PREDICTION OF GROUNDWATER IMPACTS FOR EXCAVATIONS

Ross James Best

Senior Principal, Coffey Geotechnics Pty Ltd

ABSTRACT

Groundwater inflow and levels associated with excavations are important considerations for construction and operation of the completed development. Drawdown associated with excavation has potential to result in settlement, impacts on vegetation and ecosystems and the distribution of existing groundwater contamination. Inflows to excavations need to be dealt with including possible need for treatment prior to release to the surface water system.

The paper presents methods which can be used to address a range of groundwater issues associated with excavation drawing upon closed form analytical methods. The methods presented are illustrated with examples drawn from practice.

Topics discussed include:

- Prediction of maximum groundwater level over the design life of a project
- Prediction of the rate of groundwater inflow to an excavation
- Prediction of groundwater level drawdown associated with excavation.

1 INTRODUCTION

Prediction of the effects on the groundwater system due to excavation are important for the successful development of projects. Analysis methods range from brief hand calculation to a range of analytical methods and numerical methods. Over recent years there has be a tendency to make predictions predominantly using computer based numerical methods. This has the attraction of reducing the mathematical demands on the practitioner but can result in lack of appreciation of important aspects of the groundwater assessment.

A rich heritage of analytical methods is available and these are often overlooked in excavation related groundwater analysis. This paper provides a description of some methods the author has found useful for practical problems.

Groundwater evaluations in relation to excavations are often needed to predict:

- Groundwater levels under normal conditions and during extreme events,
- Inflows to excavations during construction and in the long term,
- Drawdown impacts on the area around the excavation.

2 PREDICTION OF GROUNDWATER LEVELS

The starting point for an assessment of interaction between an excavation and the groundwater system is the assessment of the exiting groundwater regime including an appraisal of the geology, hydrogeology and hydraulic properties of the ground and an assessment of groundwater levels. The assessment of groundwater levels typically requires appraisal of the average conditions as this is required to predict the extent of impact of the excavation. It may also be important to predict extreme conditions associated with unusually high rain fall or flood events as this affects the maximum seepage rates to groundwater pressures over the life of an in ground structure.

2.1 AVERAGE CONDITIONS

Groundwater levels are routinely measured during geotechnical and contaminated land investigations prior to excavations for buildings or civil works such as shafts. For linear infrastructure such as roads and rail lines which may involve large numbers of cutting excavations, monitoring during initial investigations may be limited to a handful of locations with little or no background monitoring available at a number of planned cuttings.

Some well-established analytical solutions can provide a useful basis for assessment of typical groundwater levels during early stages of planning and design. Other methods can be helpful in predicting the changes in groundwater level which may arise during periods of high rainfall or in response to flooding or other water level rise in nearby water bodies.

Road or rail cuttings may cut spurs or pass across the lower slopes of hills. A situation of this kind is illustrated in Figure 1 below.

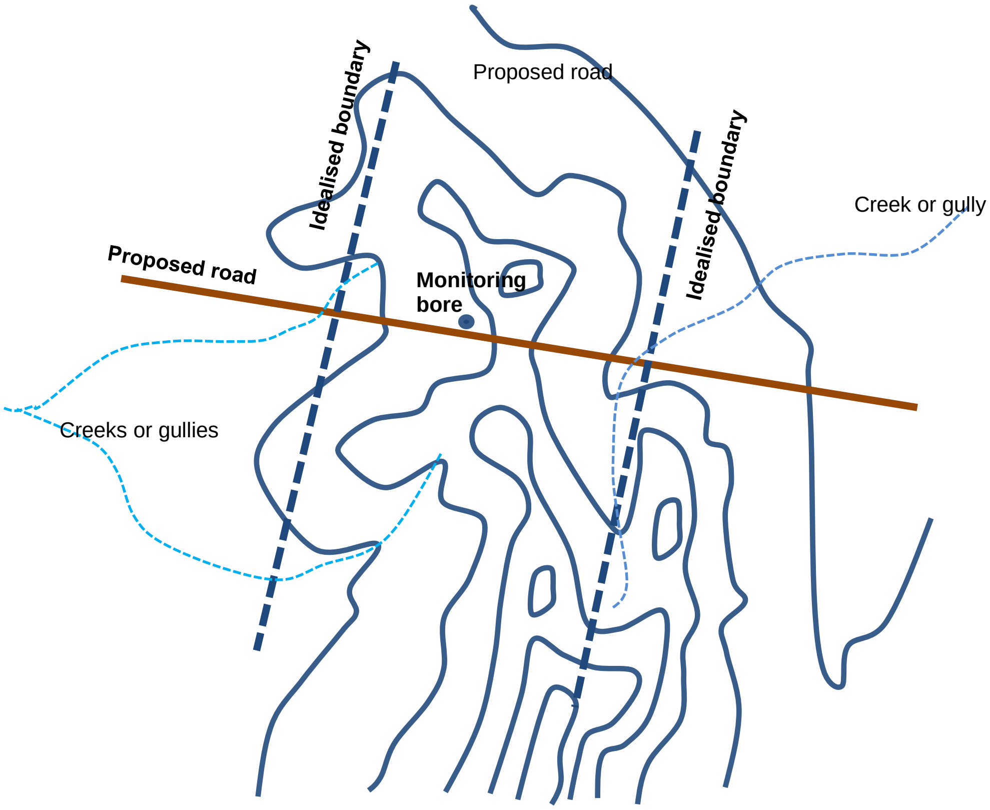


Figure 1: Linear excavations across spurs and hillsides

In these situations a prediction of average groundwater level can be made using the simplified models illustrated in Figure 2 by treating the ground as having uniform permeability above an impermeable horizon. Groundwater level can be treated as stable in flanking creeks or gullies or in low lying ground surrounding hills or spurs. The parameters required to make the assessment are the thickness and lateral permeability of the main water bearing horizon and the average rate of net infiltration to the water table.

As an aside, there are several terms in common use which describe the property of a porous medium to allow fluid flow:

- *Hydraulic conductivity* is used to describe the property of a porous medium governing the flow of water
- *Permeability* is commonly used by engineers to mean hydraulic conductivity as described above
- *Intrinsic permeability* is a term used to describe a property of the porous medium which can be used to develop expressions for conductivity of flow of a range on fluids (not only water).

A good discussion of these distinctions is provided by Freeze and Cherry (1979).

In this paper the term *permeability* is used to describe the property governing seepage of water through saturated porous media and the symbol k is used. This is taken as a constant of proportionality providing the rate of water seepage flow through unit area under unit hydraulic gradient.

