4.0 Assessment Methods

This section presents quantitative tools which can be used to estimate the stream depletion effect of a pumping well on a nearby stream. As with all quantified groundwater assessments, they are a gross simplification of the complex variability that exists in naturally deposited groundwater systems. However, the methods described are considered to be the most appropriate means of estimating stream depletion effects.

Section 4.1 describes an analytical method developed by Dr Bruce Hunt of the University of Canterbury. It is appropriate for relatively uniform laterally extensive aquifer systems with a single continuous stream flow that can be approximated as a linear feature across the zone that is influenced by the pumping well. For other situations where the aquifer has well defined zones of variable parameters and/or where the stream connection to the aquifer is discontinuous, the effects can best be quantified by the use of a numerical model, as described in Section 4.2.

Before any quantified assessment is undertaken, it is essential that a realistic conceptual model of the stream and aquifer interaction is defined. The conceptual model must consider the following points:

» *the lateral extent of the aquifer and the location of any boundaries;*

» *the likely variability of the aquifer hydraulic conductivity and storativity;*

» *the location of stream flow that will occur for the duration of any calculation period;*

» *the nature of the streambed and its effect on water flow between the stream and the aquifer.*

This conceptual understanding will form the basis for selecting and applying the most appropriate method to quantify the stream depletion effect.

4.1 Analytical Equations

The original analytical equation to assess stream depletion effects was developed by Theis (1941) in the form of an integral which was evaluated with an infinite series. The equation was rewritten by Glover and Balmer (1954) using the complimentary error function, erfc, as follows:

$$\frac{q}{Q} = \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right)$$

where q is the stream depletion flow rate $[L^3/T]$;

Q is the constant flow rate abstracted at the well $[L^3/T]$;

S is the aquifer storage coefficient [dimensionless];

T is the aquifer transmissivity $[L^2/T]$;

t is the duration of the pumping period [T]; and

ℓ is the shortest distance between the well and the stream edge [L], based on the stream being approximated as a straight line feature.

The equation assumes that the stream fully penetrates the aquifer and forms a recharge boundary to the aquifer.

Glover and Balmer’s form of the equation is the basis of a United States Geological Survey paper by Jenkins (1977). In outlining the purpose of his paper Jenkins observed that, “*The average user retreats in dismay when faced by the mysticism of ‘line source integral’, ‘complimentary error function’, or ‘the second repeated integral of the error function’. The primary purpose of this report is to provide tools that will simplify the seemingly intricate computations and to give examples of their use.*”

Jenkins presented simple curves to estimate stream depletion effects and this approach, using the Glover and Balmer form of the equation has, until recently, been the most commonly used analytical tool for assessing stream depletion effects.

However, the use of the Glover and Balmer/Jenkins equation has been criticised based on comparative numerical modelling studies undertaken by Spalding and Khaleel (1991) and Sophocleous et al. (1995). They concluded that the equation tended to over-estimate stream depletion effects because, in reality, most streams only partially penetrate an aquifer and pumping wells may be able to create drawdown effects on the far side of the stream. Furthermore, many streambeds may have a “clogging nature” which has lower hydraulic conductance properties than the surrounding aquifer.

To address these concerns, Dr Bruce Hunt of the University of Canterbury has recently developed a new analytical equation which allows for the effects of both partial penetration and streambed clogging (Hunt, 1999). The Hunt equation is similar in form to the Glover and Balmer equation:

$$\frac{q}{Q} = \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda\ell}{2T}\right)\mathrm{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{S\ell^2}{4Tt}}\right)$$

where q is the stream depletion flow rate [L^3/T];

Q is the constant flow rate abstracted at the well [L^3/T];

S is the aquifer storage coefficient [dimensionless];

T is the aquifer transmissivity [L^2/T];

t is the duration of the pumping period [T];

ℓ is the shortest distance between the well and stream edge [L], based on the stream being approximated as a straight line feature; and

λ is the constant of proportionality between the seepage flow rate from the stream per unit length of streambed and the difference between stream and groundwater levels [L/T], as described in the panel on page 37 and in Figure 20.

