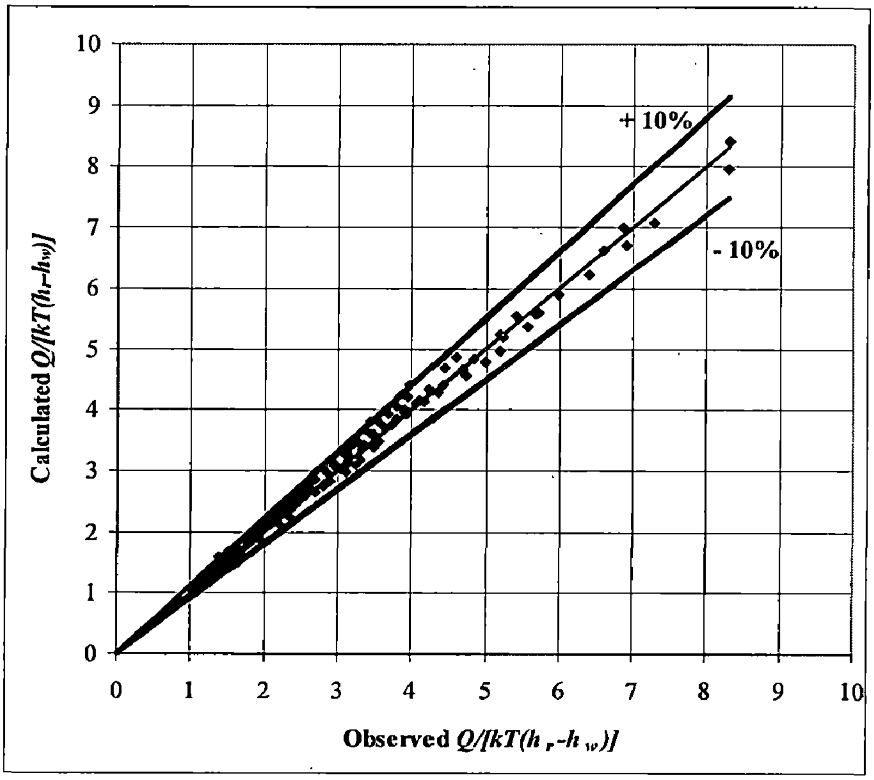


Figure 5.8: Modified observed versus calculated $Q/[kT(h_r\text{-}h_w)]$

From the equations above, it is concluded that the yield increases when the distance from the river decreases. Thus, from quantity point of view, the distance of collector well should be as close to river as possible, but the quality of water may be poor. The yield can also be increased by increasing the length and diameter of collector pipe, but for a particular condition, it may be difficult to drive the lateral for longer distance and for larger diameter.

The yield of a collector well can be enhanced by increasing the number of laterals. Keeping this in mind, the systems of radial collector well with different number of laterals as shown in Figure 5.2 have been modeled assuming R/T = 5 z/T = 0.5 and d/T = 0.1. The variations of $Q/[kT(h_r-h_w)]$ versus l/T for different number of laterals are shown in Figure 5.9.

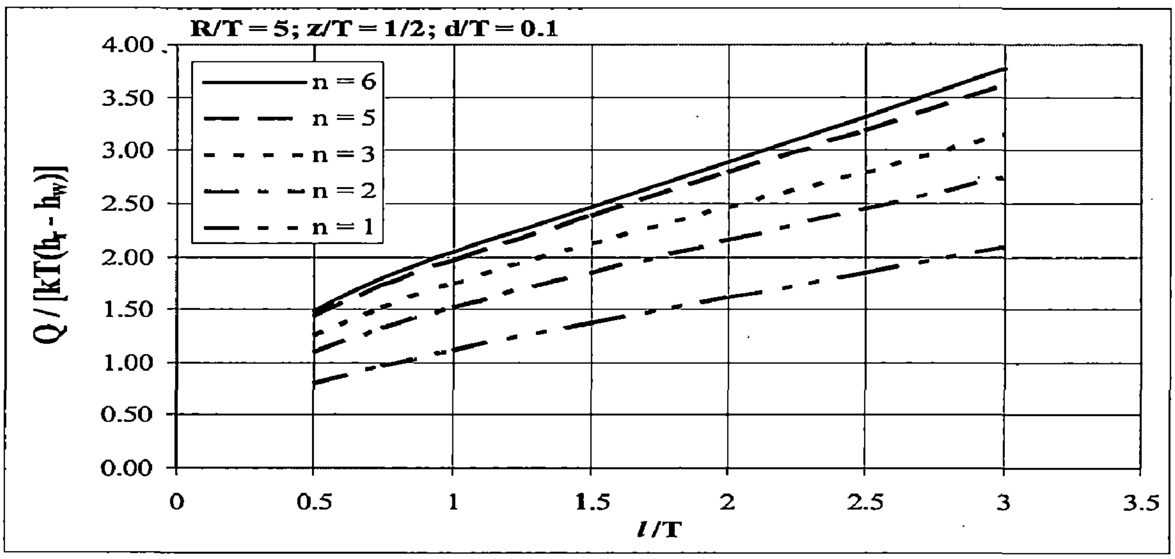


Figure 5.9: $Q/[kT(h_r-h_w)]$ versus l/T for different lay outs of Figure 5.2

From Figure 5.9, it is noticed that an increase in number of laterals results in an increase in the inflow into lateral but not in same proportion. Further, keeping total lengths same, increase of inflow due to increase in number of laterals is less significant than the increase of inflow due to increase in length of laterals. In order to incorporate the effect of number of laterals, the general relationship of Equation (5.1) can be modified as:

$$\frac{Q}{kT(h_r - h_w)} = f\left(n; \frac{R}{T}; \frac{l}{T}; \frac{d}{T}\right) = \eta(n)^a \frac{\left(\frac{l}{T}\right)^b \left(\frac{d}{T}\right)^c}{\left(\frac{R}{T}\right)^d} \tag{5.4}$$

From regression analysis of the inflow values obtained from modeling of various configurations of Figure 5.2 using MODFLOW, the following relationship is proposed for R/T more than 5.

$$\frac{Q}{kT(h_r - h_w)} = 3.19n^{0.33} \frac{\left(\frac{l}{T}\right)^{0.51}\left(\frac{d}{T}\right)^{0.11}}{\left(\frac{R}{T}\right)^{0.46}} \tag{5.5}$$

This relationship, predicts $Q/[kT(h_r-h_w)]$ with a maximum error $\pm$ 5% as shown in Figure 5.10.

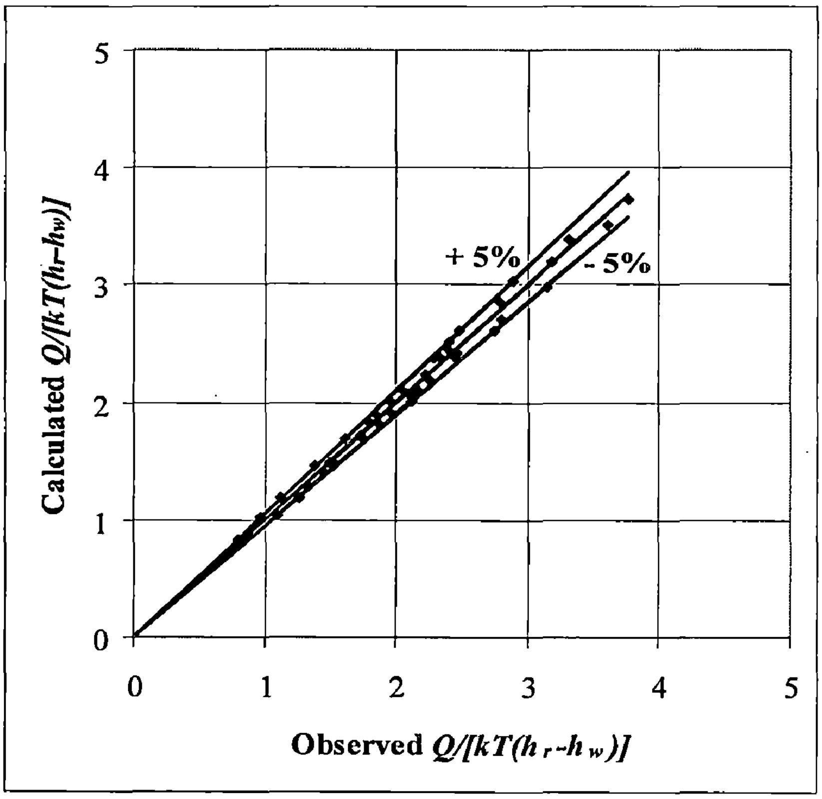


Figure 5.10: Observed versus calculated $Q/[kT(h_r-h_w)]$ for different lay outs of Figure 5.2