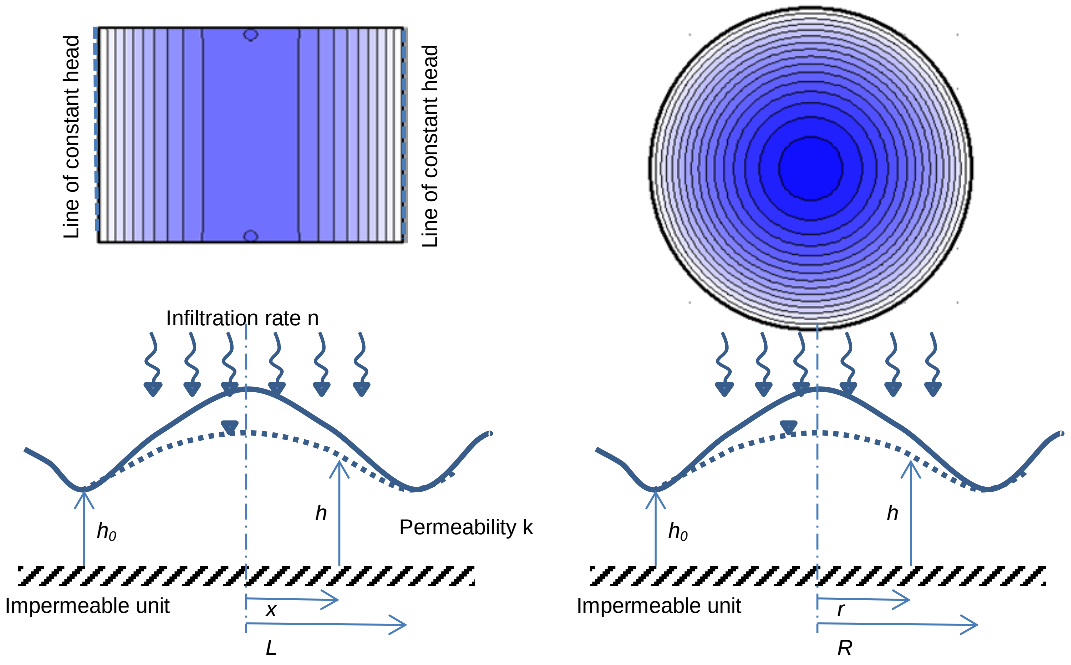


Figure 2 - Flow between two head controlled boundaries such as rivers and within a circular hill

While the idealised conditions illustrated in Figure 2 will never be perfectly met the simplification does provide a useful means of prediction of groundwater level where there is a reasonable basis for assessment of infiltration rate (n) and permeability (k). If the groundwater profile is known the relationship between infiltration and permeability can be interpreted. This could provide a basis for prediction in nearby areas with similar conditions where no measurements were available.

Employing the Dupuit-Forchheimer assumption (disregarding vertical flow and treating flow as horizontal) for the case of a strip it can readily be shown that:

$$h = \sqrt{{h_0}^2 + \frac{n\,(L^2 - x^2)}{k}} \qquad \text{Eqn 1}$$

$$h_{max} = \sqrt{{h_0}^2 + \frac{n\,L^2}{k}} \qquad \text{Eqn 2}$$

For the case of a circular hill it can readily be shown that:

$$h = \sqrt{{h_o}^2 + \frac{n\,(R^2 - r^2)}{2k}} \qquad \text{Eqn 3}$$

$$h_{max} = \sqrt{{h_o}^2 + \frac{n\,R^2}{2k}} \qquad \text{Eqn 4}$$

The groundwater level distribution depends upon the ratio of the rate of infiltration to the permeability. Note that the reference point is important and must be taken from the base of the permeable horizon. It is interesting to note that the head distribution beneath a circular hill is similar in form to that beneath a strip.

In areas which are flat or gently sloping groundwater levels tend to stabilise near the ground surface with the depth controlled by the balance between surface infiltration and losses from surface and near surface effects of evaporation, evapo-transpiration and seepage to drainage features such as creeks, road drainage. In some areas, groundwater extraction for water supply or other purposes has a significant effect on groundwater levels and would need to be considered.

The relationships illustrated in Figures 2 and in Equations 1 to 4 relate to average or typical groundwater conditions and they don’t address fluctuations in groundwater level associated with individual rainfall events. They do not apply when the groundwater mound resulting from rainfall infiltration approaches the ground surface. Under these conditions it is helpful to assume that under typical conditions groundwater level is at an equilibrium position were losses from evapo-transpiration and seepage to drainage features is in balance with the average rate of infiltration. Disturbance to this equilibrium caused by excavation can then be assessed based upon the interpreted lateral permeability and the rate of infiltration.

2.2 CHANGES IN GROUNDWATER LEVEL

Fluctuation about average or typical conditions will occur as a result of changes in rainfall and in response to changes in the water level at the boundaries.

A short duration period of high rainfall and corresponding above average infiltration in uniform terrain would result in a step increase in groundwater level. This will quickly reduce close to boundaries where stable groundwater levels occur and will decay more slowly with increasing distance from boundaries. This is analogous the consolidation behaviour familiar to geotechnical engineers. Results from consolidation theory can be applied to the corresponding groundwater problem as the processes involved are similar.

In practice prediction of the possible magnitude of groundwater level fluctuation is best guided by measurement of groundwater level over time. Manual measurement at regular intervals are helpful where groundwater levels changes slowly in response to rainfall but in many cases regular measurements of this kind will fail to record the maximum groundwater level rise for a particular event. Continuous groundwater level monitoring is much more helpful for identifying peak response.

Figure 3 presents the results of continuous monitoring of groundwater level at a location within the Botany Sands near a drain. Figure 3 also illustrates the results of a simple fitted model based on the assumption that in the absence of rainfall groundwater level would eventually fall to a selected level at a rate which is proportional to the difference between the current level and the long term level and groundwater level rises by an amount proportional to daily rainfall recorded at a nearby weather station. The modelled response was obtained by selection of the long term level the rate of decay and the increase associated with daily rainfall. More elaborate infiltration relationships are possible but the adopted model provided a reasonable fit over the monitoring period. This model was then used in conjunction with a long term rainfall record to model groundwater level variation for the historical rainfall record to predict the likelihood of particular groundwater levels being exceeded.

