# The protection of groundwater dependent ecosystems in Otago, New Zealand

**Gabor Bekesi · Sean Hodges**

**Abstract** Surface waters (streams, rivers, and wetlands) are the most important groundwater dependent ecosystems (GDEs) in Otago, New Zealand. Pumping wells in the vicinity can deplete water in the GDE. In Otago, most of the surface water resources are allocated and a method, which would assist in the implementation of water management policy, is needed to acknowledge the strong hydraulic link between surface and shallow groundwater. A simplified method has been developed which derives a numerical relationship between the bore pumping rate and the distance between the bore and surface water body beyond which depletion is considered insignificant. A range of GDE depletion scenarios are examined at various combinations of hydraulic parameters to find a minimum distance for a given pumping rate, at which 90% of the modelled surface water depletion scenarios become less than a threshold GDE depletion after a specified time. A buffer zone, based on the minimum distance is placed around GDEs, and groundwater abstraction rights within the buffer are subject to stricter rules. Applicants wishing to abstract from bores within the buffer zone will need to address the environmental impact of the proposed activity on the GDE.

**Résumé** Les eaux de surface (cours d'eau et zones humides) sont les plus importants écosystèmes dépendants des eaux souterraines (GDEs) in Otago en Nouvelle Zélande. Les puits de pompage les plus proches peuvent diminuer la quantité d'eau des GDEs. En Otago, la plus part des eaux de surface sont allouées et une méthode spécifique est nécessaire pour reconnaître le lien hydraulique fort entre eaux de surface et souterraine et appuyer une politique de gestion des eaux. Une méthode simplifiée a été développée, sous la forme d'une relation numérique entre le pompage d'un puits et la distance de ce puits à la zone humide, distance pour laquelle le prélèvement est considéré comme insignifiant. Plusieurs types de scénarios d'impacts sur les GDEs ont été examinés suivant différentes combinaisons de paramètres hydrauliques, conduisant à une distance minimum pour un débit de pompage donné pour lequel 90 % des eaux de surface modélisées subissent un épuisement seuil après un temps déterminé. Une zone tampon, basée sur la distance minimum est placée autour des GDEs, et le droit au prélèvement d'eau souterraine dans cette zone est sujet à des règles strictes. Les candidats au prélèvement dans la zone tampon devront définir les impacts de leur activité proposée sur les GDEs.

**Resumen** Las aguas superficiales (ríos, arroyos, y humedales) son los ecosistemas dependientes de agua subterránea (GDEs) más importantes en Otago, Nueva Zelandia. El bombeo de pozos en la región puede agotar el agua en los GDEs. La mayor parte de los recursos hídricos superficiales en Otago ya están asignados y se necesita un método que permita reconocer el fuerte vínculo hidráulico entre el agua superficial y el agua subterránea somera y que pueda apoyar la implementación de una política de manejo hídrico. Se ha desarrollado un método simplificado que aporta una relación numérica entre el ritmo de bombeo en el pozo y la distancia entre el pozo y el cuerpo de agua superficial, más alla de la cual el agotamiento se considera insignificante. Se ha examinado un rango de escenarios de agotamiento de GDEs con varias combinaciones de parámetros hidráulicos para encontrar la distancia minima para una tasa de bombeo dada a la cual el 90% de los escenarios de agotamiento de agua superficial modelada llegan a ser menores a un valor normal de fondo de agotamiento GDE después de un tiempo especificado. Una zona de amortiguamiento basada en la distancia mínima se coloca alrededor de los GDEs y los derechos de explotación de aguas subterráneas dentro de la zona de amortiguamiento están sujetos a reglas estrictas. Los aplicantes que deseen extraer agua de pozos emplazados en la zona de amortiguamiento necesitarán elaborar el estudio de impacto ambiental de la actividad propuesta en el GDE.