***Illustrative example*:**

Consider a case of a confined aquifer near a straight river reach as illustrated in Figure 5.1. The hydraulic conductivity of aquifer is estimated to be k = 70 m/day and aquifer thickness, T = 7 m. It is proposed to install a collector well at 100 m from shoreline with permissible drawdown of 6 m. The laterals of collector well have a diameter of 0.3 m and length of 30 m each and are placed in the center of aquifer.

- Estimate the discharge which the collector well would produce if it is placed parallel to the river as shown in Figure 5.1.
- Estimate the discharge for a collector well if it has 6 collector pipes equally spaced around the caisson as shown in Figure 5.2(e).

Solution:

Case 1

$k = 70$ m/day, $T = 7$ m, h_r-$h_w = 6$ m, $l = 30$ m, $2l = 60$ m, $R = 100$ m, $d = 0.3$ m. Therefore, $R/T = 100/7 = 14.29$; $l/T = 30/7 = 4.29$; $d/T = 0.3/7 = 0.04$.

Using Equation (5.2) with η, a, b, and c for $R/T \geq 5$, the value of $Q/[kT(h_r\text{-}h_w)] = 2.02$.

Thus, the discharge is,

$$Q = 5938.8 \text{ m}^3\text{/day.}$$

Case 2

$R/T = 100/7 = 14.29$; $l/T = 30/7 = 4.29$; $d/T = 0.3/7 = 0.04$; $n = 6$,

Using Equation (5.5), the value of $Q/[kT(h_r\text{-}h_w)] = 2.5$.

Thus, the discharge is,

$$Q = 7350 \text{ m}^3\text{/day.}$$

5.4 CONCLUSIONS

Radial collector well receives water through riverbank filtration which acts as slow-sand filter and is a low-cost efficient alternative for supplying drinking water. Sustainability of such an alternative depends upon the hydro-geological conditions and the flow availability in the river. The location of radial collector well depends upon the level of pollution in the river and the permitted draw down for the desired quantity of flow in the well. In this study, performance of such collector well located near a straight reach of a river using numerical modelling as suggested in MODFLOW has been discussed. The maximum inflow into laterals in confined aquifer will occur if the laterals are placed in the center of aquifer thickness. As the length, diameter, and number of lateral are increased, the production rate is increased. The production rate also increased as the radial collector well is located nearer to the water body. The inflow into the lateral increases quasi linearly with the increase of length and diameter of lateral as it increases the flow area. Increase of inflow due to increase in number of laterals is less significant than the increase of inflow due to increase in length of laterals. New relationship has been proposed for estimating the yield for different configurations of laterals and their locations. Further, sensitivity of flow with respect to various parameters has been discussed. In this chapter, the influence of percentage perforation and length of blind portion is not considered.

CHAPTER VI

COLLECTOR WELL NEAR A MEANDERING RIVER REACH

6.1 INTRODUCTION

In alluvial plain, rivers generally meander. In such situation, specific capacity of well located near the concave side of the meandering reach will be more than that of the well located on the convex side. Conceptually, a well located in the concave side of a meandering river reach can be considered as a well at the centre of an island. An island provides a favourable setting for high groundwater yields as the well located in an island can potentially capture surface water from several directions. Further, in practice, laterals of a radial collector well are kept partly screened. Non-perforated portion (blind) is kept near the caisson, as provision of perforated pipes near the caisson is not advantageous due to pronounced interference of laterals near the caisson. Thus, it is desirable to investigate the effect of non perforated section on the yield of radial collector well. In this chapter, flow to a radial collector well near a meandering river reach having partly perforated multiple laterals is analyzed.

6.2 STATEMENT OF THE PROBLEM

A collector well of pipe diameter d, length l, percentage perforation p and number of collector pipe n, is located at a distance R from a meandering river reach or in the concave side (or located at the center of an island of radius R) in a thin aquifer thickness T as shown in Figure 6.1. The laterals are of equal length placed at equal angular interval. Part of each lateral near the caisson is blind (non-perforated). The blind part is of length l_b and the screened (perforated) part is of length l_s. The screened part of the lateral is assumed as a constant head boundary. The water level in the river is at height h_r measured from the middle of the thin aquifer (vertical location of a collector well z) which is assumed as the datum. The collector well is pumped at a constant rate Q. A steady state flow condition is attained. In the steady state condition, the water level in the caisson is at a height h_w above the datum. It is required to quantify the specific capacity of the collector well for specified R, d, l, l_s, n and p.