Hunt's equation is based on the following assumptions:

- *The ratio of vertical to horizontal velocity components is small (the Dupuit approximation);*
- *The aquifer is of infinite extent and is homogeneous and isotropic in all horizontal directions;*
- *Drawdowns are small enough compared with saturated aquifer thicknesses to allow the governing equations to be linearised;*
- *The streambed cross section has horizontal and vertical dimensions that are small compared to the saturated aquifer thickness and the stream extends from* $y = -\infty$ *to* $y = \infty$ *along* $x = 0$*;*
- *The well flow rate, Q, is constant for* $0 < t < \infty$*;*
- *Changes in water surface elevation in the river created by pumping are small compared with changes created in the water table elevation on the aquifer side of the semipervious layer;*
- *Seepage flow rates from the river into the aquifer are directly proportional to the change in piezometric head across the semipervious layer.*

These are all quite realistic assumptions for an analytical groundwater equation and are similar to those that are typically used for calculating drawdown around a pumping well. Consequently, the Hunt equation is recommended in this guideline as the most appropriate analytical tool to estimate stream depletion effects.

It is interesting to note that the equation has the following characteristics:

$$\frac{q}{Q} \rightarrow 0 \text{ as } t \rightarrow 0$$

i.e. when the well first starts pumping, there is relatively little water taken from the stream.

$$\frac{q}{Q} \rightarrow 1 \text{ as } t \rightarrow \infty$$

i.e. when the well has been pumping continuously for a very long time most of the well water is drawn from the stream.

$$\frac{q}{Q} = \operatorname{erfc}\left(\frac{\sqrt{S\ell^2}}{4Tt}\right) \text{when} \frac{\lambda\ell}{T} = \infty$$

i.e. the Hunt solution is equivalent to the Glover and Balmer/Jenkins solution if the streambed is assumed to be very conductive. Consequently, if no information is available on streambed clogging it will be conservative (from the stream point of view) to assume no clogging – in which case the Jenkins approach is a reasonable approximation.

To aid in the use of this equation, Figure 23 has been prepared to estimate stream depletion effects. Figure 23 shows the relation between the stream depletion factor (sdf) for pumping of duration t, and the rate of stream depletion q at time t, expressed as a ratio to the pumping rate from the well (Q). A family of curves is shown for different values of a dimensionless parameter referred to as the streambed factor (sbf) which reflects the effect of streambed clogging. It is defined as follows:

$$\text{sbf} = \frac{\lambda \ \ell}{T}$$

where λ is the streambed conductance [L/T]

ℓ is the separation distance between the stream and the well [L]

T is the aquifer transmissivity [L^2/T]

It is important to recognise that sbf is a dimensionless parameter to be used in conjunction with sdf in the graph in Figure 23. On its own, sbf is not a useful parameter for screening stream depletion effects due to the inconsistent influence of the parameters ℓ and T in the definition of sbf.

When sbf is 100 or greater, the curve in Figure 23 is the same curve that was presented in Jenkins (1977). However, when sbf reduces to values <10, noticeable reductions in stream depletion effects start to occur.

As noted in Jenkins (1977), the effects of intermittent pumping can quite reasonably be approximated by using the average pumping rate over the period of interest.

The following example has been prepared to demonstrate the application of Figure 23 to quantitatively assess stream depletion effects.