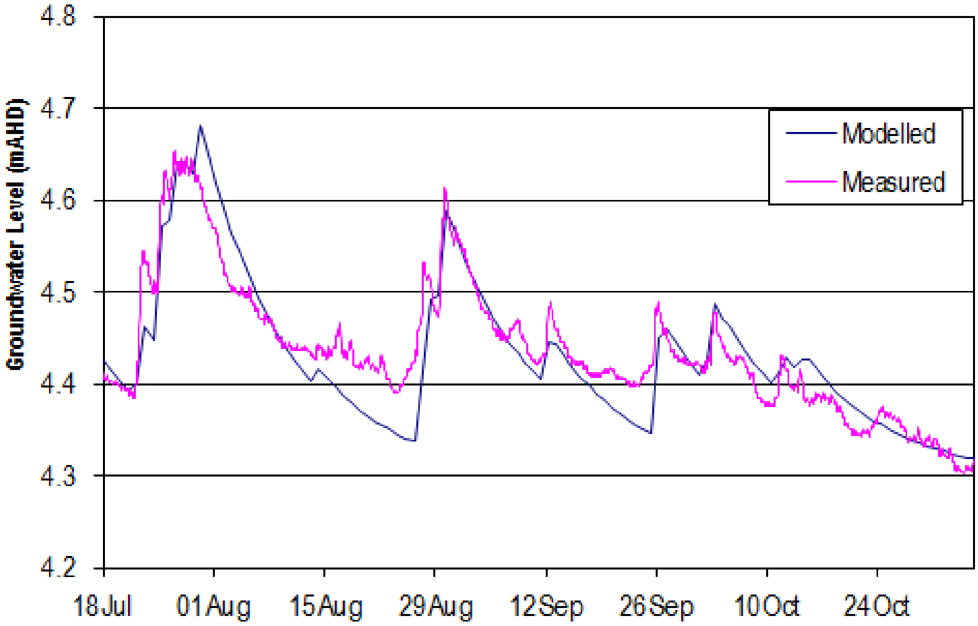
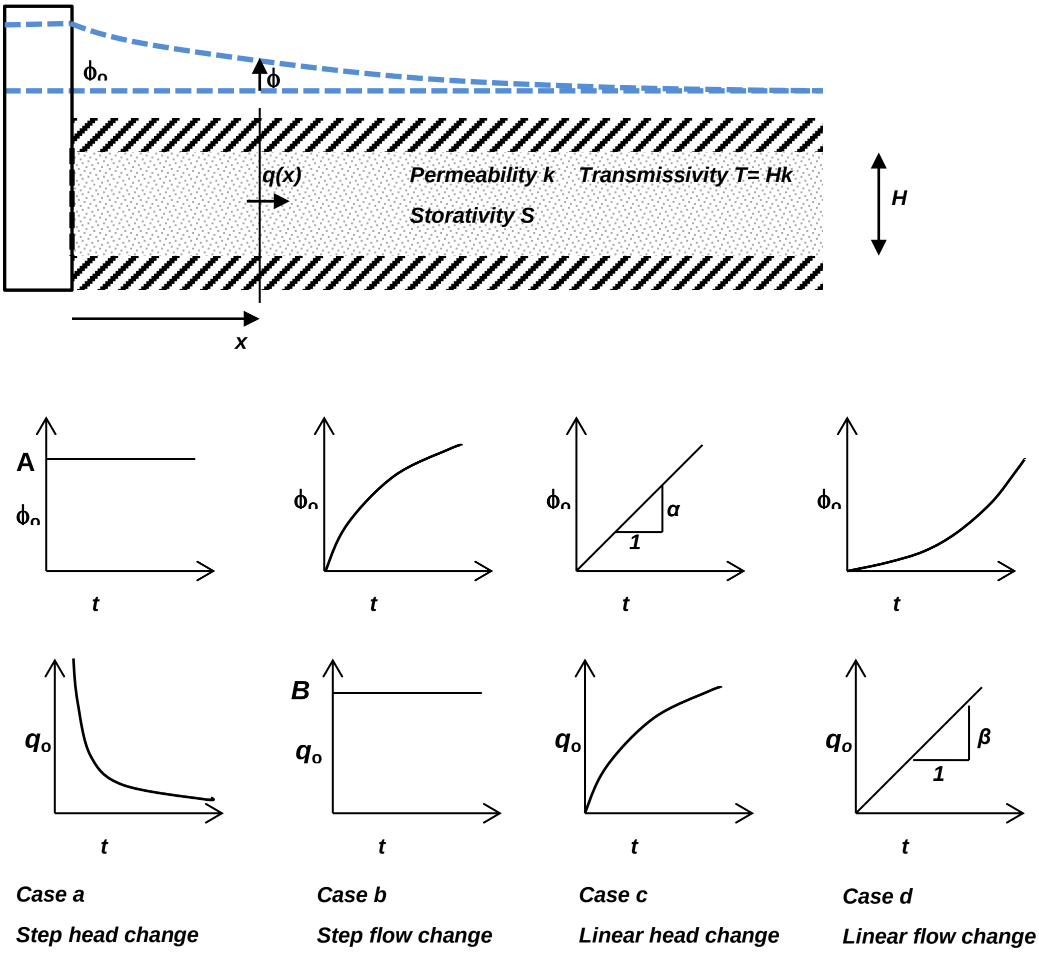


Figure 3: Groundwater response to rainfall and simple heuristic model

Groundwater response to change in water level in rivers other water bodies can also be of interest. A useful collection of analytical results is compiled by Edelman (1972) and illustrated in Figure 4. These analytical relationships allow the development of a model of groundwater response a nominated distance from a river subject to a flood event.



Case a
Step head change

Case b
Step flow change

Case c
Linear head change

Case d
Linear flow change

Figure 4: Various cases for change to flow in a canal at the edge of an extensive aquifer (see Edelman 1972)

Table 1 – Analytical Solutions – Flow near canal

Case	Head in aquifer	Flow in aquifer	Definitions (see also Figure 4)
a Step head change	$\emptyset_a = -A\,f_1$	$q_a = \frac{-A\,a\,f_0}{\sqrt{t}}$	$u = \sqrt{\frac{x^2 S}{4Tt}}$ $a = \frac{1}{2}\sqrt{ST}$ $f_0 = \frac{2}{\pi}e^{-u^2}$ $f_2 = \frac{f_0}{2} + uf_1$ $f_1 = -\mathrm{erfc}(u)$ $f_3 = \frac{u}{4}f_0 + \left(\frac{u^2}{2} + \frac{1}{4}\right)f_1$ $f_4 = \frac{u^2+1}{12}f_0 + \left(\frac{u^3}{6} + \frac{u}{4}\right)f_1$ Note: erfc is the complementary error function.
b Step flow change	$\emptyset_b = \frac{-B\sqrt{t}\,f_2}{a}$	$q_b = -B\,f_1$	
c Linear head change	$\emptyset_c = -4\,\alpha\,t\,f_3$	$q_c = -4\,\alpha\,a\sqrt{t}\,f_2$	
d Linear flow change	$\emptyset_d = -\frac{4\,\beta\,t^{3/2}\,f_4}{a}$	$q_d = -4\,\beta\,t\,f_3$	

The hydrograph for a river can be represented in a piecewise linear fashion and the results of the relationships in Figure 4 can be combined in a spread sheet tool to predict groundwater response to flood hydrographs. This is illustrated in Figure 5 for prediction of response to a flood event lasting one day at a distance of 30 m from the river (T=50 m^2/d, S=0.05).