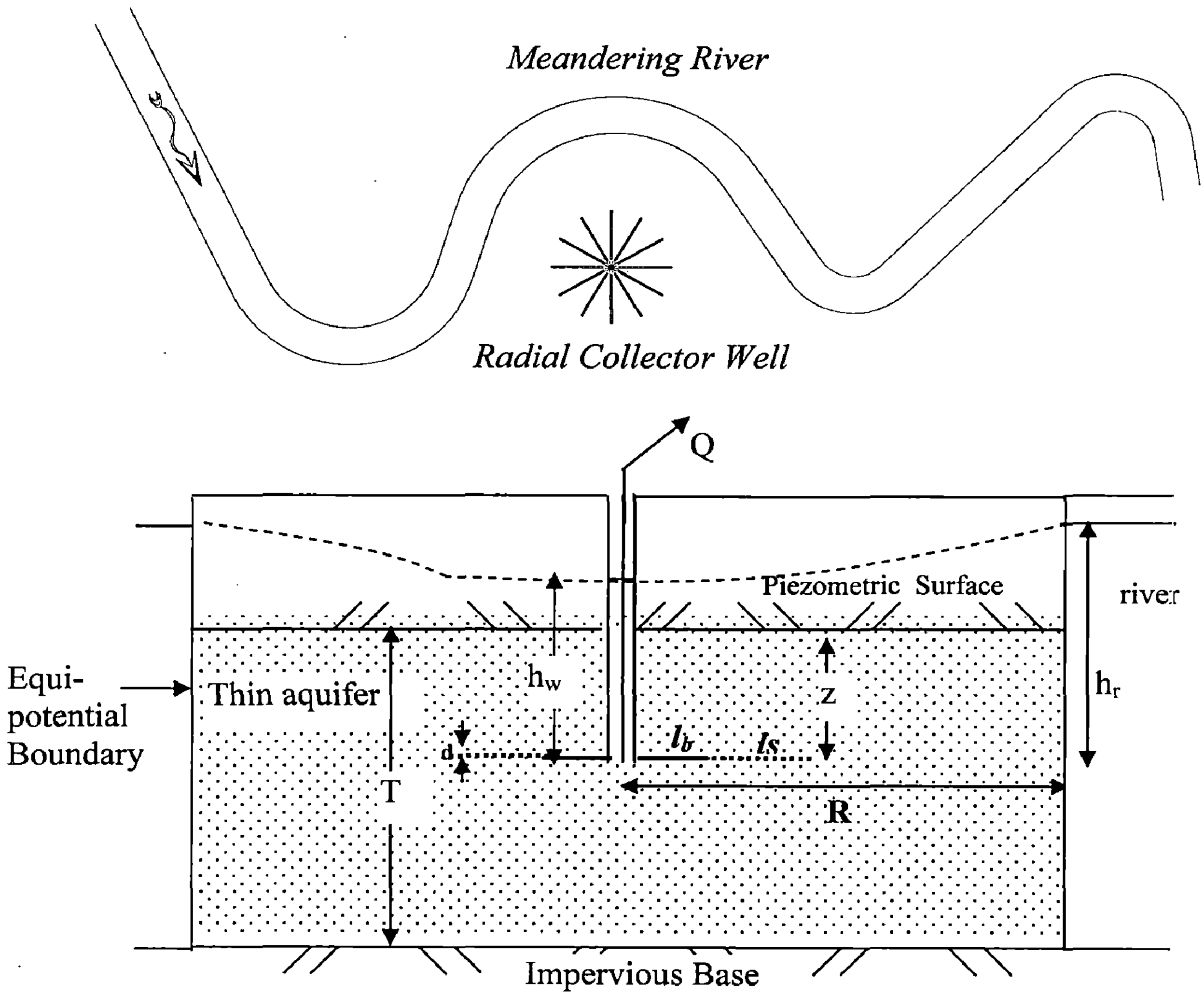


Figure 6.1: Plan view and detail of collector well with n partly screened laterals near a meandering river reach

The following assumptions are made in the analysis:

- The aquifer is homogenous and isotropic.
- The flow is in steady state.
- The meandering rivers reach forms part of a circle.
- Interference of the caisson on the flow characteristics is negligible.

Following parameters are considered for modeling the collector well. The collector wells were placed at an elevation z/T = 0.5, thickness of aquifer T were 4, 6, and 8 m, hydraulic conductivity k = 70 m/day, permissible drawdown h_r-h_w = 5 m, distance of lateral R were 50 and 60 m, diameter of lateral d were 0.3 and 0.5 m, length of lateral l were: 25, 30, and 35 m, length of blind portion (l_b) were 5 m, and percentage of perforation p were 10%, 15%, and 20%. A concept of equivalent conductivity (K_e) from Equation (3.13) is used to modelling the geometry of pipe, opening slots, and percentage perforation. The slot opening size a, thickness of pipe t, acceleration due to gravity g, and fluid kinematic viscosity υ are assumed as follows : a = 0.005 m, t = 0.01 m, g = 9.8 m/s^2, $\upsilon = 10^{-6}$ m^2/s. The modelling of collector well located in the aquifer near a meandering river reach is already mentioned in section 3.2.2.

6.3 RESULTS AND DISCUSSIONS

The collector well with above-mentioned details has been modeled using MODFLOW, and the hydraulic head distribution, flow path, and quantity of inflow to the lateral (Q) are obtained. The hydraulic head distribution and flow lines are shown in Figure 6.2.

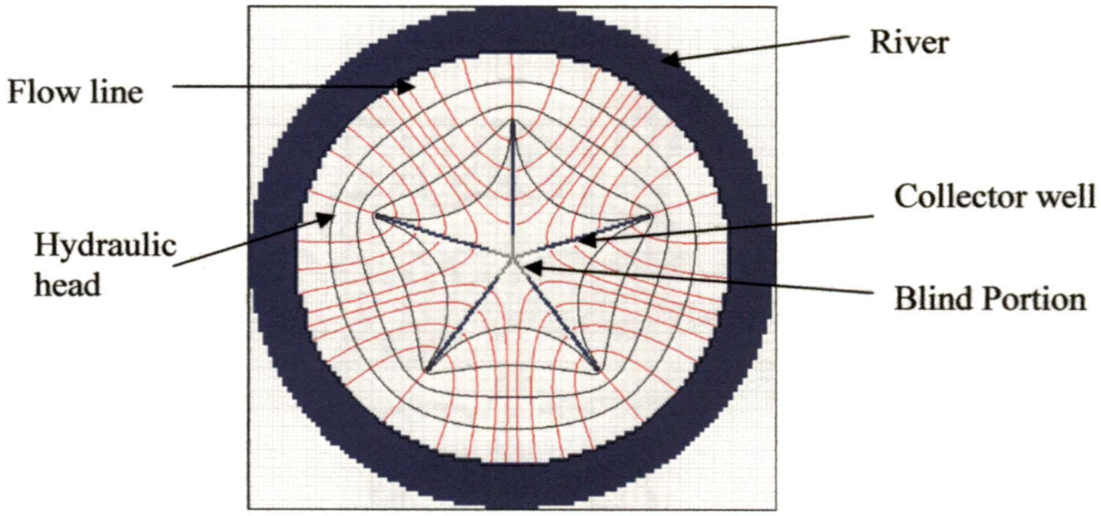


Figure 6.2: Hydraulic head and flow lines obtained from MODFLOW

The dimensionless inflow to the lateral, $Q/[kT(h_r-h_w)]$, are obtained for different geometry of the collector well systems. The complete result tables are given in Appendix A. It has been observed that the inflow to the collector pipe is influenced by the distance from the river (island radius), length of collector pipe, number of collector pipe, portion of screened length, diameter of collector pipe, and percentage of perforation. The relationship between the parameters which influence the performance of collector well adjacent to meandering river can be written as:

$$\frac{Q}{kT(h_r - h_w)} = f\left(n; p; \frac{l}{R}; \frac{l_s}{l}; \frac{d}{T}\right) = \dot{\eta}(n)^a (p)^b \left(\frac{d}{T}\right)^c \left(\frac{l}{R}\right)^d \left(\frac{l_s}{T}\right)^e \tag{6.1}$$

The following relationship can be generated using regression analysis of the dimensionless yield computed using MODFLOW.

For n = 3, and 5

$$\frac{Q}{kT(h_r - h_w)} = 6.38(n)^{0.42} (p)^{0.15} \left(\frac{d}{T}\right)^{0.14} \left(\frac{l}{R}\right)^{0.82} \left(\frac{l_s}{l}\right)^{0.14} \tag{6.2}$$

For n = 6, 8, and 12

$$\frac{Q}{kT(h_r - h_w)} = 7.71(n)^{0.26} (p)^{0.12} \left(\frac{d}{T}\right)^{0.07} \left(\frac{l}{R}\right)^{1.0} \left(\frac{l_s}{l}\right)^{0.13} \tag{6.3}$$