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## Introduction

In Otago, New Zealand, water from many rivers is fully allocated, and in some cases allocation exceeds mean annual flow. The abstraction of surface water is suspended when the flow decreases to the nominated minimum flow. While the setting of minimum flows for rivers in Otago was a significant step forward for water management, it also increased demand for generally more reliable and secure groundwater supplies. Although most Otago aquifers are associated with surface water, surface and groundwater resources are still administered separately with the exception of few catchments. Groundwater abstraction rights were issued until recently with no or little regard to effects on nearby surface water. Policies that recognize the strong hydraulic link between surface and shallow groundwater need to be implemented. This note presents the development of a simple buffer zone to protect surface waters from further depletion until more sophisticated tools are available.

## Groundwater dependent ecosystems (GDEs)

Groundwater dependent ecosystems are parts of the environment that are defined by their dependence on the permanent or temporary presence or influence of groundwater (SKM 2001). Six types of GDEs (SKM 2001; and URS 2000) are recognized:

- Terrestrial vegetation
- River base flow systems
- Aquifer and cave ecosystems
- Wetlands
- Terrestrial fauna
- Estuarine and near-shore marine ecosystems

Surface waters (streams, rivers, and wetlands) are the most important GDEs in Otago, New Zealand, therefore the rest of this document focuses on groundwater–stream interactions. Most concepts can be used for springs, wetlands and lakes with minor or no alteration and the terms GDE and stream are, in this article, interchangeable.

## Groundwater–surface water interaction

Groundwater and surface water are hydraulically linked or interrelated systems. Seasonal streams normally recharge groundwater in higher altitudes while base flow in streams is often dependent on groundwater at lower altitudes. Declines in groundwater levels can dry up streams even when the total amount of groundwater stored in the basin remains huge (Sophocleous 2001, 2002).

The decline of groundwater levels around pumping wells near a stream creates gradients that capture some of the groundwater flow that would have, without pumping, discharged as stream baseflow. At sufficiently large pumping rates, these declines induce flow out of the stream and into the aquifer. The sum of these two effects leads to stream flow depletion (Sophocleous 2001).

Stream flow depletion is time-dependent. Initially water flows to the pumping well from (groundwater) storage. The cone of depression around the pumping well grows as water is pumped from the aquifer storage. Once the cone of depression intersects the stream, water will flow from the stream towards the well. The number of variables involved in such systems and their inherent variability means that, even in a simple case, reliable estimation of stream flow depletion requires site-specific data.

## The Jenkins solution

Stream depletion by groundwater *in a simple case* can be expressed by the Jenkins (1977; also known as Glover) solution (Sopocleous et al. 1995):

$$q = Q\ \mathrm{erfc}\left[ r \middle/ (4tT/S)^{0.5} \right]$$

where:

$q$ is the stream depletion ($L^3/T$)
$Q$ is the pumping rate from the bore ($L^3/T$)
erfc is the complimentary error function
$r$ is the distance between the pumping well and the stream ($L$)
$t$ is the time ($T$)
$T$ is the transmissivity of the aquifer ($L^2/T$)
$S$ is the storativity of the aquifer (dimensionless)

For the purpose of this article, it is assumed that transmissivity and storativity can be used for unconfined aquifers to describe the hydraulic conductivity, saturated thickness, and specific yield. Although transmissivity and storativity are terms used for confined aquifers, if the drawdown is small with respect to the aquifer thickness, the Jenkins solution can equally be used for unconfined aquifers (Hunt et al. 2001). The Dupuit approximation, assuming streamlines are horizontal in the aquifer, is also made in the Jenkins solution.

The Jenkins solution is used for regulatory purposes because it is conservative and is relatively simple. It requires only the variables $Q$, $t$, and $r$ (parameters that are acquired in the process of application for legal water rights) and aquifer hydraulic parameters $T$ and $S$. The Jenkins solution assumes a perfect hydraulic connection between stream and groundwater, and a homogenous, isotropic, horizontal aquifer. In addition, it is assumed that both the stream and well fully penetrate the aquifer, and that there is no recharge (other than from the stream) to the aquifer.