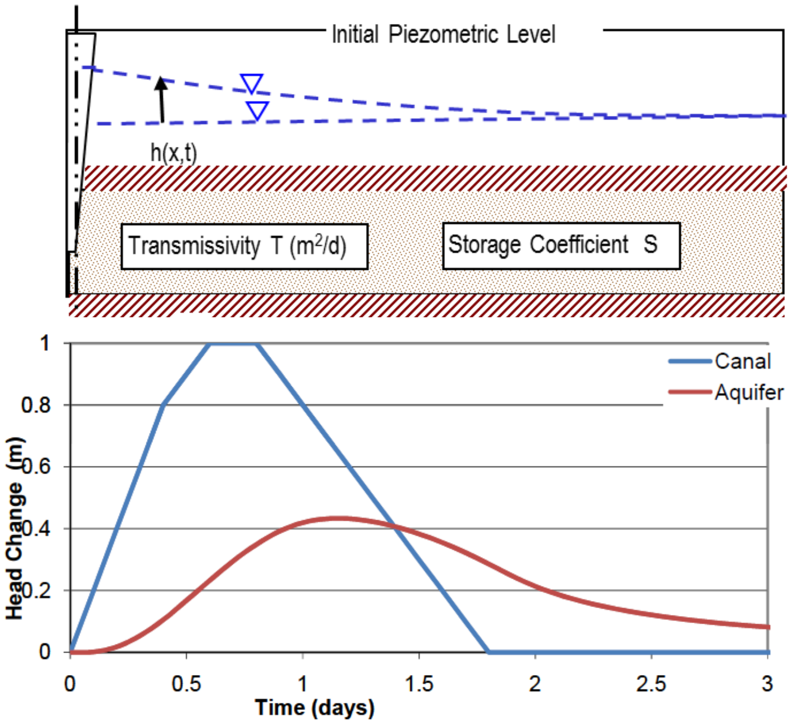


Figure 5: Modelled groundwater response to a flood hydrograph

The analytical solutions presented in Figure 4 and Table 1 apply to extensive systems. It is possible to extend these using image methods to address the range of conditions in Figure 4. The image methods involve superposition of a series of canals in an extensive system enforce barrier boundaries or nominated level boundaries. A good discussion of this process is described by Edelman (1972) and is illustrated for a barrier boundary in Figure 6.

In Figure 6, a canal is represented at position A and boundary which prevents lateral flow (such as a sheet pile wall or building basement) is represented at position B. Groundwater level between A and B should match the modelled changes at the canal A and have zero gradient at the barrier boundary at B. The initial groundwater level is represented by a broken line just above the change the permeable zone.

The resulting groundwater level at a particular time for some change in the canal at A if it were in an extensive aquifer persisting to the right is represented by the solid emanating from A. Note that this produces a gradient at the position of the boundary. To neutralise that gradient, the groundwater changes due to an image canal (identical to that at A) at position 1 are superimposed (the solid line emanating from 1). This has the effect of producing an equal and opposite gradient at the boundary thus representing the no-flow condition.

While the groundwater level changes caused by the image canal at position 1 result in zero gradient at the barrier (position B). There is also a change in groundwater level produced at position A. To correct this groundwater changes resulting from a second image canal at position 2 equal in strength to the effect imposed at A but opposite in sign are applied. This results in an equal but opposite effect at position to that caused by the image canal at position 1. This results in matching of the desired response at position A but introduces a non-zero gradient at the position of barrier (B).

Further image canals are introduced to successively enforce the correct head conditions at A and the no-flow condition at B. With each additional image the conditions between A and B become closer to the desire result. Note that image canals at equal distance on either side of A are opposite in sign resulting in no combined change at A and not that image canals at equal distance on either side of B are of the same sign resulting in no change in gradient at B.

A similar process can be used to represent the presence of a constant head boundary near a canal.

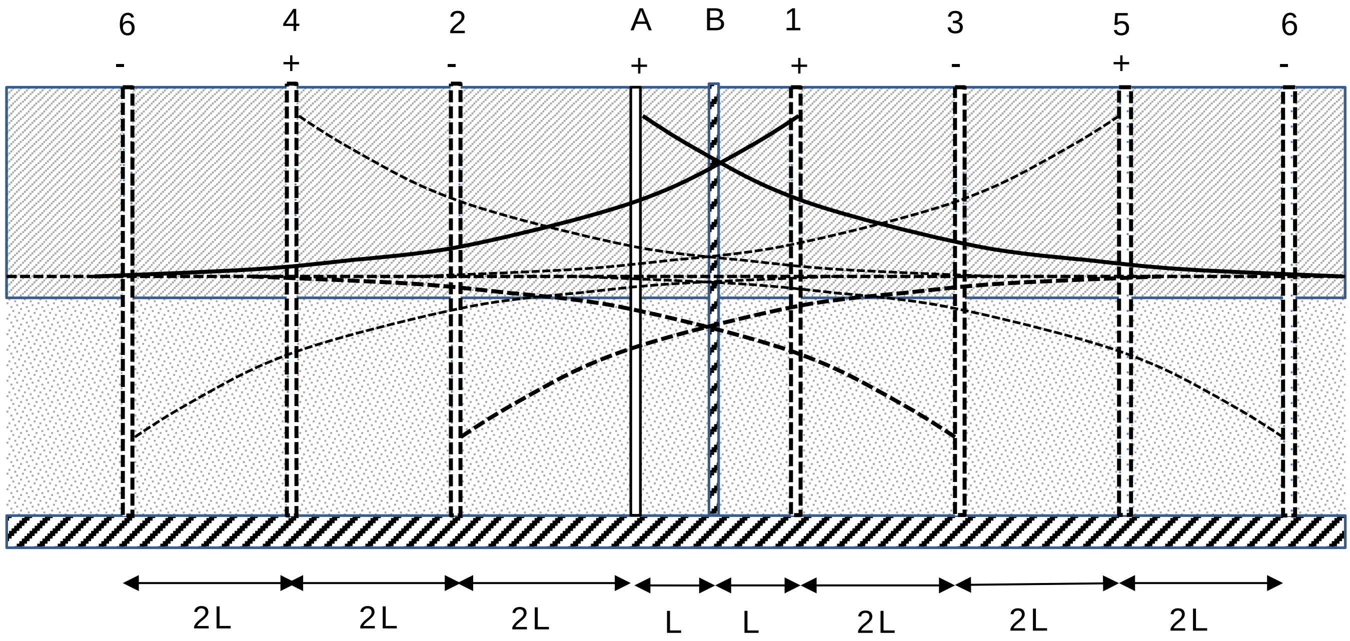


Figure 6: Modelling of a no-flow barrier boundary near a canal using superposition

3 PREDICTION OF INFLOW TO EXCAVATIONS

It is useful to divide the assessment of inflow to an excavation into cases where engineering measures are include to restrict seepage to an excavation from those where groundwater is allow to seep to an excavation unimpeded. Typical measures to control the rate of seepage include the use of cut off wall such as sheet piling, secant piles (where adjacent piles overlap to form a consistent barrier to seepage) and diaphragm walls where panels connected by water stops are installed into the ground. Typically cut off walls are installed to penetrate a permeable horizon and to be founded in a horizon of comparatively low permeability. As illustrated in Figure 7.