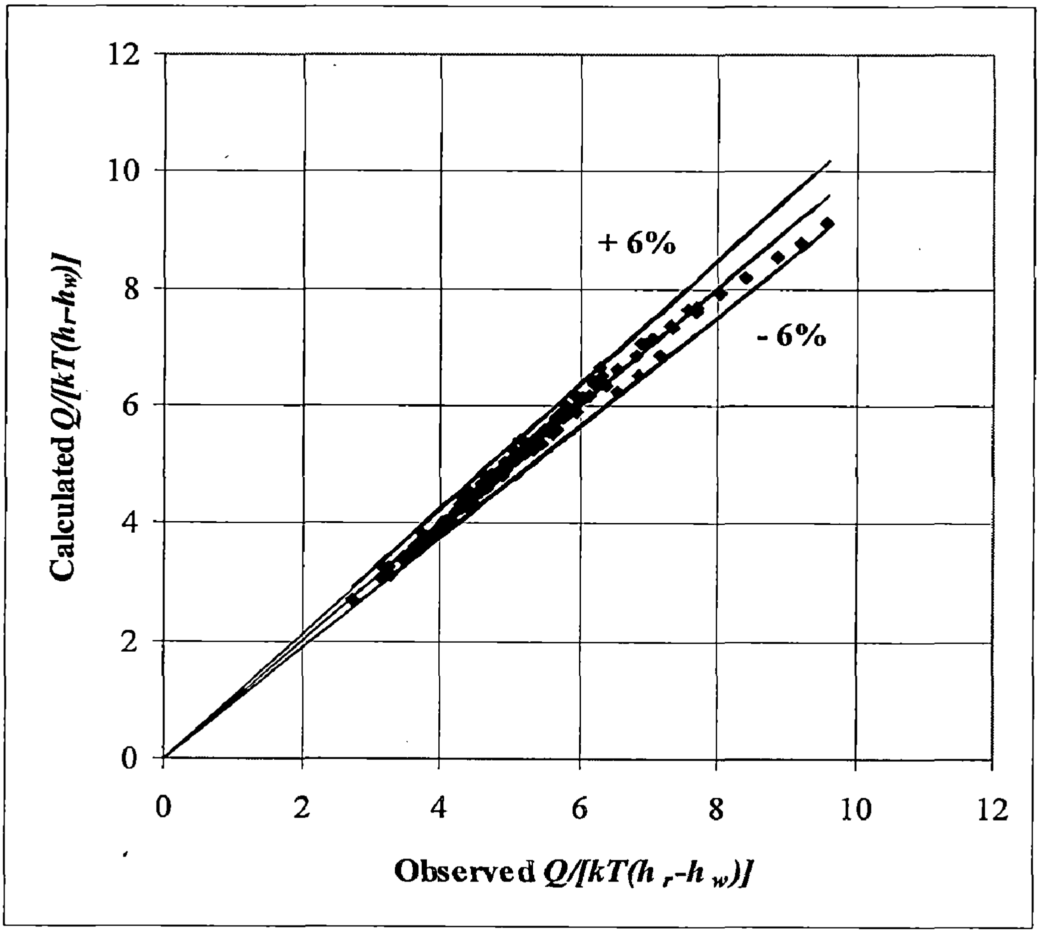


Figure 6.3: Observed versus calculated $Q/[kT(h_r-h_w)]$

The dimensionless yield $Q/[kT(h_r-h_w)]$ obtained using MODFLOW and calculated values obtained using equation (6.2) and (6.3) are plotted to analyse the error. It is found that the maximum error falls within a band width of $\pm$ 6% as shown in Figure 6.3.

***Illustrative example*:**

Consider a case of a confined aquifer near a meandering river as illustrated in Figure 6.1. The hydraulic conductivity of aquifer is estimated to be k = 70 m/day and aquifer thickness, T = 6 m with permissible drawdown of 5 m. It is proposed to install a collector well at the middle of aquifer with diameter, d = 0.3 m, length, l = 50 m, l_s = 30 m, and percentage of perforation, p = 10%.

- Estimate the discharge for a collector well if is installed at 100 m from shoreline and has 8 collector pipes equally spaced around the caisson.
- Calculate the entrance velocity and the maximum axial velocity corresponding to the estimated discharge.

Solution:

$k = 70$ m/day, $T = 6$ m, h_r-$h_w = 5$ m, $l = 50$ m, $l_s = 30$ m, $R = 100$ m, $d = 0.3$ m, $p = 10\%$, $n = 8$.

Therefore, $l/R = 50/100 = 0.5$; $l_s/T = 30/6 = 5$; $d/T = 0.3/6 = 0.05$.

Using Equation (6.3)

$$Q/[kT(h_r\text{-}h_w)] = 5.02$$

Thus, the discharge is,

$$Q = 10540 \text{ m}^3\text{/day}$$

The entrance velocity (v_1) and maximum axial velocity (v_2) computed using equation (3.14) and (3.15) are: $v_1 = 0.01$ m/s; $v_2 = 0.22$ m/s;

These velocities are within the permitted limit.

6.4 CONCLUSIONS

Radial collector well receives water through riverbank filtration which acts as slow-sand filter and is a low-cost efficient alternative for supplying drinking water. Sustainability of such an alternative depends upon the hydro-geological conditions and the flow availability in the river. The location of radial collector well depends upon the level of pollution in the river and the permitted draw down for the desired quantity of flow in the well. In this study, performance of a collector well located near a meandering river using numerical modelling as suggested in MODFLOW has been discussed. As the length, screened portion of the length, diameter, number of lateral and percentage perforation increased, and the production rate increased. The production rate also increased as the radial collector well is located nearer to the water body. A relationship has been proposed for estimating the yield for different configurations of laterals and their locations. Further, sensitivity of flow with respect to various parameters has been discussed.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The importance of drinking water is immeasurable and the health benefits of drinking water are innumerable, therefore, sustainable drinking water sources are needed. Groundwater can provide adequate quantity and high quality of water, thus can be use as a sustainable source of drinking water. Groundwater conventionally is abstracted by using vertical well. Nowadays, collector wells have become a common abstraction to be proposed as an alternate drinking water source as it can have enough quantity and good quality of water. Collector wells are commonly used near the shore of a lake or near a river to obtain a large amount of relatively good quality water from adjacent sand or gravel beds. Radial collector well is also used in place of multiple vertical wells to obtain water from a relatively shallow aquifer. It is observed that little analytical work has been carried out on the flow to a radial collector well located near a river. A radial collector well consists of group of horizontal pipes, hence from theory of flow to a horizontal pipe, total flow to a radial collector well can be estimated. From the literature review, it is clear that there are two basic approaches to find solution of flow to a horizontal well. These two approaches are: either constant flux or constant head boundary condition persist along the horizontal well.

Flow to a collector well is a case of three dimensional flows. It is complicated to develop an analytical works. Popular software MODFLOW can be used to model the flow to a collector well. In this study Processing Modflow for Windows version 5.3.0 is used. In MODFLOW, the parameters which are considered are the grid size, layer type, boundary condition, layer thickness, initial head, hydraulic conductivity, and effective porosity. The multilayer approach by discretizing the aquifer vertically in a number of layers is used to simulate ground water flow to a collector well. At the level of the collector pipes/laterals of the collector well, the thickness of the layer is considered as that of the diameter of the lateral and the lateral is modeled with constant head.

A numerical method using MODFLOW has been derived for evaluating the performance of a collector well laid under riverbed, located in the aquifer near a straight river reach, and located in the aquifer near a meandering river reach. The modelling has been done for various diameters, lengths of lateral, vertical elevations of lateral, aquifer thickness, distances from the well to the river, and percentage of perforations. Based on the study, following conclusions are drawn:

1. The collector well is laid under the riverbed
   a. The yield per unit length of collector well is influenced by diameter of the pipe and the vertical location of the pipe.
   b. MODFLOW under estimates the production rate as compared to Hantush's solution. The difference may occur mainly because of Hantush and Papadopulos's equation is derived for larger width to diameter ratio than that considered in MODFLOW.
   c. The flow concentration near the tip of the collector pipe decreases with increasing length.
   d. The collector pipe should not be considered as uniform sink.
2. The collector well is located in the aquifer near a straight river reach
   a. The maximum inflow into laterals in confined aquifer will occur if the laterals are placed in the center of aquifer thickness.
   b. As the length, diameter, and number of lateral are increased, the production rate is increased. The production rate also increase as the radial collector well is located nearer to the water body.

c. The inflow into the lateral increases quasi linearly with the increase of length and diameter of lateral as it increases the flow area.

d. Increase of inflow due to increase in number of laterals is less significant than the increase of inflow due to increase in length of laterals.

e. New relationship has been proposed for estimating the yield for different configurations of laterals and their locations.