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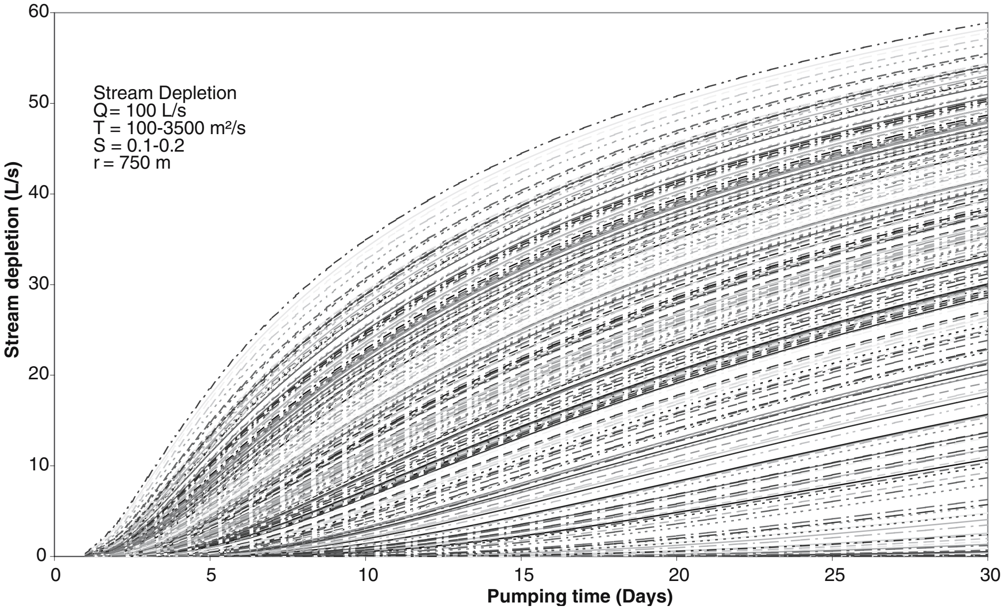

**Fig. 1** Using the Jenkins model, the calculated range for stream depletion will be up to 59 L/s, at 750 m distance from a bore, pumping 100 L/s, after 30 days of continuous pumping

In reality, the assumptions listed above are seldom correct. More complex models (Hunt 1999, 2005; Hunt et al. 2001; Kollet and Zlotnik 2003) describe the complexity and site-specific nature of groundwater–surface water interaction. To illustrate the Jenkins stream depletion solution using ranges for transmissivity and storativity, Fig. 1 shows stream depletion from a bore situated 750 m from the stream. After 30 days of pumping at 100 L/s, stream depletion is determined as being up to 59 L/s. Mean stream depletion is 34 L/s, median is 36 L/s. Ninety percent of calculated stream depletion values in Fig. 1 are less than 52 L/s.

Each curve corresponds to a single scenario and 250 scenarios were modelled. Each scenario is based on fixed values of $T$ and $S$, taken randomly from a range of values indicative of an unconfined aquifer. Ranges, instead of fixed parameters, were used to reflect the inherent uncertainty in hydrogeological data and the complexity of groundwater flow (Bekesi and Hodges 2002).

## Methodology to protect the needs of groundwater dependent ecosystems (GDEs)

A methodology that lends itself to the protection of GDEs is buffering. A buffer zone is placed around GDEs with the consequence of groundwater abstraction rights within the buffer being subjected to stricter rules. Applicants within the buffer zone or GDE interference zone will have to address the environmental impact of the proposed activity on streams.

The main advantages of buffering are that it is simple to implement and understand, and rules are transparent for potential groundwater users. Disadvantages include the fact that the specific needs of certain GDEs such as maintaining groundwater level fluctuations within a prescribed range, maintaining groundwater quality, or the timing of water level extremes, are not considered. Such requirements require site-specific studies.

The radius of the GDE interference zone can be fixed or variable. A fixed radius is easy to implement, but could be unjust to smaller applications because fixed zones are normally calculated for worst-case scenarios that occur at large pumping rates. Variable radius buffering could take the size of the water right into consideration: larger buffer for larger rights.