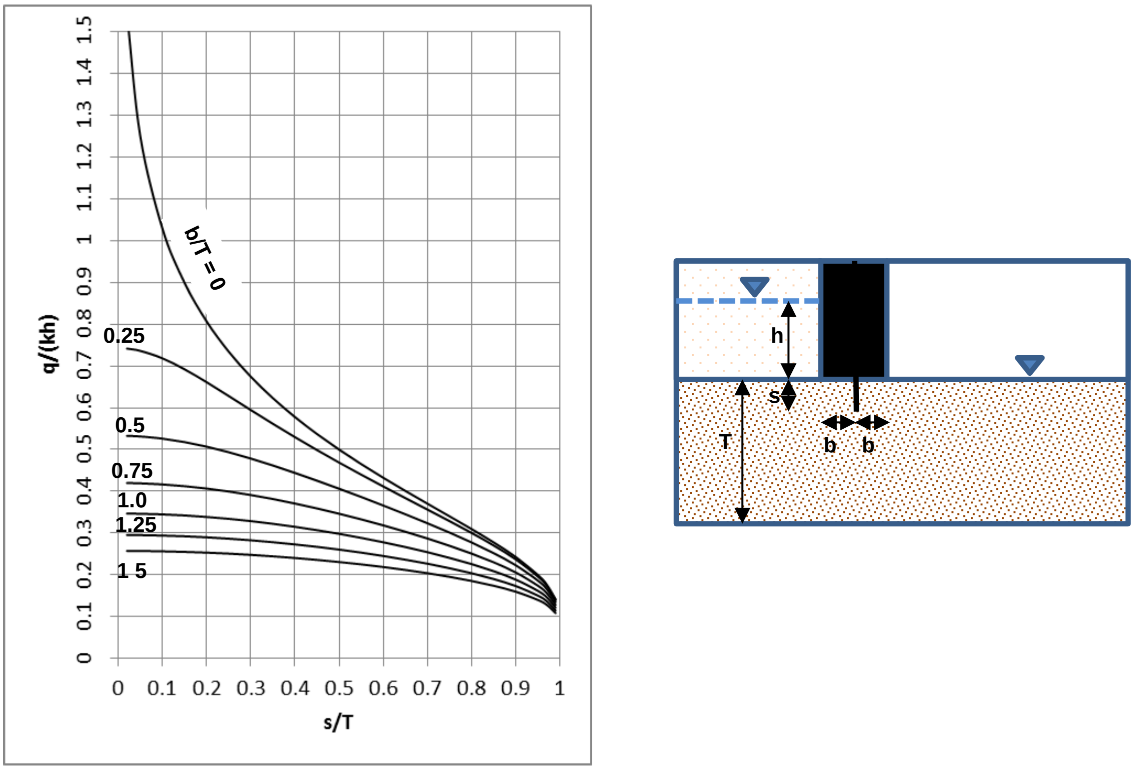


Figure 7: Cut off wall to reduce seepage to an excavation (see Harr 1962 after Polubarinova-Kochina 1952)

Closed form solutions to idealisations of this problem were developed by Kochina-Pouloborinova (1952) and a useful collation of these is presented by Harr (1962) including the solutions for flow rate and exit gradients for flow to a trench between two cut off walls within a deep permeable formation and solutions where two layers of different permeability are present beneath the toe of the cut off wall. While these cases can be readily modelled using commercially available finite element modelling tools, the use of analytical methods provides a means of rapid assessment of alternative designs and allows interpretation of the sensitivity of the rate of seepage to changes in the cut off wall design.

Figure 7 presents the results for seepage beneath a cut off wall penetrating different depths into permeable ground underlain by an impermeable unit. For the purposes of predictions it is common to assume groundwater level outside the wall does not change. Note that changes to the depth of the cut off wall have a modest influence on the rate of seepage for cases of practical interest where the cut off penetrates between 10% and 20% of the permeable horizon (in other words doubling the depth of penetration of the cut off wall) results in only 20% reduction in seepage rate. It is also useful to note that seepage rates increase sharply as the gap between the toe of the cut of wall and underlying impermeable ground increases. If the cut off wall penetrates to essentially impermeable ground the seepage rate would be negligible but increase sharply if a window of permeable material remains. It is therefore preferable to penetrate to effectively impermeable ground if this is practicable rather than tolerating even a narrow window of permeable ground beneath the toe of a cut off wall.

Not all shoring walls for excavations provide a barrier to groundwater inflow. Use of soldier pile walls with shotcrete infill is common for support of excavations in relatively low permeability ground including clay and weathered shale. While seepage rate and potential zone of impact are typically small in low permeability settings, predictions may be required to address regulatory requirements or for design of permanent drainage. An analytical tool which is useful in this regard is illustrated in Figure 8. The excavation is idealised as being circular and the ground profile is treated as having a horizon of uniform lateral permeability over lying an impermeable base. Infiltration capacity in surrounding the excavation is treated as uniform. The method addressed long terms impacts and so the estimate of inflow does not address the initial rate of inflow. Initial inflows can readily be assessed using the well-known Thiess (1935) equation for transient flow to a well described for example in Freeze and Cherry (1979).

