Modelling ET Capture during Groundwater Pumping

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EXTENDED ABSTRACT

Australian floodplain wetlands are sites of extraordinary biological diversity with abundant and diverse populations of waterbirds, native fish, invertebrate species, aquatic plants, and microbes. Understanding groundwater surface water interactions that have significant ecological implications in floodplains is crucial to their management. Groundwater pumping leads to stream depletion and in areas of relatively shallow groundwater tables can also capture evapotranspiration (ET) discharge as a result of lowering the groundwater table. The latter may be viewed to be advantageous from a stream depletion point of view but can actually harm riparian vegetation that is directly dependent on groundwater ET. Most stream depletion models do not account for ET capture during pumping, water that would have otherwise been consumed by plants. Hence such models would overestimate actual stream depletion. On the other hand, the direct effects of groundwater pumping on ET reduction (that can potentially lead to plant health deterioration), have not been thoroughly modelled.

In this paper, we investigate this problem using explicit analytical solutions implemented in a GIS platform using The Invisible Modelling Environment (TIME). Firstly, we use the well-known Theis solution to describe the two-dimensional change in groundwater heads as a result of groundwater pumping. A nonlinear model is used to estimate the decline in ET, which varies with soil, land cover type, and initial depth to groundwater. We establish criteria to constrain the spatial and temporal scales of the problem. We estimate ET capture for two different land-covers and on a sandy loam soil. This is a first of suite of models for studying groundwater surface water interactions being developed within project D3 of the eWater Cooperative Research Centre.

It is shown that the capture of ET during groundwater pumping can be very significant. Dimensionless plots for ET capture are presented; they encompass the combined effects of distance from a pump to a river, pumping rate and aquifer transmissivity on the spatial extent of the influence zone for ET capture. For the case of unbounded aquifers considered in this paper, the cone of depression spans well behind and on either side of the pump. The effective influence zone for ET-capture relates to the distance between the pump and the river '*a*'; it was found to span about *8a* behind the pump and *5a* on either side of the pump. The time required for the realisation of a certain pumping impact varies directly with aquifer diffusivity and inversely with the square of the distance between the river and the pump.

ET-capture increases as the ratio of pumping rate to aquifer transmissivity increases and as the distance from the pump to the river increases. The latter delays the time scales for ET capture. Soil texture has two opposing effects on ET capture. For a certain pumping rate at steady state, coarse textured soils have a smaller depression cone compared to finer soils due to their larger hydraulic conductivity. However, coarse textured soils have a steeper ET-function, which means that for the same drawdown, ET-decline is higher than the case of fine textured soils. Specific yield affects the timing of the drawdown as well as the transient shape of the depression cone. Vegetation type dictates the rooting depth representing the length along which ET occurs; a higher drawdown is required to capture ET in areas with deep-rooted vegetation compared to shallow-rooted vegetation. The initial depth to groundwater table plays a very critical role. ET capture is maximised when the initial groundwater level is just at the transition depth, depth at which ET commences to decline. If the initial groundwater is shallow enough such that the steady state water table after pumping remains above the transition depth, then ET capture is non-existent (ET=potential ET). If the initial groundwater depth is below the extinction depth (where ET≅0), there would be no ET captured.

The magnitude of ET capture can be a significant amount that can offset stream depletion. The impacts of groundwater pumping, especially in floodplains with shallow groundwater tables, may have a significant adverse impact on riparian vegetation.

1. INTRODUCTION

During groundwater (GW) pumping, as the cone of depression progresses towards a nearby stream, groundwater depletion occurs. When this cone reaches the stream, the rate of groundwater discharge to the stream reduces, and surface water may even start to infiltrate the aquifer; thus marking the start of stream depletion. After a long period of pumping, the cone of depression takes its final shape (i.e. steady state is reached), and a portion, or in some cases all, of the pumping will be balanced by a reduction in or reversal of flow from the aquifer to the stream. The groundwater drawdown can also cause a decline in actual evapotranspiration (Theis, 1940).