The purpose of this note is to derive a simple rule to relate the pumping rate, $Q$, and the distance between the bore and stream, $r$, to stream depletion, $q$. To do this, a range of stream depletion scenarios are examined for various values of hydraulic parameters ($T$ and $S$), and a simplified relationship $f(Q)$ is developed. This relationship is based on finding a minimum distance, $r_{5,90,30}$, for a pumping rate, $Q$, at which 90% of the modelled stream depletion scenarios, $q_{5,90,30}$, become less than 5 L/s (threshold stream depletion) after 30 days:

$$r_{5,90,30} = f_{5,90,30}(Q)$$

and

$$q_{5,90,30} \leq Q\, erfc\left[ r_{5,90,30} \Big/ (4 t_{30} T/S)^{0.5} \right]$$

where $t_{30}$ represents a fixed time (here 30 days), correlating to continuous pumping time.

Several parameters are chosen subjectively. The choice of time duration can be different than 30 days, depending on climate, soil, and crop type influencing irrigation

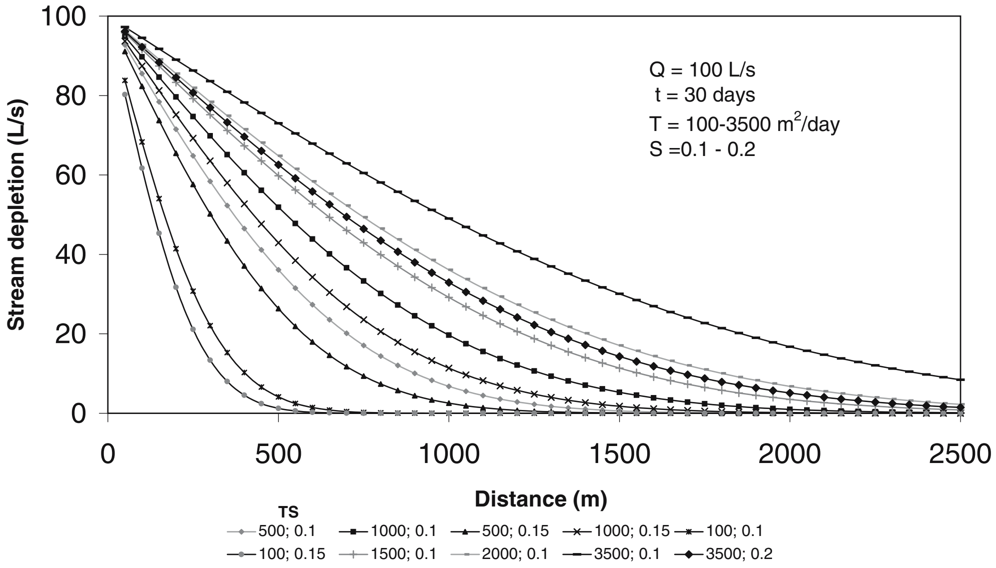

**Fig. 2** Stream depletion as the function of distance between bore and stream after 30 days of pumping at 100 L/s. Various transmissivity and storativity values (*T*, *S*) are shown. *Triangle markers*, for example, using the Jenkins model, represent a $T$=500 m$^2$/day and an $S$=0.15 scenario

demand. Longer times can also be chosen, for example, if groundwater is used mainly by industrial or drinking water supply bores that are operated every day. Similarly, the choice of 90th percentile is subjective; if a more conservative approach is warranted, a higher percentile can be used. In Otago, the combination of 5 L/s, 90% confidence, and 30 days of continuous pumping was accepted as the upper limit for an acceptable risk for stream depletion. Lowering the threshold stream depletion or increasing the confidence percentile will introduce larger minimum distances required between the bore and stream.

## The derivation of variable radius buffer zones

Ten stream depletion scenarios are shown in Fig. 2 for various transmissivity values, *T*, and storativity values, *S*. High transmissivity (more water can be transmitted from