3. The collector well is located in the aquifer near a meandering river reach

a. The production rate increased as the radial collector well located nearer the water body and as the length, screened portion of the length, diameter, and number of lateral and percentage perforation increase.

b. The blind portion has been considered to minimize the interference caused by use of multiple laterals.

c. A relationship has been proposed for estimating the yield for different configurations of laterals and their locations.

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APPENDIX A

RESULT TABLES

A.1 COLLECTOR WELL UNDER RIVERBED

Table A.1.1: A comparison of $Q/[kl(h_r-h_w)]$ for different d and z_i obtained using Hantush's equation and MODFLOW

d (m)	d/b	z_i (m)	z_i/b	Hantush Solution	MODFLOW	
				$Q/[kl(h_r-h_w)]$	Q (m^3/day)	$Q/[kl(h_r-h_w)]$
1	0.10	3.5	0.35	2.22	770.51	1.93
1	0.10	4.5	0.45	1.99	705.42	1.76
1	0.10	5.5	0.55	1.81	653.33	1.63
1	0.10	6.5	0.65	1.65	606.04	1.52
1	0.10	7.5	0.75	1.48	557.68	1.39
0.5	0.05	3.5	0.35	1.80	576.06	1.44
0.5	0.05	4.5	0.45	1.65	539.75	1.35
0.5	0.05	5.5	0.55	1.52	508.56	1.27
0.5	0.05	6.5	0.65	1.41	478.45	1.20
0.5	0.05	7.5	0.75	1.29	445.70	1.11
0.3	0.03	3.5	0.35	1.58	508.35	1.27
0.3	0.03	4.5	0.45	1.46	479.91	1.20
0.3	0.03	5.5	0.55	1.36	454.85	1.14
0.3	0.03	6.5	0.65	1.27	430.10	1.08
0.3	0.03	7.5	0.75	1.17	402.45	1.01
0.2	0.02	3.5	0.35	1.44	461.36	1.15
0.2	0.02	4.5	0.45	1.34	437.76	1.09
0.2	0.02	5.5	0.55	1.25	416.65	1.04
0.2	0.02	6.5	0.65	1.17	395.49	0.99
0.2	0.02	7.5	0.75	1.09	371.37	0.93

Table A.1.2: Flow concentration distribution for $d = 0.3$ m, $z_i = 5$ m, and $l = 20$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	11.0988	0.975	1.0000	11.5	11.3381	0.425	1.0216
1.5	11.1008	0.925	1.0002	12.5	11.4132	0.375	1.0283
2.5	11.1051	0.875	1.0006	13.5	11.5114	0.325	1.0372
3.5	11.1118	0.825	1.0012	14.5	11.6422	0.275	1.0490
4.5	11.1214	0.775	1.0020	15.5	11.8210	0.225	1.0651
5.5	11.1341	0.725	1.0032	16.5	12.0755	0.175	1.0880
6.5	11.1508	0.675	1.0047	17.5	12.4671	0.125	1.1233
7.5	11.1724	0.625	1.0066	18.5	13.1769	0.075	1.1872
8.5	11.1999	0.575	1.0091	19.5	15.7415	0.025	1.4183
9.5	11.2351	0.525	1.0123	Total	122.71056		
10.5	11.2802	0.475	1.0163	MIN	11.09880		

Table A.1.3: Flow concentration distribution for $d = 0.3$ m, $z_i = 5$ m, and $l = 30$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	11.0548	0.983	1.0000	16.5	11.1440	0.450	1.0081
1.5	11.0550	0.950	1.0000	17.5	11.1668	0.417	1.0101
2.5	11.0556	0.917	1.0001	18.5	11.1953	0.383	1.0127
3.5	11.0564	0.883	1.0001	19.5	11.2314	0.350	1.0160
4.5	11.0576	0.850	1.0002	20.5	11.2771	0.317	1.0201
5.5	11.0592	0.817	1.0004	21.5	11.3356	0.283	1.0254
6.5	11.0612	0.783	1.0006	22.5	11.4111	0.250	1.0322
7.5	11.0638	0.750	1.0008	23.5	11.5097	0.217	1.0411
8.5	11.0671	0.717	1.0011	24.5	11.6408	0.183	1.0530
9.5	11.0711	0.683	1.0015	25.5	11.8198	0.150	1.0692
10.5	11.0761	0.650	1.0019	26.5	12.0746	0.117	1.0922
11.5	11.0823	0.617	1.0025	27.5	12.4663	0.083	1.1277
12.5	11.0900	0.583	1.0032	28.5	13.1762	0.050	1.1919
13.5	11.0995	0.550	1.0040	29.5	15.7409	0.017	1.4239
14.5	11.1112	0.517	1.0051	Total	177.18688		
15.5	11.1258	0.483	1.0064	MIN	11.05484		

Table A.1.4: Flow concentration distribution for $d = 0.3$ m, $z_i = 5$ m, and $l = 40$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	11.0486	0.988	1.0000	21.5	11.0821	0.463	1.0030
1.5	11.0486	0.963	1.0000	22.5	11.0898	0.438	1.0037
2.5	11.0487	0.938	1.0000	23.5	11.0993	0.413	1.0046
3.5	11.0488	0.913	1.0000	24.5	11.1111	0.388	1.0057
4.5	11.0489	0.888	1.0000	25.5	11.1257	0.363	1.0070
5.5	11.0492	0.863	1.0000	26.5	11.1439	0.338	1.0086
6.5	11.0495	0.838	1.0001	27.5	11.1667	0.313	1.0107
7.5	11.0498	0.813	1.0001	28.5	11.1953	0.288	1.0133
8.5	11.0503	0.788	1.0002	29.5	11.2313	0.263	1.0165
9.5	11.0509	0.763	1.0002	30.5	11.2771	0.238	1.0207
10.5	11.0516	0.738	1.0003	31.5	11.3356	0.213	1.0260
11.5	11.0524	0.713	1.0003	32.5	11.4111	0.188	1.0328
12.5	11.0534	0.688	1.0004	33.5	11.5097	0.163	1.0417
13.5	11.0547	0.663	1.0005	34.5	11.6408	0.138	1.0536
14.5	11.0562	0.638	1.0007	35.5	11.8198	0.113	1.0698
15.5	11.0581	0.613	1.0009	36.5	12.0746	0.088	1.0929
16.5	11.0604	0.588	1.0011	37.5	12.4663	0.063	1.1283
17.5	11.0631	0.563	1.0013	38.5	13.1762	0.038	1.1926
18.5	11.0665	0.538	1.0016	39.5	15.7409	0.013	1.4247
19.5	11.0707	0.513	1.0020	Total	232.15626		
20.5	11.0758	0.488	1.0025	MIN	11.0486		