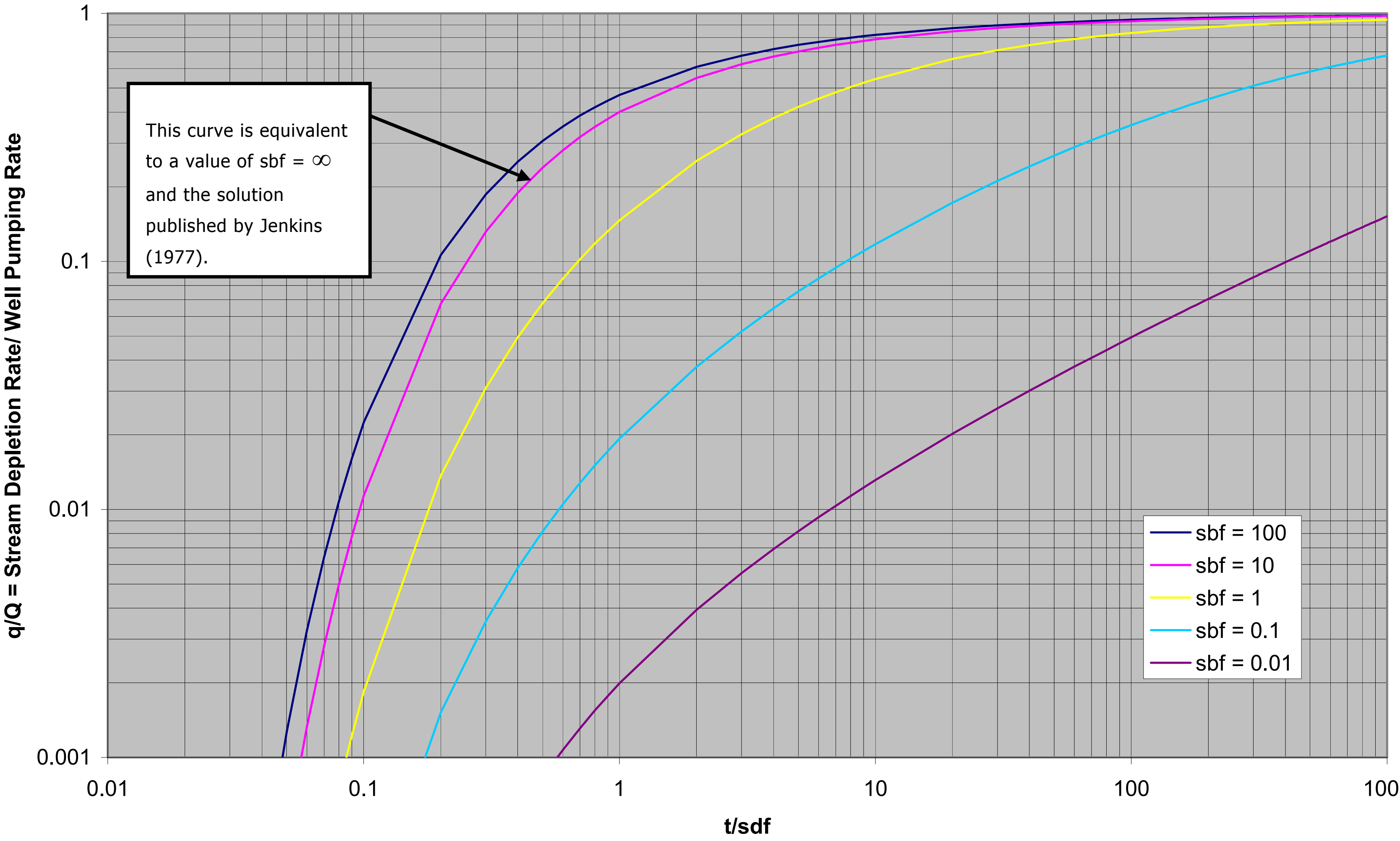

Figure 23: Curves to determine the rate of stream depletion

A shallow groundwater well in an unconfined aquifer pumps at 30 L/s for 20 hours per day, 4 days out of 5. The aquifer has a hydraulic conductivity of 80 m/day (K), a storage coefficient of 0.1 (S) and is 10 m thick (b). The well is located 200 m (ℓ) from a 5 m wide stream (W). The streambed is 1 m thick (M) and across this thickness the vertical hydraulic conductivity is one hundred times less than the hydraulic conductivity of the aquifer (i.e. K' = 0.8 m/day).