Webb and Leake (2006) pointed out that the explicit linkage of the fate of riparian vegetation and conjunctive use of groundwater and surface water needs to be more thoroughly understood if protection of this kind of ecosystem is a future management priority. Stromberg et al. (1996) pointed out that groundwater depletion threatens many riparian ecosystems in arid and semi-arid regions around the world. They found out that many ecological indicators varied with depth to groundwater and indicated that the abundance of obligate wetland herbs declined sharply at groundwater depths below 0.25 m. Shafroth et al. (2000) have reported that groundwater level declines of 1 m have caused mortality of saplings of cottonwood and willow. Mature cottonwood trees have been killed by abrupt, permanent drops in water table of 1 m, with lesser declines of 0.5 m reducing stem growth (Scott et al., 1999, 2000). During a 19-year study period, Cooper et al. (2006) have shown that regional groundwater pumping had led to an average drawdown of 1.58 m, which resulted in decreasing the groundwater component of evapotranspiration (ET) by 62%. Furthermore, they indicated that this drawdown has triggered change in site vegetation composition, coverage, and likely rooting characteristics.

ET is a major component of the water budget in vegetated areas that have relatively shallow groundwater tables. A case study in the Shashe River in Botswana has shown that the amount of water taken by transpiration is far more than the quantities pumped for water supply (Bauer et al., 2006). In areas of shallow groundwater table, transpiration directly from groundwater by near-shore vegetation can intercept base flow that would otherwise discharge to a stream (Winter, 1998; Sophocleous, 2002). Furthermore, it can induce infiltration of stream water into the aquifer (Meyboom, 1964); it is not uncommon for transpiration from groundwater to create cones of depression that cause surface water to seep out through the near-shore parts of its bed. Groundwater ET results in diurnal fluctuations of groundwater water tables as well as stream flows (Bond et al., 2002). Chen (2007) has demonstrated via numerical modelling that groundwater ET can bring deeper groundwater to the water table by hydraulic lift, which impacts groundwater quality investigations.

Depending on the positioning of the root zone with respect to the groundwater table, the plant can extract water directly from groundwater, or from the vadoze zone, or from both. Gardner (1958) proposed that an exponential decay function can best describe the behaviour of ET with respect to changes in depth to groundwater table. The most common modelling approach, which had been implemented in MODFLOW (McDonald and Harbough, 1988), assumes that groundwater ET decays linearly with increasing depth to groundwater table and ultimately reaching zero at the extinction depth. Banta (2000) proposed a piece-wise linear function that has the flexibility to capturing the non-linear relationship of ET versus depth to groundwater. Shah et al. (2007) confirmed that an exponential decay function is suitable to describe this relationship and parameterised it for various soil classes and land covers.

There are numerous analytical solutions for estimating groundwater drawdown and the associated stream depletion; they are derived for a variety of conceptual systems of pumping. Theis (1941) obtained the first unsteady solution for the stream depletion due to abstractions from a fully penetrating well. Glover and Balmer (1954) re-wrote the Theis solution in terms of the complimentary error function; this solution is most commonly used to evaluate stream depletion. Hantush (1965) and Hunt (1999) considered a streambed lined with less permeable sediments. Hantush (1967) and Rassam et al. (2004) developed analytical solutions for depletion of flow with multiple discharge edges. Hunt (1999) and Hunt (2003) proposed analytical solutions that incorporate the effects of finite stream width, shallow stream penetration, and semi-confined aquifers. Knight et al. (2005) developed a solution that accounts for the effects of presence of a no-flow boundary condition (finite flow domain).

None of the above mentioned analytical solutions account for the impacts of groundwater ET on stream depletion. ET decreases when the groundwater table falls below a certain level (herein termed the transition zone, after Shah et al., 2007). Hence, groundwater pumping that causes drawdown may lead to a reduction (or capture) of ET. Therefore, neglecting this phenomenon would lead to an overestimation of stream depletion. Many studies have emphasised the role of ET as a discharge mechanism for groundwater (Nichols, 1993), while others have quantified its magnitude using numerical models (Chen and Chen, 2004; Chen and Shu, 2006). The latter reported that the rate of ET capture can be as high as 9.4% in a pumping time of 90 days.

In this paper, we use an analytical solution that predicts two dimensional groundwater head changes due to a step change in groundwater extraction. We use the non-linear relationship of ET versus depth to groundwater to estimate the actual ET at any location in the flow domain. Subsequently, we estimate the amount of ET captured during pumping at various rates, and at various distances from the stream. The solution was coded in The Invisible Modelling Environment (TIME) of Rahman et al. (2003). This is the first stage of a more comprehensive floodplain model, which will account for a suite of processes such as bank storage, over-bank flooding and infiltration. The work is part of the SW/GW interaction project (D3) of the eWater Cooperative Research Centre.