Table A.1.5: Flow concentration distribution for $d = 0.3$ m, $z_i = 5$ m, and $l = 50$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	11.0477	0.990	1.0000	26.5	11.0604	0.470	1.0011
1.5	11.0477	0.970	1.0000	27.5	11.0631	0.450	1.0014
2.5	11.0477	0.950	1.0000	28.5	11.0665	0.430	1.0017
3.5	11.0477	0.930	1.0000	29.5	11.0707	0.410	1.0021
4.5	11.0477	0.910	1.0000	30.5	11.0758	0.390	1.0025
5.5	11.0478	0.890	1.0000	31.5	11.0820	0.370	1.0031
6.5	11.0478	0.870	1.0000	32.5	11.0898	0.350	1.0038
7.5	11.0479	0.850	1.0000	33.5	11.0993	0.330	1.0047
8.5	11.0479	0.830	1.0000	34.5	11.1111	0.310	1.0057
9.5	11.0480	0.810	1.0000	35.5	11.1257	0.290	1.0071
10.5	11.0481	0.790	1.0000	36.5	11.1439	0.270	1.0087
11.5	11.0483	0.770	1.0001	37.5	11.1667	0.250	1.0108
12.5	11.0484	0.750	1.0001	38.5	11.1953	0.230	1.0134
13.5	11.0486	0.730	1.0001	39.5	11.2314	0.210	1.0166
14.5	11.0488	0.710	1.0001	40.5	11.2771	0.190	1.0208
15.5	11.0491	0.690	1.0001	41.5	11.3357	0.170	1.0261
16.5	11.0494	0.670	1.0002	42.5	11.4111	0.150	1.0329
17.5	11.0498	0.650	1.0002	43.5	11.5098	0.130	1.0418
18.5	11.0503	0.630	1.0002	44.5	11.6409	0.110	1.0537
19.5	11.0509	0.610	1.0003	45.5	11.8199	0.090	1.0699
20.5	11.0516	0.590	1.0003	46.5	12.0746	0.070	1.0930
21.5	11.0524	0.570	1.0004	47.5	12.4663	0.050	1.1284
22.5	11.0534	0.550	1.0005	48.5	13.1763	0.030	1.1927
23.5	11.0547	0.530	1.0006	49.5	15.7409	0.010	1.4248
24.5	11.0562	0.510	1.0008	Total	287.296		
25.5	11.0581	0.490	1.0009	MIN	11.0477		

Table A.1.6: Flow concentration distribution for $d = 0.3$ m, $z_i = 2.5$ m, and $l = 20$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	9.7622	0.975	1.0000	11.5	10.0128	0.425	1.0257
1.5	9.7642	0.925	1.0002	12.5	10.0951	0.375	1.0341
2.5	9.7685	0.875	1.0006	13.5	10.2048	0.325	1.0453
3.5	9.7752	0.825	1.0013	14.5	10.3533	0.275	1.0606
4.5	9.7847	0.775	1.0023	15.5	10.5592	0.225	1.0816
5.5	9.7976	0.725	1.0036	16.5	10.8545	0.175	1.1119
6.5	9.8146	0.675	1.0054	17.5	11.3045	0.125	1.1580
7.5	9.8368	0.625	1.0076	18.5	12.0882	0.075	1.2383
8.5	9.8654	0.575	1.0106	19.5	14.6613	0.025	1.5019
9.5	9.9023	0.525	1.0144	Total	108.02172		
10.5	9.9503	0.475	1.0193	MIN	9.7622		

Table A.1.7: Flow concentration distribution for $d = 0.3$ m, $z_i = 2.5$ m, and $l = 30$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	9.7208	0.983	1.0000	16.5	9.8085	0.450	1.0090
1.5	9.7210	0.950	1.0000	17.5	9.8317	0.417	1.0114
2.5	9.7214	0.917	1.0001	18.5	9.8613	0.383	1.0145
3.5	9.7222	0.883	1.0001	19.5	9.8990	0.350	1.0183
4.5	9.7233	0.850	1.0003	20.5	9.9475	0.317	1.0233
5.5	9.7248	0.817	1.0004	21.5	10.0106	0.283	1.0298
6.5	9.7268	0.783	1.0006	22.5	10.0933	0.250	1.0383
7.5	9.7292	0.750	1.0009	23.5	10.2033	0.217	1.0496
8.5	9.7323	0.717	1.0012	24.5	10.3521	0.183	1.0649
9.5	9.7362	0.683	1.0016	25.5	10.5582	0.150	1.0861
10.5	9.7410	0.650	1.0021	26.5	10.8537	0.117	1.1165
11.5	9.7470	0.617	1.0027	27.5	11.3038	0.083	1.1628
12.5	9.7545	0.583	1.0035	28.5	12.0876	0.050	1.2435
13.5	9.7638	0.550	1.0044	29.5	14.6608	0.017	1.5082
14.5	9.7755	0.517	1.0056	Total	155.82975		
15.5	9.7901	0.483	1.0071	MIN	9.7208		

Table A.1.8: Flow concentration distribution for $d = 0.3$ m, $z_i = 2.5$ m, and $l = 40$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	9.7152	0.988	1.0000	21.5	9.7468	0.463	1.0032
1.5	9.7152	0.963	1.0000	22.5	9.7543	0.438	1.0040
2.5	9.7153	0.938	1.0000	23.5	9.7637	0.413	1.0050
3.5	9.7153	0.913	1.0000	24.5	9.7754	0.388	1.0062
4.5	9.7155	0.888	1.0000	25.5	9.7900	0.363	1.0077
5.5	9.7157	0.863	1.0000	26.5	9.8084	0.338	1.0096
6.5	9.7159	0.838	1.0001	27.5	9.8317	0.313	1.0120
7.5	9.7163	0.813	1.0001	28.5	9.8612	0.288	1.0150
8.5	9.7167	0.788	1.0001	29.5	9.8990	0.263	1.0189
9.5	9.7172	0.763	1.0002	30.5	9.9475	0.238	1.0239
10.5	9.7178	0.738	1.0003	31.5	10.0106	0.213	1.0304
11.5	9.7186	0.713	1.0003	32.5	10.0933	0.188	1.0389
12.5	9.7195	0.688	1.0004	33.5	10.2033	0.163	1.0502
13.5	9.7207	0.663	1.0006	34.5	10.3521	0.138	1.0656
14.5	9.7221	0.638	1.0007	35.5	10.5582	0.113	1.0868
15.5	9.7239	0.613	1.0009	36.5	10.8537	0.088	1.1172
16.5	9.7260	0.588	1.0011	37.5	11.3038	0.063	1.1635
17.5	9.7286	0.563	1.0014	38.5	12.0876	0.038	1.2442
18.5	9.7318	0.538	1.0017	39.5	14.6608	0.013	1.5091
19.5	9.7358	0.513	1.0021	Total	204.14382		
20.5	9.7407	0.488	1.0026	MIN	9.7152		

Table A.1.9: Flow concentration distribution for $d = 0.3$ m, $z_i = 2.5$ m, and $l = 50$ m

x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)	x (m)	Q (m^3/day)	(x/l)	(Q_x/Q_l)
0.5	9.7144	0.990	1.0000	26.5	9.7260	0.470	1.0012
1.5	9.7144	0.970	1.0000	27.5	9.7286	0.450	1.0015
2.5	9.7144	0.950	1.0000	28.5	9.7318	0.430	1.0018
3.5	9.7144	0.930	1.0000	29.5	9.7358	0.410	1.0022
4.5	9.7144	0.910	1.0000	30.5	9.7407	0.390	1.0027
5.5	9.7144	0.890	1.0000	31.5	9.7468	0.370	1.0033
6.5	9.7145	0.870	1.0000	32.5	9.7543	0.350	1.0041
7.5	9.7145	0.850	1.0000	33.5	9.7637	0.330	1.0051
8.5	9.7146	0.830	1.0000	34.5	9.7754	0.310	1.0063
9.5	9.7146	0.810	1.0000	35.5	9.7900	0.290	1.0078
10.5	9.7147	0.790	1.0000	36.5	9.8084	0.270	1.0097
11.5	9.7149	0.770	1.0000	37.5	9.8317	0.250	1.0121
12.5	9.7150	0.750	1.0001	38.5	9.8613	0.230	1.0151
13.5	9.7152	0.730	1.0001	39.5	9.8990	0.210	1.0190
14.5	9.7154	0.710	1.0001	40.5	9.9476	0.190	1.0240
15.5	9.7156	0.690	1.0001	41.5	10.0106	0.170	1.0305
16.5	9.7159	0.670	1.0002	42.5	10.0934	0.150	1.0390
17.5	9.7162	0.650	1.0002	43.5	10.2033	0.130	1.0503
18.5	9.7167	0.630	1.0002	44.5	10.3522	0.110	1.0657
19.5	9.7172	0.610	1.0003	45.5	10.5583	0.090	1.0869
20.5	9.7178	0.590	1.0004	46.5	10.8538	0.070	1.1173
21.5	9.7186	0.570	1.0004	47.5	11.3038	0.050	1.1636
22.5	9.7196	0.550	1.0005	48.5	12.0877	0.030	1.2443
23.5	9.7207	0.530	1.0007	49.5	14.6609	0.010	1.5092
24.5	9.7221	0.510	1.0008	Total	252.62409		
25.5	9.7239	0.490	1.0010	MIN	9.7144		