From this information we can determine the following:

Transmissivity = Kb = 80 m/day x 10 m = 800 m^2/day

$$sdf = \frac{\ell^2 S}{T} = \frac{(200\,m)^2 \times 0.1}{800\,m^2 \;/\; day} = 5 \;\; days$$

$$\lambda = \frac{K' W}{M} = \frac{0.8\,m \,/\, day \times 5m}{1\,m} = 4\,m \,/\, day$$

$$sbf = \frac{\lambda \ell}{T} = \frac{4\,m \,/\, day \times 200\,m}{800\,m^2 \;/\; day} = 1$$

With this information, the calculated stream depletion rate can be read off Figure 23 for the average pumping rate over different time periods, as tabulated below.

Pumping Period t (days)	Average Abstraction Rate Q (L/s)	$\frac{t}{sdf}$	$\frac{q}{Q}$	Stream Depletion Rate q (L/s)
0.83 (20 hours)	30	0.167	0.009	0.3
5	20	1	0.15	3
30	20	6	0.45	9
60	20	12	0.57	11.4
90	20	18	0.64	12.8

Using the principle of superposition, it can also be calculated that if after 60 days the abstraction ceased for 30 days the resultant effect on the stream depletion rate would be:

$q_{90} - q_{30} = 12.\ 8 - 9.0 = 3.8$ *L/s*

i.e. a reduction in the stream depletion rate of around 9 L/s, but a residual effect of around 4 L/s in the stream would still occur 30 days after pumping ceased.

4.2 Numerical Models

Inaccuracies in the estimates from the analytical equation can be caused by heterogeneity in both the aquifer and the stream. If the heterogeneity of the hydrogeologic system is such that it cannot be reasonably represented by the analytical equation described in section 4.1 then a numerical model could be used to assess the stream depletion effect.

There are a wide range of numerical models available for simulating groundwater flow. It is most important that a properly verified modelling code is utilised and that any modelling simulation is presented with appropriate checks to confirm its velocity. The discussion that follows focuses on the MODFLOW software (McDonald and Harbaugh, 1996) which is the most widely accepted groundwater flow model in New Zealand at the present time. However, the comments that are made below could be generically applied to any other modelling package that is utilised.

MODFLOW is a three-dimensional finite difference model for simulating the flow of water through a porous media. The area being modelled is divided vertically into layers and laterally, into a gird of rectangular cells with unique, uniform aquifer properties being defined for each cell. The movement of water between cells is calculated through the iterative solution to a sequence of finite difference equations.

It is beyond the scope of this guideline to give detailed instructions on the use of MODFLOW, however, for those persons with competence in the use of MODFLOW, the following notes outline the key features that should be present in a MODFLOW model that is developed to assess stream depletion effects. The MODFLOW programme is divided into a number of packages that define different characteristics for a particular aspect of the numerical simulation. Those packages required to formulate a stream depletion assessment are described below:

(i) The BASIC Package

The input data for the Basic package defines the following model characteristics:

- » *it defines the model grid, i.e. the rows, columns and layers;*
- » *it defines the time steps and stress periods for the simulation (a stress period is a period where the external model boundaries remain constant. Within each simulation, a stress period is divided up into a number of smaller time steps);*
- » *it specifies the initial head distribution within the aquifer at the start of the simulation;*
- » *it specifies the boundary conditions for the model grid.*

For the purposes of a stream depletion model it is important to remember that each model cell represents uniform aquifer properties. Consequently, a fine grid size (perhaps on the order of 10 m x 10 m) should be used in the vicinity of both the stream and the pumping well, where head change and groundwater fluxes may be greatest.

Similarly, a small time step must be used at the start of each stress period, although this can be easily accommodated by the use of MODFLOW's time step multiplier – a common approach is to divide each stress period into 10 time steps (NSTP) with a multiplier (TSMULT) of 1.5.