2. METHODS

The conceptualisation of the groundwater extraction problem is demonstrated in Figure 1 where a pump located at a distance '*a*' from a river (left-hand side boundary) causes a cone of depression in the groundwater table. Because of symmetry along the x-axis, only half the problem needs to be modelled (area above x-axis in Figure 1). The free water surface height resulting from a unit step change of recharge or groundwater extraction (negative recharge) at (*x, y*)=(*a, 0*) is as follows (Theis, 1941):

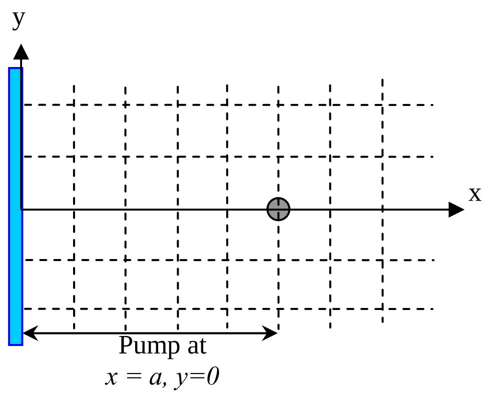

Figure 1. Conceptualisation of pumping problem; left-hand side boundary represents a river

$$h(x,y,a,t) = h_i - \frac{P}{4\pi T}\left[\int_{\frac{r_1^2}{4Dt}}^{\infty} \frac{\exp(-u)}{u}du - \int_{\frac{r_2^2}{4Dt}}^{\infty} \frac{\exp(-u)}{u}du\right] \quad (1)$$

where a is the distance from the pump to the river, T is the aquifer transmissivity (m^2/day), D is the aquifer diffusivity (T/S in m^2/day, where S is the storage coefficient), t is the time (days), h_i is the initial head taken as the aquifer thickness (i.e., datum for heads is the aquifer base), P is the pumping rate (m^3/day), $r_1^2 = (x-a)^2 + y^2$ and $r_2^2 = (x+a)^2 + y^2$ where x and y represent, in respective order, the horizontal and vertical coordinates of the point of interest where the head is being predicted. The Theis (1941) solution assumes that a single-layer homogenous aquifer fully penetrates a straight stream and the other aquifer boundaries extending to infinity. It assumes that T and S are constant in space and time, which means that transient changes in T (e.g., as a result of drawdown during pumping) are neglected; this assumption holds when the magnitude of drawdown relative to aquifer thickness is small. In the current analysis, we are evaluating ET capture, therefore we are interested in drawdowns in the vicinity of 0.5-1 m; this would only cause a marginal reduction in aquifer transmissivity. We assume that the initial steady state head in the aquifer is in equilibrium with a PET equal to 3 mm/year. This means that at initial conditions, all groundwater ET comes from stream depletion.

The decline in ET due to lowering the water table is calculated according to the decay model proposed by Shah et al. (2007):

$$ET_a = \frac{ET}{PET} = 1 \qquad \text{for} \qquad d \le d' \qquad (2a)$$

$$ET_a = \frac{ET}{PET} = e^{-b(d-d')} \qquad \text{for} \qquad d > d' \qquad (2b)$$

where PET is potential evapotranspiration, d is the depth to GW table, b is a decay coefficient, and d' is known as the transition depth where ET shifts from atmospheric control to soil-moisture control. We use sandy loam soil where the parameters of Equation (2b) for grass and forest land covers are d' =0.60 m and 0.82 m, and b=0.039 and 0.016, respectively (Shah et al., 2007). In this exercise (and unless otherwise indicated), we assume that initial GW level, which is in equilibrium with the stream level, is located at a depth equal to d', this means that GW pumping will immediately cause a decline in ET, which represents a worst case scenario. The ET functions used are shown in Figure 2. The cumulative captured ET is estimated across a flow domain that covers the cone of depression resulting from the pumping activity.