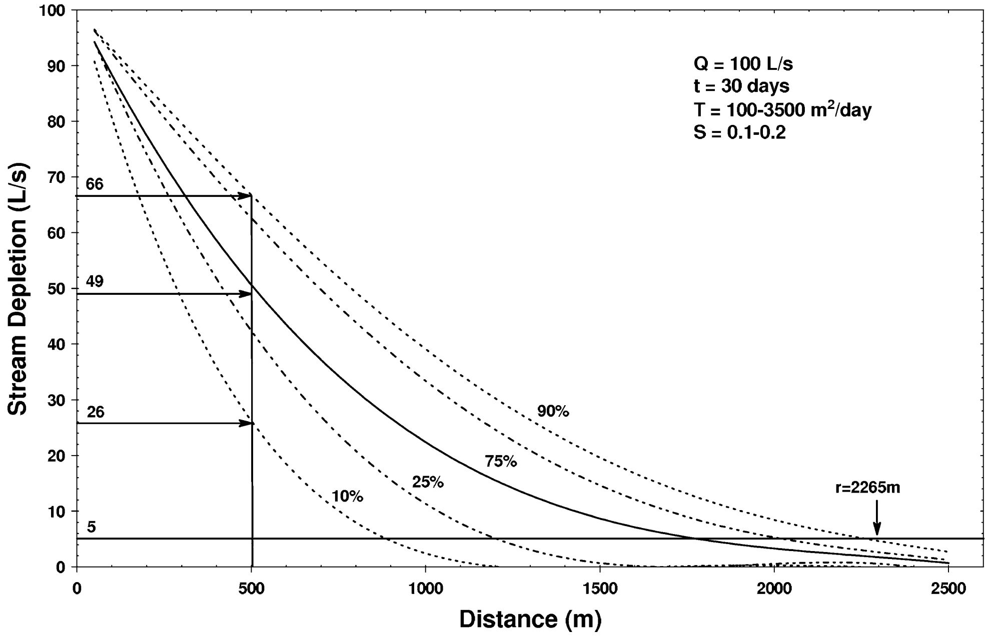

**Fig. 3** Stream depletion as the function of distance between bore and stream after 30 days of pumping at 100 L/s. *Solid black line* represents means, *dashed lines* represent 25th and 75th percentiles, *dotted lines* represent 10th and 90th percentiles. Transmissivity 100–3,500 m$^2$/day, specific yield 0.1–0.2. 250 scenarios were modelled

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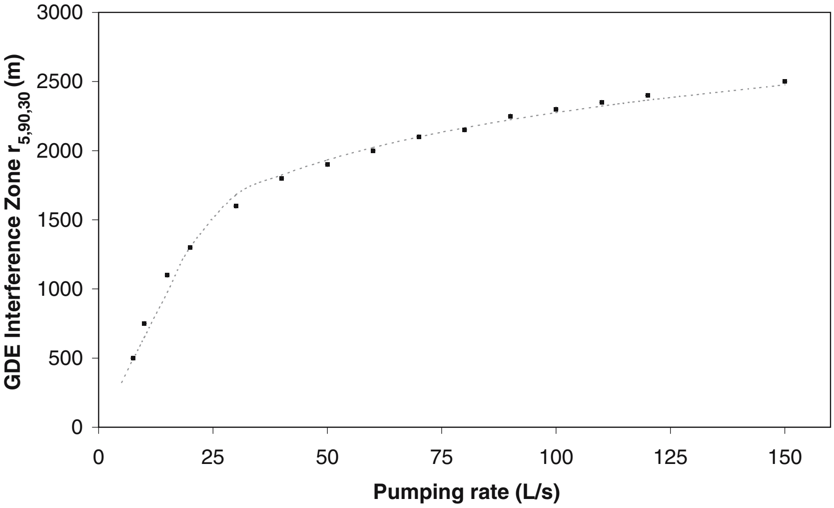

**Fig. 4** The relationship between the bore pumping rate and the GDE interference zone (after 30 days of continuous pumping, 90% of the modelled scenarios were below the threshold of 5 L/s) is represented by *black squares* and approximated by the *dotted grey line*

the river) and low specific yield (less water stored in the aquifer) result in high stream depletion.

Stream depletion becomes small at around 2,000 m distance as most of the curves fall below 5 L/s. Figure 3 quantifies these results by showing various percentiles for stream depletion. For example, at 500 m distance, the mean stream depletion is 49 L/s. Ten percent of the results are below or equal to 26 L/s (10th percentile) and 90% of the results are less or equal to 66 L/s (90th percentile), indicated by dotted lines. After 30 days of constant pumping, the distance at which 90 of the modelled 100 scenarios are less than 5 L/s is estimated as $r_{5,90,30}$= 2,265 m.