In contrast to the fine grid required around the pumping well and the stream, a coarser grid is required away from the area of interest so that the model can run efficiently, with the minimum number of rows, columns and layers. When expanding the grid size, the dimensions of each adjacent row or column should not increase by more than 50% between adjacent cells. Also, the horizontal dimensions of each grid cell should not be more than 10 times bigger in one direction than the other.

The external boundaries to the model should either coincide with real aquifer boundaries, or they should be placed at sufficient distances that they do not interfere with the accuracy of the simulation in the area of interest. The magnitude of any artificial boundary effects should be checked by running the model through two simulations, one without the well pumping and one with the well pumping. If the results show that a large proportion of the well water is coming from artificially located boundaries then the model grid must be redesigned to shift the artificial boundaries further away so that they do not interfere with the solution.

(ii) The BLOCK CENTRED FLOW Package

The input data for the Block Centred Flow Package defines the grid geometry, the hydraulic conductivity and storage coefficient parameters of each cell and the top and bottom elevations of the layers. These input parameters should be determined from the conceptual hydrogeological model, on the basis that the simplest model is the best. Ideally large groups of cells should have constant aquifer parameters and sharp contrasts in parameters should be avoided, unless there is a good hydrogeological basis for such a change.

Anisotropy in the aquifer parameters can be specified for those areas where this has been shown to occur.

(iii) RIVER Package and STREAM Package

Modflow has two packages that can be used to specify the stream: the RIVER package and the STREAM package. Both packages specify the cells in which the stream occurs, the stage height of water in the stream, the height of the bottom of the streambed and the conductance of the streambed. The flow between the stream and the aquifer, for each model cell, is shown graphically in Figure 24, and calculated as:

$\text{QRIV} = \text{CRIV}\,(\text{HRIV} - h)$ for $h > \text{RBOT}$

i.e. the flow to or from the river varies depending on the head in the aquifer

$\text{QRIV} = \text{CRIV}\,(\text{HRIV} - \text{RBOT})$ for $h \leq \text{RBOT}$

where: QRIV is flow to or from the stream

HRIV is the stage height of the stream

h is the head that the model calculates for the aquifer cell in which the stream occurs

RBOT is the height of the bottom of the streambed

CRIV is the hydraulic conductance of the stream-aquifer interconnection

$$\text{CRIV} = \frac{K' L W}{M}$$

where: K′ is the hydraulic conductivity of the streambed [L/T];

L is the length of the streambed as it passes across the model cell [L]:

W is the width of the streambed as it passes across the model cell [L];

M is the thickness of the streambed [L]:

It is interesting to note that the value of CRIV per unit length of the stream $\left(\frac{CRIV}{L}\right)$ is the same value as the streambed conductance (λ) described in section 3.2.

The Modflow River and Stream packages assume that the flow from the river is constant when the head in the aquifer is lower than the base of the streambed. This is not entirely consistent with the guidelines of Hunt and Bouwer described in section 3.1.1. To allow for situations where this is thought to occur, it may be desirable to set RBOT at a lower elevation than the real streambed (i.e. down to the elevation below which constant leakage will occur).