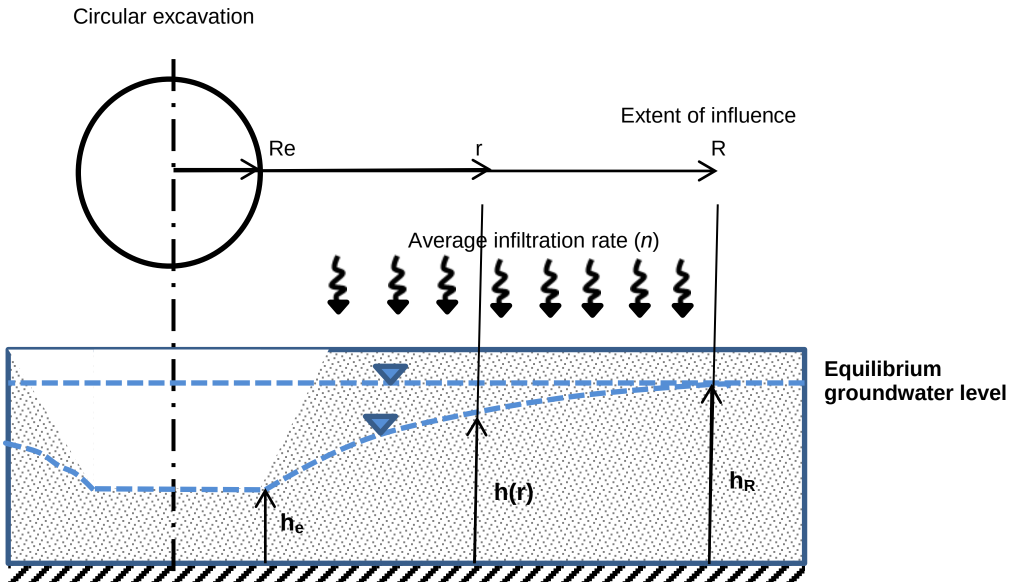


Figure 8: Groundwater level variation near a stable water level

It can readily be shown, as discussed in Edelman (1972), that the groundwater level above the impermeable base is given by:

$$h(r) = \sqrt{{h_e}^2 + \frac{n}{k}\left(R^2 \ln\left(\frac{r}{R_e}\right) - \frac{(r^2 - {R_e}^2)}{2}\right)} \qquad \text{Eqn 5}$$

Where R is the point beyond which groundwater level is unaffected. This can be found by trial and error as the value of R for which groundwater level is at h_R, the pre-development level. Figure 9 shows the relationship between the radius of influence R expressed as a multiple of the excavation radius and the non-dimensional parameter λ defined in Equation 6.

$$\lambda = \frac{k({h_R}^2 - {h_e}^2)}{n{R_e}^2} \qquad \text{Eqn 6}$$

Total groundwater seepage, Q, to the excavation is given by:

$$Q = \pi\, n\, (R^2 - {R_e}^2) \qquad \text{Eqn 7}$$

These relationships have proven useful for assessment of seepage and extent of influence. The extent of influence is a function of the ratio of potential infiltration rate to the ground permeability and the magnitude of the drawdown.

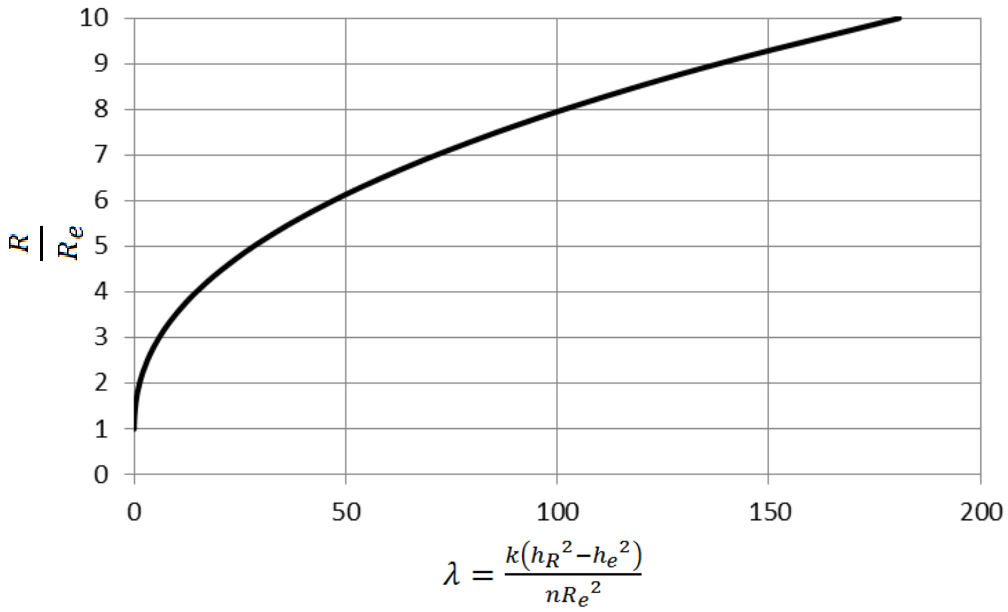


Figure 9: Extent of influence of circular excavation

4 PREDICTION OF IMPACT FROM EXCAVATIONS

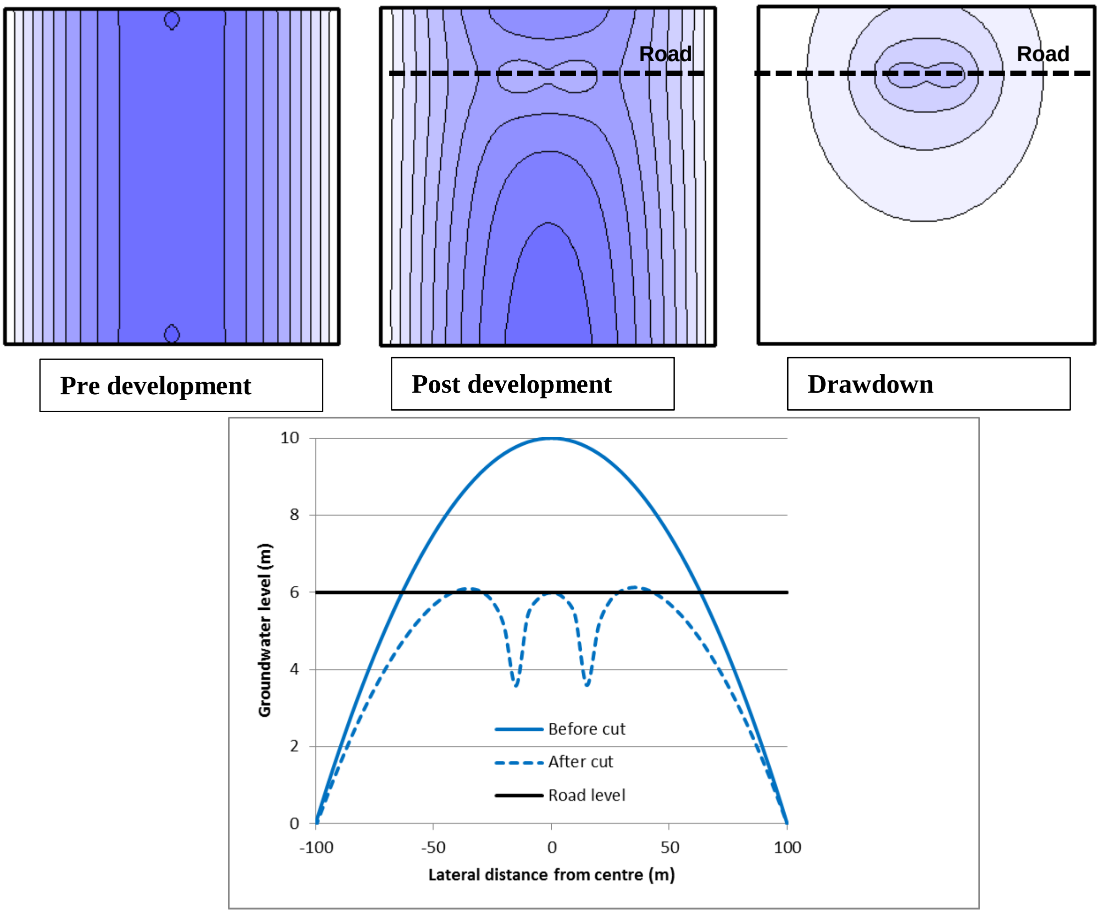
4.1 GROUNDWATER FLOW TO ROAD EXCAVATIONS