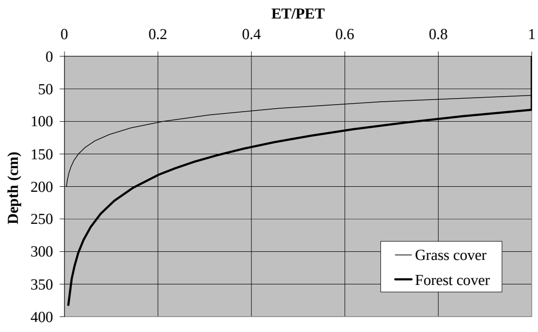

Figure 2. ET functions for two land covers on sandy loam soil; ET is evapotranspiration and PET is potential evapotranspiration

Since Equation 1 models an unbounded aquifer, the cone of depression is expected to extend to large distances during large time scales. The concept of dimensionless time (τ) is used to constrain the time scale for ET capture where τ is defined as tD/a^2; we halt the calculations for ET capture when 80% of stream depletion is realised (at τ=7.8; Rassam et al., 2004). The influence zone for ET decline is defined by plotting ET/PET versus x/a for various P/D ratios; we extend our flow domain in the *x*- and *y*-directions to where actual ET becomes 90% of the initial ET at that location (i.e., where ET capture becomes less than 10%, it is considered to be negligible). This influence zone is discretised in the x- and y-directions using 10m×10m grid cells are to estimate the total daily ET captured. ET capture is calculated as follows:

$$ET_c(t) = \sum_{1}^{y} \sum_{1}^{x} A_c (PET - ET_a) \qquad (3)$$

Where ET_c is the total ET capture at any time step, x and y are the number of grid cells in the horizontal and vertical directions, respectively, A_c is the grid cell area, PET and ET_a are potential and actual evapotranspiration, respectively, and t is time. ET_a is estimated from Equation 2.

The cumulative captured ET is then compared to stream depletion, which is estimated using the Glover and Balmer (1954) solution:

$$D_p(a,t) = P \times erfc\left[\frac{a}{2\sqrt{(Dt)}}\right] \qquad (4)$$

where D_p represents stream depletion (the fraction of pumped water coming from the stream, m^3/day), and *erfc* is the complimentary error function. Equation 4 originates from the Theis (1941) solution and is most commonly used to estimate stream depletion because it has a simple mathematical formulation.

3. RESULTS

The potential extent of ET capture relates directly to the volume of cone of depression resulting from the pumping activity. Whether this potential translates to an actual capture depends on what fraction of this depression cone lies within the transition and extinction depths for ET; maximal capture would occur when the entire (or most) of the depression cone lies within these extents. The size of the depression cone varies linearly with the ratio P/D, that is, doubling this ratio would lead to doubling the volume of the depression cone. We will see that the ratio P/D is an essential parameter for evaluating ET capture.

Figure 3 is a dimensionless plot that shows the influence zone of ET capture for various ratios of P/D at various distances along the axis of pumping. Figure 3 shows that at x/a>9 actual ET becomes >90% of potential ET (PET), which was deemed accurate enough for ET capture calculations. A similar exercise for the orthogonal direction revealed that PE/PET>0.9 occurred when x/a>5 on either side of the pump. Therefore, the flow domain needed to be 9a wide (in the x-direction that is orthogonal to the river) and 5a long on either side of the pump (in the y-direction that is parallel to the river). These cases represent a worse case scenario where the initial GW level is at the transition level, that is, pumping would immediately cause a reduction in ET.

Figure 4 shows the extent of ET capture for two land covers, namely grass and forest, on a sandy loam soil. The non-dimensional plot shows how ET capture (represented as a fraction of initial ET before commencement of pumping) varies with the ratio of P/D. Note that the shallow-rooted grass exhibits a higher ET capture due to a steeper ET-decline function. The worst case scenario for each case is realised when the initial depth to groundwater (GW_i) becomes equal to its d' (0.6 m and 0.82 m, for grass and forest, respectively). A true comparison between the two land covers occurs when the initial GW_i is equal for both cases (e.g., 0.6 m). This case highlights the crucial effect of initial depth to groundwater relative to the transition depth d' on ET capture. Figure 4 shows that for the case of forest cover with GWi=0.6m<d', there is an initial lag due to the early drawdown occurring between depths 0.6 m and 0.82 m (d'), which does not capture any ET.