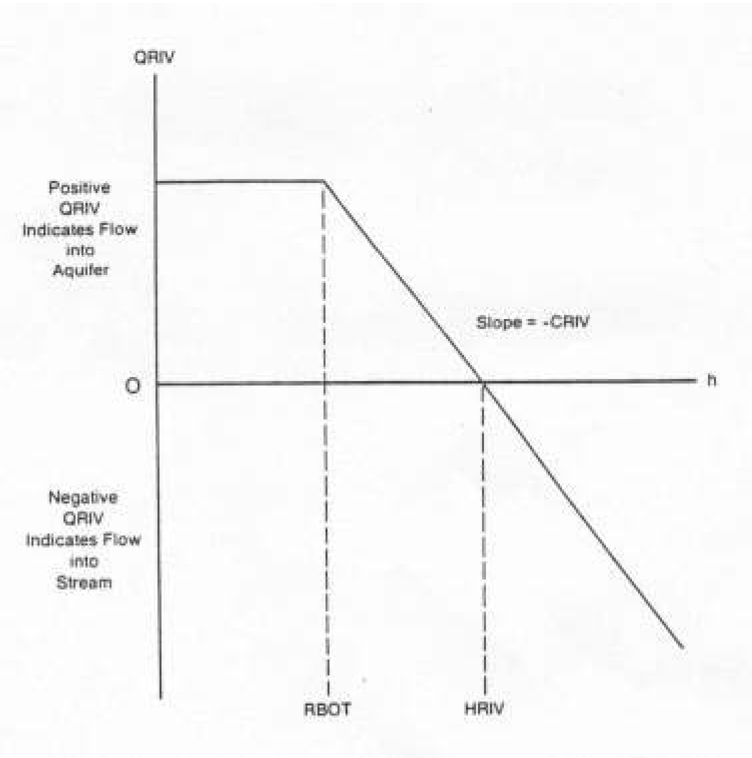

Figure 24 Plot of flow (QRIV) from a stream into or out of the modelled aquifer as a function of the head (h) in the modelled aquifer. RBOT is the elevation of the bottom of the streambed and HRIV is the elevation of the water in the stream (from McDonald and Harbaugh, 1983).

The RIVER package specifies a constant stage height for each stress period and operates under the assumption that the stage height remains constant, regardless of the movement of water between the stream and the aquifer. This package is most appropriate for simple simulations where the stream has a steady flow, significantly in excess of any possible stream depletion rates.

In contrast, the STREAM package provides the option of specifying an initial stage height and stream flow at the start of the model simulation. Throughout the model simulation, the stage height and stream flow are then determined by the interaction in flow between the aquifer and the steam. The STREAM package can allow the stream to go dry, if losses to the aquifer are sufficiently great.

(iv) WELL Package

The input to the well package specifies the location of the well and the pumping rate. A constant pumping rate is specified for each stress period.

(v) Solver Package

Modflow has a number of options for solver packages:

» *Strongly Implicit Procedure Package (SIP);*

» *Slice Successive Overrelaxation Package (SSOR);*

» *Preconditioned Conjugate-Gradient Package (PCG2);*

» *WHS Solver for Visual MODFLOW (WHS).*

Various solvers can be trialled, but all should give satisfactory solutions to stream depletion simulations. One of the key parameters for each solver is the specification of the head change criterion for convergence (HCLOSE). This determines that the iteration during each time step is concluded when the maximum absolute value of head change from all cells between the two most recent interactions is less than the value specified. In most cases a value of 0.001 m or less should be sufficient.

(vi) Running MODFLOW Simulations for Stream Depletion Assessments

In carrying out these modelling exercises it is important that the stream depletion effect caused by the pumping well must be carefully isolated from the other groundwater flow interactions that occur within a MODFLOW simulation. To achieve this it is recommended that stream depletion assessments should be run on the following basis:

» *Firstly, a steady-state simulation should be run with no well pumping. The water budget at the end of this simulation must show a low percentage error (ideally below 1%) to confirm that the model has run correctly. The resulting aquifer heads, stream flow and stage heights should then be used as the input data for the stream depletion simulation.*

» *The stream depletion simulation should be run with a minimum of three stress periods:*

  » *firstly with no well pumping;*

  » *secondly with the well pumping;*

  » *thirdly with no well pumping.*

The water budget output at the end of each stress period must be carefully checked. The percentage error must be low (ideally well below 1%) to confirm that the model has run correctly. Furthermore, the proportional distribution of water inflow and outflow to the model must also be carefully checked for each stress period. In particular, if a significant proportion of the pumped well water is sourced from artificially placed model boundaries *then an artificial result is obtained and the model must be run again, with more appropriate boundary definition.*

Once these checks have been satisfactorily complied with, the model output can be used to quantify the magnitude and timing of the stream depletion effect.