Road and rail projects typically involve a number of cuts to achieve the desired horizontal and vertical alignment. These cuts often involve excavation across ridges, spurs or through the slopes of hills. During design, the groundwater conditions tend to be defined by a limited number of piezometric records at a few of the cuts and a scattering of records from such things as records from installation of licenced groundwater bores or perhaps monitoring results for other projects. In addition to this information, ground surface contours and a general appreciation of the geological setting and possibly the results of testing carried out on project piezometers yielding an assessment of hydraulic conductivity may be available.

Section 2 discussed the prediction of groundwater levels. As part of road alignment design the significance of road cutting on the groundwater system needs to be assessed to identify potential impacts on groundwater dependent ecosystems and groundwater users in the vicinity of cuttings which intersect the groundwater table. Where major impacts are possible, it may be necessary to carry out detailed numerical analysis using finite element or finite difference modelling tools but for initial evaluation predictions of impacts using analytical methods provide a useful starting point.

One method of assessment of seepage rate and the extent of influence of road cuttings across spurs is illustrated in Figure 10. The approach is to superimpose the drawdown resulting from the cutting excavation onto the groundwater level mound across the spur. The following process has proven useful:

1) Predict existing groundwater level distribution along the road alignment making use of monitoring at the location of using parameters assessed for similar conditions
2) Identify the maximum drawdown assuming groundwater level will be lowered to the level of floor of the cutting
3) Predict the extent of drawdown representing the influence of the cutting on the groundwater system by two equivalent wells which would result in the appropriate drawdown level at the deepest part of the cutting (a good choices for the location of these equivalent wells is to have them separated by about 25% of the predicted length of the cutting below the pre-development groundwater level).



Pre development

Post development

Drawdown

Figure 10: Evaluation of drawdown due to a road cutting across a spur or ridge

This analysis process takes account of the geometry of the road and as pumping rate from the equivalent wells is chosen to provide the anticipated maximum drawdown the results are independent of the choice of groundwater permeability and rainfall infiltration. The approach contains a number of simplifications but provides a useful screening tool for prediction of the extent of impact. If the ground permeability or infiltration rate can be assessed the approach yields a prediction of the rate of seepage to the road cutting under average conditions. The drawdown associated with groundwater extraction from two wells within a strip of land bounded by fix head conditions can be obtained from the well know Thiem solution for steady flow to a well and by using the principal of superposition and multiple image wells to take account of the valleys between the spur where groundwater levels are assumed to be unchanged.

A similar process can be applied for road cuttings across rounded topography near the base of hills or spurs. In this case the head distribution prior to development is based upon uniform infiltration to a circular area and the wells are modelled using the solution for pumping within a circular line of stable groundwater level. The method of evaluation of steady flow to a point source within an aquifer bounded by a circular constant head boundary can be readily developed by an image method and is described in Verruit (1982). The analysis of drawdown due to construction of a road cutting across the lower slope of a hill is illustrated in Figure 11.