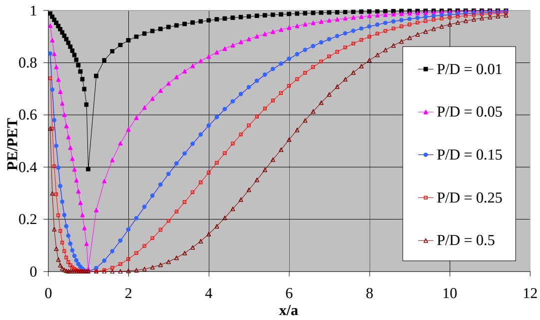

Figure 3. Influence zone for ET capture; D is diffusivity, P is pumping rate, and ET/PET represents relative actual evapotranspiration

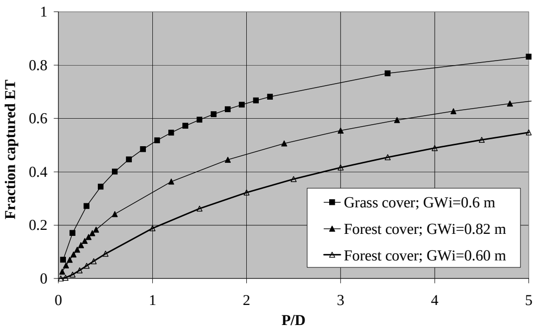

Figure 4. ET capture for grass and forest covers; GW_i is initial depth to groundwater table, D is diffusivity, and P is pumping rate

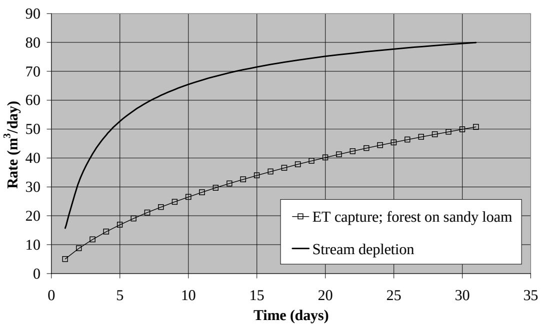

Figure 5. Comparison of ET capture to stream depletion for grass and forest covers; y-axis is either pumping or ET rates

Figure 5 shows that ET capture is very significant when compared to stream depletion. It worthwhile emphasizing that this is indeed a worst case scenario where the initial GW depth is set equal to the transition depth. In areas where the initial GW table is deeper than the extinction depth or it is so shallow that the steady state GW table after pumping is shallower than the transition depth, then ET capture would be zero.

4. DISCUSSION AND CONCLUSIONS

The capture of ET during groundwater pumping can be very significant. Dimensionless plots for ET capture are presented; they encompass the combined effects of distance from pump to river, pumping rate and aquifer tansmissivity on the spatial extent of the influence zone. The adopted exponential decay ET-function exhibits a very high sensitivity of actual ET to small changes in groundwater heads. For the case of unbounded aquifers considered in this paper, the cone of depression spans well behind and on either side of the pump. The effective influence zone for ET-capture relates to the distance between the pump and the river '*a*'; it spans about *8a* behind the pump and *5a* on either side of it.

The magnitude of ET capture depends on the following factors. (1) The ratio of pumping rate to aquifer diffusivity (P/D); increasing P/D results in a larger depression cone (and hence a larger influence zone for ET capture); the volume of the depression cone varies linearly with P/D. (2) The distance from the pump to the river leads to a larger depression cone and hence higher ET capture; however, a larger distance would lead a more delayed ET capture. (3) Soil texture has two opposing effects on ET capture. For a certain pumping rate at steady state, coarse textured soils have a smaller depression cone compared to finer soils due to their larger hydraulic conductivity. However, coarse textured soils have a steeper ET-function, which means that for the same drawdown, ET declines is higher than the case of fine textured soils. (4) Vegetation cover dictates the rooting depth along which ET is active; it would require a higher drawdown to capture ET in areas with deep-rooted vegetation compared to shallow-rooted vegetation. (5) Initial depth to groundwater table, which is very crucial parameter. If the initial groundwater is shallow enough such that the steady state water table after pumping remains above the transition depth, then ET capture is non-existent (ET=PET). If the initial groundwater depth is below the extinction depth, there would similarly be no ET captured (ET≅0). ET capture is maximised when the initial groundwater level is just at the transition depth.

The time scales for drawdown (and hence ET capture) can be described using the concept of dimensionless time. The time required for the realisation of a certain pumping impact varies directly with aquifer diffusivity and inversely with the square of the distance between the river and the pump. The current solution neglects the fact that the captured ET becomes a source of water that recharges the aquifer; hence the cone of depression, and ET capture are both being overestimated. Further work is being undertaken to estimate the extent of overestimation.

Depending on the above-mentioned factors, the magnitude of ET capture can be a significant amount that can offset stream depletion. The impacts of groundwater pumping, especially in floodplains of shallow groundwater table may have a significant adverse impact on riparian vegetation.

5. ACKNOWLEDGEMENTS:

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