A.2 COLLECTOR WELL ADJACENT TO A STRAIGHT RIVER REACH

Table A.2.1: Non dimensional $Q/[kT(h_r-h_w)]$ for different R/T, l/T, and d/T

R/T	l/T	d/T = 0.1	d/T = 0.08	d/T = 0.05	d/T = 0.04	d/T = 0.03
		$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$
1	1	2.34	2.21	1.93	1.80	1.68
1	2	3.91	3.73	3.34	3.14	2.95
1	3	5.41	5.18	4.67	4.42	4.17
1	4	6.87	6.60	5.98	5.67	5.37
1	5	8.31	7.99	7.28	6.91	6.55
2	1	1.91	1.82	1.63	1.53	1.40
2	2	2.96	2.85	2.61	2.48	2.31
2	3	3.92	3.79	3.50	3.35	3.14
2	4	4.83	4.69	4.36	4.18	3.94
2	5	5.72	5.56	5.19	4.99	4.71
3	1	1.71	1.61	1.48	1.40	1.29
3	2	2.54	2.42	2.27	2.17	2.04
3	3	3.26	3.13	2.96	2.85	2.70
3	4	3.94	3.80	3.61	3.49	3.32
3	5	4.60	4.44	4.24	4.11	3.91
4	1	1.59	1.53	1.39	1.32	1.22
4	2	2.29	2.22	2.07	1.99	1.88
4	3	2.88	2.81	2.64	2.56	2.43
4	4	3.43	3.36	3.18	3.08	2.94
4	5	3.96	3.88	3.69	3.58	3.43
5	1	1.51	1.45	1.32	1.26	1.17
5	2	2.13	2.06	1.93	1.86	1.76
5	3	2.64	2.57	2.43	2.36	2.25
5	4	3.10	3.04	2.89	2.81	2.69
5	5	3.55	3.48	3.32	3.24	3.11
10	1	1.29	1.24	1.15	1.10	1.03
10	2	1.72	1.68	1.59	1.54	1.47
10	3	2.05	2.01	1.92	1.87	1.80
10	4	2.33	2.29	2.21	2.16	2.09
10	5	2.59	2.56	2.47	2.42	2.35

Table A.2.2: Non dimensional $Q/[kT(h_r-h_w)]$ for different z/T

z/T	R/T = 5 ; l/T = 5	
	Q (m^3/day)	$Q/[kT(h_r-h_w)]$
0.33	351.09762	3.51
0.40	353.35696	3.53
0.50	354.60028	3.55
0.60	353.38616	3.53
0.67	351.1113	3.51

Table A.2.3: Non dimensional $Q/[kT(h_r-h_w)]$ for different number of laterals, n

R/T	d/T	l/T	1 Lateral	2 Lateral	3 Lateral	5 Lateral	6 Lateral
			$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kT(h_r-h_w)]$	$Q/[kl(h_r-h_w)]$
5	0.1	0.5	0.80	1.10	1.26	1.44	0.10
5	0.1	0.75	0.97	1.33	1.52	1.73	0.08
5	0.1	1	1.12	1.52	1.74	1.97	0.07
5	0.1	1.5	1.38	1.85	2.11	2.39	0.05
5	0.1	2	1.61	2.15	2.46	2.78	0.05
5	0.1	2.5	1.84	2.44	2.80	3.19	0.04
5	0.1	3	2.09	2.74	3.14	3.61	0.04
14.3	0.04	4.29	1.65	1.88	2.12	2.33	2.39
10	0.03	3	1.54	1.78	1.98	2.21	2.28

A.3 COLLECTOR WELL NEAR A MEANDERING RIVER

Table A.3.1: *$Q/[kT(h_r-h_w)]$* with R=50 m, p=20%, T=5 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.50	5.00	5.00	4.00	0.10	0.20	0.80	7061.00	4.03
5	0.50	5.00	5.00	4.00	0.10	0.20	0.80	8592.25	4.91
6	0.50	5.00	5.00	4.00	0.10	0.20	0.80	9102.73	5.20
8	0.50	5.00	5.00	4.00	0.10	0.20	0.80	9727.89	5.56
12	0.50	5.00	5.00	4.00	0.10	0.20	0.80	10719.37	6.13
3	0.60	6.00	5.00	5.00	0.10	0.17	0.83	8341.83	4.77
5	0.60	6.00	5.00	5.00	0.10	0.17	0.83	10402.45	5.94
6	0.60	6.00	5.00	5.00	0.10	0.17	0.83	11061.79	6.32
8	0.60	6.00	5.00	5.00	0.10	0.17	0.83	11928.39	6.82
12	0.60	6.00	5.00	5.00	0.10	0.17	0.83	13233.37	7.56
3	0.70	7.00	5.00	6.00	0.10	0.14	0.86	9826.56	5.62
5	0.70	7.00	5.00	6.00	0.10	0.14	0.86	12559.94	7.18
6	0.70	7.00	5.00	6.00	0.10	0.14	0.86	13481.51	7.70
8	0.70	7.00	5.00	6.00	0.10	0.14	0.86	14693.04	8.40
12	0.70	7.00	5.00	6.00	0.10	0.14	0.86	16769.49	9.58

Table A.3.2: *$Q/[kT(h_r-h_w)]$* with R=50 m, p=2 %, T=6 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.50	4.17	5.00	3.33	0.08	0.20	0.80	8025.32	3.82
5	0.50	4.17	5.00	3.33	0.08	0.20	0.80	9865.39	4.70
6	0.50	4.17	5.00	3.33	0.08	0.20	0.80	10483.96	4.99
8	0.50	4.17	5.00	3.33	0.08	0.20	0.80	11237.48	5.35
12	0.50	4.17	5.00	3.33	0.08	0.20	0.80	12460.80	5.93
3	0.60	5.00	5.00	4.17	0.08	0.17	0.83	9492.31	4.52
5	0.60	5.00	5.00	4.17	0.08	0.17	0.83	11931.31	5.68
6	0.60	5.00	5.00	4.17	0.08	0.17	0.83	12717.63	6.06
8	0.60	5.00	5.00	4.17	0.08	0.17	0.83	13744.14	6.54
12	0.60	5.00	5.00	4.17	0.08	0.17	0.83	15335.29	7.30
3	0.70	5.83	5.00	5.00	0.08	0.14	0.86	11175.90	5.32
5	0.70	5.83	5.00	5.00	0.08	0.14	0.86	14370.60	6.84
6	0.70	5.83	5.00	5.00	0.08	0.14	0.86	15448.67	7.36
8	0.70	5.83	5.00	5.00	0.08	0.14	0.86	16861.11	8.03
12	0.70	5.83	5.00	5.00	0.08	0.14	0.86	19338.17	9.21