These observations can be used to develop a relationship between stream depletion and distance from a stream for policy purposes. Assuming a wide range of transmissivities (100–3,500 $m^2$/day) and specific yields (0.1–0.2), a distance-stream depletion graph can be constructed, where 90% of the modelled scenarios are below the threshold of 5 L/s (see Fig. 4). For example, for a pumping rate of 50 L/s, a bore will have to be at least 1,930 m distance from the stream in order to have 90% of the modelled scenarios resulting in less than 5 L/s stream depletion. The dotted curve shown in Fig. 4 can be described as:

$$r_{5,90,30} = 65\,Q \quad for \quad 5\,L/s < Q \leq 25\,L/s$$
$$r_{5,90,30} = 1138 \log Q \quad for \quad Q > 25\,L/s$$

This relationship can be used to formulate a policy for placing a GDE interference zone around the GDEs. For example, a moderate-sized application, for 30 L/s of water from a bore situated within 1,680 m of a GDE, will have to address the impact of the proposal on the GDE. An application to abstract a larger amount, 75 L/s, would require the bore to be at least 2,130 m away to avoid addressing the impact on the stream. Using the example of Fig. 1, for a groundwater right of 100 L/s, the width of the modelled GDE interference zone is 2,275 m.

This new methodology has only been used in the Otago region for a few months; therefore, its application has been limited. The central part of the Otago region is characterized by semi-arid climate, low rainfall (350–600 mm/year) and low diffuse recharge (less than 50 mm/year) to groundwater. Aquifers are recharged from episodic flood events. Most groundwater is slowly discharged back to surface water courses. An application for 90 L/s of irrigation water was received for a bore that is situated 750 m from a fully allocated river. The mean annual flow of the river is 6,400 L/s, mean annual low flow is 1,400 L/s; and 4,200 L/s is allocated for irrigation. In addition, several flow measurements indicate approximately 300 L/s is lost from river flows of approximately 4,000 L/s. The loss occurs from the reach of the river that is nearest to the bore. The bore taps a silty, sandy gravel unconfined aquifer, with a saturated thickness of 22 m. The hydraulic conductivity and specific yield are unknown.

Using the current method, for 90 L/s, the GDE interference zone is 1,138 log 90=2,223 m. As the actual distance to the river (750 m) is less, the applicant was requested to provide an environmental impact assessment using site-specific data. The applicant is currently conducting pumping tests and simultaneous river flow measurements to assess the impact on the river.

Targeting 95% confidence would result in a similar but more conservative estimate (larger GDE interference zone):

$$r_{5,95,30} = 76\,Q \quad for \quad 5L/s < Q \leq 25\,L/s$$
$$r_{5,95,30} = 1213 \log Q \quad for\,Q > 25\,L/s$$

Using a 90-day continuous pumping period would result in GDE interference zones that are significantly larger than those for 30 days:

$$r_{5,95,90} = 110\,Q \;\; for \;\; 5\,L/s < Q \leq 25\,L/s$$
$$r_{5,95,90} = 1976 \log Q \;\; for \;\; Q > 25\,L/s$$

## Conclusions

GDE interference zones can be calculated for policy purposes using a range of hydraulic properties for aquifers, and several subjectively chosen parameters (threshold GDE depletion, pumping time, and confidence). For the Otago region the empirical relationship developed is:

$$r_{5,90,30} = 65\,Q \;\; for \;\; 5\,L/s < Q \leq 25\,L/s$$
$$r_{5,90,30} = 1138 \;\; for \;\; Q > 25\,L/s$$

using 5-L/s threshold GDE depletion, 90th percentile, and 30 days of pumping.

Applicants who wish to obtain a legal water right for groundwater pumping within the GDE interference zone would be required to show that their proposal does not significantly affect the neighbouring stream or GDE. As for any model, the results are based on a set of assumptions (those used by the Jenkins formula for depletion) and are not intended to replace site-specific complex hydrogeological studies.

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