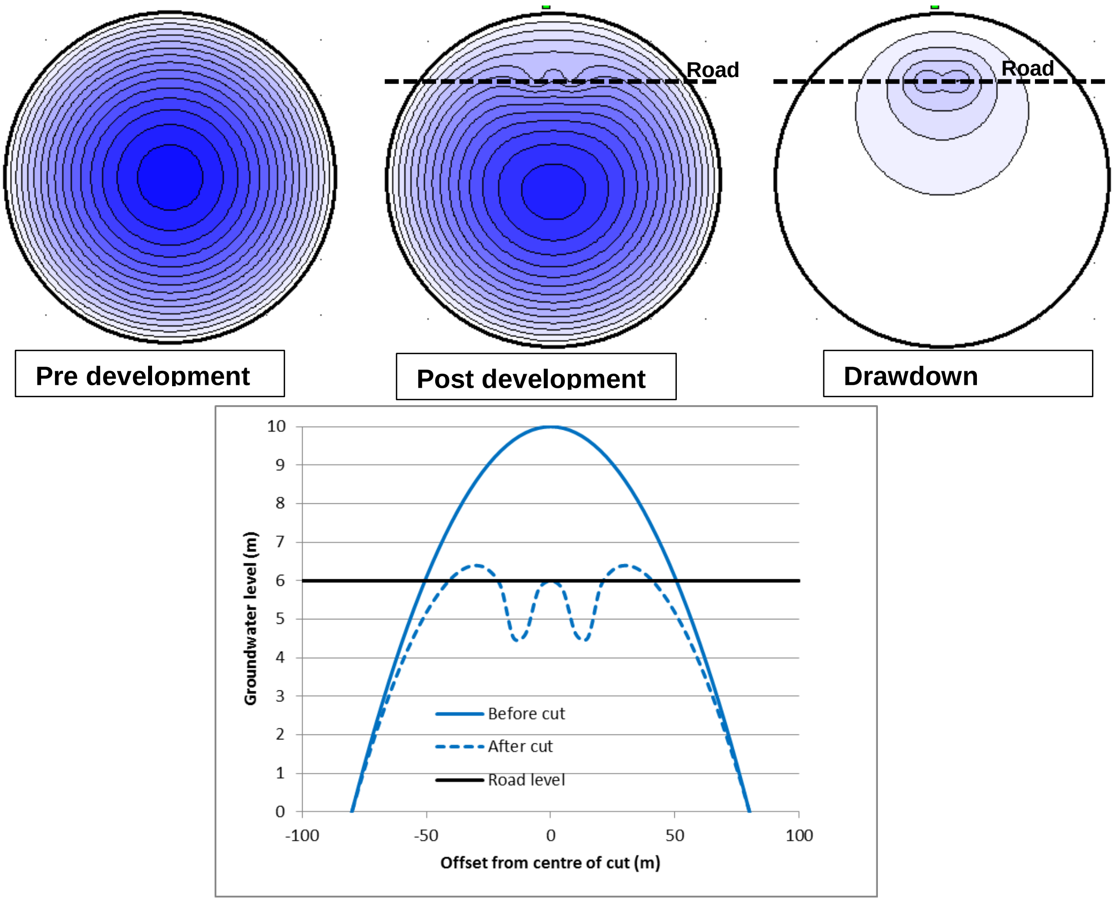


Figure 11: Evaluation of drawdown across the slopes of a hill

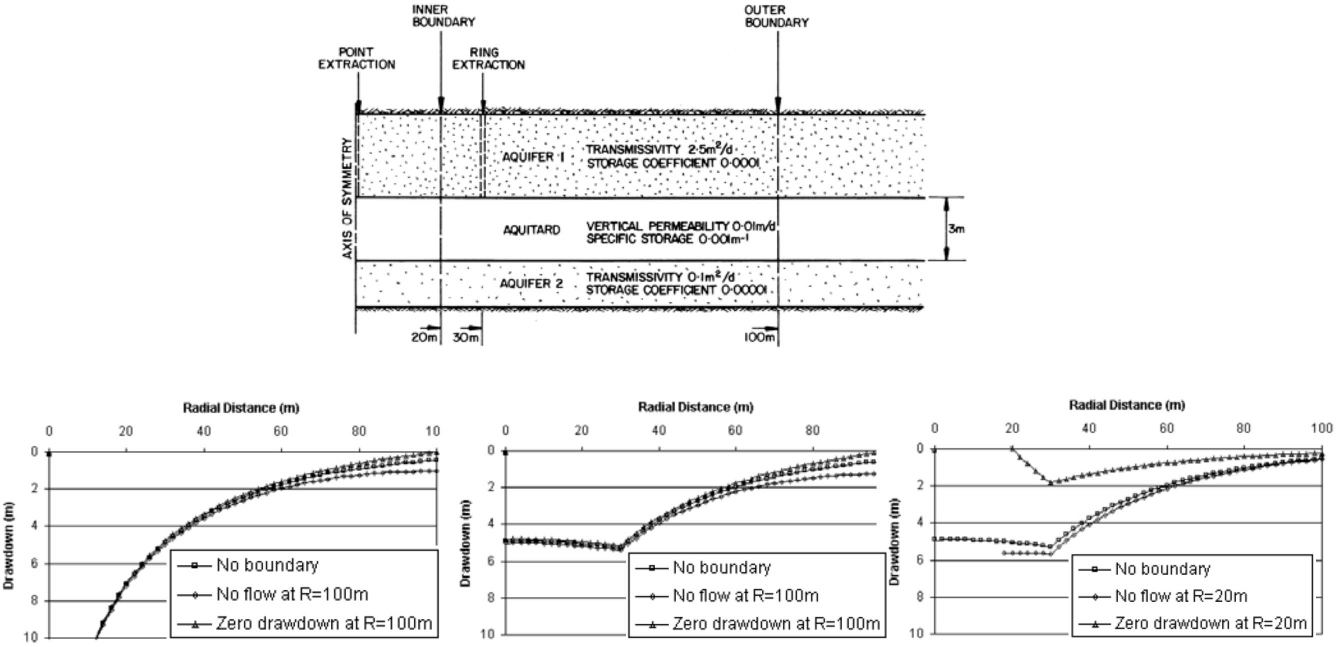
5 LAYERED SYSTEMS

Layered aquifer systems comprising a series of predominantly horizontal units with consistent hydrogeological properties occur frequently. Analysis of these systems is often required for a range of practical problems including mine and construction dewatering, groundwater supply studies, design of depressurisation systems and interpretation of results of pumping tests. Numerical tools such finite element and finite difference methods are available to handle general groundwater flow problems but use of analytical solutions for problems with simple geometry avoids protracted preparation of grids. Analytical solutions tend to deal more effectively with concentrated sources.

An analytical solution for groundwater extraction from a single aquifer was developed by Theis (1935). Hantush and Jacob (1955) developed a solution for drawdown resulting from groundwater extraction from an aquifer overlain by a leaky layer. Constant head conditions were assumed above the leaky layer and no account was taken of storage in the leaky layer. Hantush (1960) also developed a solution that included treatment of water released from a compressible leaky layer. The solution is limited to short time or long time. Boulton (1954) developed a semi-empirical method for dealing with a phenomenon called delayed yield which is commonly identified during interpretation of pumping tests. Early time behaviour is consistent with low storage within the aquifer pumped while late time behaviour is influenced by downward drainage from overlying sediments. Neuman (1975) developed a solution for groundwater extraction from anisotropic aquifers which produced response curves similar in form to those obtained by Boulton (1954).

Neuman and Witherspoon (1969) presented an analytical solution for groundwater extraction from two or three aquifers separated by confining beds. The solutions were obtained by solving the Laplace transform of the equations of flow and performing an analytical inversion of the transformed solution in time. Solutions for head in the aquifers and aquitards were obtained. Numerical evaluation of the solution involved evaluation of integrals of oscillating functions which were difficult to implement for arbitrary property selections.

Booker and Best (2000) presented a general method for analysis of layered aquifer systems which employed a numerical Laplace inversion method developed by Talbot (1979). This provided a method for analysis of groundwater extraction from a layered aquifer system for any number of aquifers separated by compressible confining layers. A solution for extraction from a point source within an extensive aquifer was presented together with treatment for a radial no-flow or constant head boundary. The approach addressed cases of a ring source and a circular source and takes account of multiple radial boundary conditions. This approach can be considered semi-analytical and is not amenable to spread sheet calculation. Modelled results for an example illustrating the use of extraction from a ring and alternate boundary conditions are presented in Figure 12. This would have application to seepage to a basement within a layered groundwater system.



Point extraction
Alternate distant boundaries

Ring extraction
Alternate distant boundaries

Ring extraction
Alternate interior boundaries

Figure 12: Layered aquifer model example (after Best and Booker 2000)

6 CONCLUSIONS

A range of methods are discussed which have application for analysis of effects of excavations on groundwater. The methods discussed are largely analytical in nature and typically required only hand calculation or use of spread sheets. They provide a useful resource when used in conjunction with numerical methods based on finite element and finite difference methods.

7 ACKNOWLEDGEMENTS

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