Table A.3.3: $Q/[kT(h_r-h_w)]$ with R=60 m, p=10%, T=4 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	6.25	5.00	5.00	0.17	0.83	0.08	4446.71	3.18
5	0.42	6.25	5.00	5.00	0.17	0.83	0.08	5477.35	3.91
6	0.42	6.25	5.00	5.00	0.17	0.83	0.08	5753.02	4.11
8	0.42	6.25	5.00	5.00	0.17	0.83	0.08	6306.88	4.50
12	0.42	6.25	5.00	5.00	0.17	0.83	0.08	6694.67	4.78
3	0.50	7.50	5.00	6.25	0.17	0.83	0.13	5604.78	4.00
5	0.50	7.50	5.00	6.25	0.17	0.83	0.13	6793.17	4.85
6	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7145.69	5.10
8	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7616.99	5.44
12	0.50	7.50	5.00	6.25	0.17	0.83	0.13	8369.04	5.98

Table A.3.4: $Q/[kT(h_r-h_w)]$ with R=60 m, p=15%, T=4 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	6.25	5.00	5.00	0.17	0.83	0.08	5267.79	3.76
5	0.42	6.25	5.00	5.00	0.17	0.83	0.08	6415.30	4.58
6	0.42	6.25	5.00	5.00	0.17	0.83	0.08	6860.92	4.90
8	0.42	6.25	5.00	5.00	0.17	0.83	0.08	7571.68	5.41
12	0.42	6.25	5.00	5.00	0.17	0.83	0.08	8107.66	5.79
3	0.50	7.50	5.00	6.25	0.17	0.83	0.13	5918.95	4.23
5	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7107.37	5.08
6	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7457.30	5.33
8	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7934.85	5.67
12	0.50	7.50	5.00	6.25	0.17	0.83	0.13	8661.53	6.19

Table A.3.5: $Q/[kT(h_r-h_w)]$ with R=60 m, p=20%, T=4 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	6.25	5.00	5.00	0.17	0.83	0.08	6044.49	4.32
5	0.42	6.25	5.00	5.00	0.17	0.83	0.08	7469.31	5.34
6	0.42	6.25	5.00	5.00	0.17	0.83	0.08	8016.43	5.73
8	0.42	6.25	5.00	5.00	0.17	0.83	0.08	8947.02	6.39
12	0.42	6.25	5.00	5.00	0.17	0.83	0.08	9643.85	6.89
3	0.50	7.50	5.00	6.25	0.17	0.83	0.13	6096.63	4.35
5	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7287.27	5.21
6	0.50	7.50	5.00	6.25	0.17	0.83	0.13	7636.61	5.45
8	0.50	7.50	5.00	6.25	0.17	0.83	0.13	8119.28	5.80
12	0.50	7.50	5.00	6.25	0.17	0.83	0.13	8832.17	6.31

Table A.3.6: $Q/[kT(h_r-h_w)]$ with R=60 m, p=10%, T=6 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	4.17	5.00	3.33	0.17	0.83	0.05	5743.64	2.74
5	0.42	4.17	5.00	3.33	0.17	0.83	0.05	7304.36	3.48
6	0.42	4.17	5.00	3.33	0.17	0.83	0.05	7759.80	3.70
8	0.42	4.17	5.00	3.33	0.17	0.83	0.05	8672.12	4.13
12	0.42	4.17	5.00	3.33	0.17	0.83	0.05	9308.19	4.43
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	7474.65	3.56
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9266.70	4.41
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9810.91	4.67
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10521.92	5.01
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11725.91	5.58

Table A.3.7: $Q/[kT(h_r-h_w)]$ with R=60 m, p=15%, T=6 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	4.17	5.00	3.33	0.17	0.83	0.05	6860.99	3.27
5	0.42	4.17	5.00	3.33	0.17	0.83	0.05	8568.09	4.08
6	0.42	4.17	5.00	3.33	0.17	0.83	0.05	9265.09	4.41
8	0.42	4.17	5.00	3.33	0.17	0.83	0.05	10392.92	4.95
12	0.42	4.17	5.00	3.33	0.17	0.83	0.05	11235.29	5.35
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	8019.88	3.82
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9807.72	4.67
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10343.84	4.93
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11059.15	5.27
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	12214.87	5.82

Table A.3.8: $Q/[kT(h_r-h_w)]$ with R=60 m, p=20%, T=6 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.42	4.17	5.00	3.33	0.17	0.83	0.05	7899.44	3.76
5	0.42	4.17	5.00	3.33	0.17	0.83	0.05	9967.18	4.75
6	0.42	4.17	5.00	3.33	0.17	0.83	0.05	10803.45	5.14
8	0.42	4.17	5.00	3.33	0.17	0.83	0.05	12228.96	5.82
12	0.42	4.17	5.00	3.33	0.17	0.83	0.05	13296.20	6.33
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	8333.09	3.97
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10118.99	4.82
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10651.35	5.07
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11371.22	5.41
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	12500.49	5.95

Table A.3.9: $Q/[kT(h_r-h_w)]$ with R=60 m, p=10%, T=8 m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.50	3.75	5.00	3.13	0.17	0.83	0.06	8919.36	3.19
5	0.50	3.75	5.00	3.13	0.17	0.83	0.06	11308.81	4.04
6	0.50	3.75	5.00	3.13	0.17	0.83	0.06	12053.69	4.30
8	0.50	3.75	5.00	3.13	0.17	0.83	0.06	13017.95	4.65
12	0.50	3.75	5.00	3.13	0.17	0.83	0.06	14710.80	5.25
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	7474.65	3.56
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9266.70	4.41
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9810.91	4.67
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10521.92	5.01
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11725.91	5.58

Table A.3.10: $Q/[kT(h_r-h_w)]$ with R=60m, p=15%, T=8m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.50	3.75	5.00	3.13	0.17	0.83	0.06	9689.98	3.46
5	0.50	3.75	5.00	3.13	0.17	0.83	0.06	12344.19	4.41
6	0.50	3.75	5.00	3.13	0.17	0.83	0.06	12815.85	4.58
8	0.50	3.75	5.00	3.13	0.17	0.83	0.06	13783.48	4.92
12	0.50	3.75	5.00	3.13	0.17	0.83	0.06	15402.80	5.50
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	8019.88	3.82
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	9807.72	4.67
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10343.84	4.93
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11059.15	5.27
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	12214.87	5.82

Table A.3.11: $Q/[kT(h_r-h_w)]$ with R=60m, p=20%, T=8m for different collector well geometry

n	l/R	l/T	l_b	l_s/T	d/T	l_b/l (%)	l_s/l (%)	Q (m^3/day)	$Q/kT(h_r-h_w)$
3	0.50	3.75	5.00	3.13	0.17	0.83	0.06	10138.90	3.62
5	0.50	3.75	5.00	3.13	0.17	0.83	0.06	12530.15	4.48
6	0.50	3.75	5.00	3.13	0.17	0.83	0.06	13256.42	4.73
8	0.50	3.75	5.00	3.13	0.17	0.83	0.06	14227.92	5.08
12	0.50	3.75	5.00	3.13	0.17	0.83	0.06	15806.16	5.65
3	0.50	5.00	5.00	4.17	0.17	0.83	0.08	8333.09	3.97
5	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10118.99	4.82
6	0.50	5.00	5.00	4.17	0.17	0.83	0.08	10651.35	5.07
8	0.50	5.00	5.00	4.17	0.17	0.83	0.08	11371.22	5.41
12	0.50	5.00	5.00	4.17	0.17	0.83	0.08	12500.49	5.95