



Water for a Healthy Country

Applicability of the unit response equation to assess salinity impacts of irrigation development in the Mallee region: supplementary analyses

D. Rassam, G. Walker, and J. Knight



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For further information contact:

Ph: 02 6246 4565

Fax: 02 6246 4564

www.csiro.au

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Executive Summary

The simple unit response equation (URE) has been successfully implemented in SIMRAT to assess the impacts of irrigation developments on discharge to the River Murray in South Australia. The perceived limitations in the applicability of the URE in the Mallee region were rigorously investigated by Rassam et al. (2004) and mainly addressed 3 concerns: firstly, doubts about the underlying theory of the URE in relation to basic concepts such as linearity and superposition, and secondly, doubts regarding the capacity of this simple approach to produce accurate results comparable to those arising from more sophisticated models, and thirdly, concerns about model applicability in the real world where the underlying assumptions might be violated (different boundary conditions, complex geometries, and aquifer heterogeneity).

Since the publication of CSIRO Technical Report 35/04 (Rassam et al., 2004), further questions were raised regarding the applicability of the URE in the Mallee region; they mainly relate to the following issues: non-uniform transmissivity and aquifer heterogeneity under large irrigation developments, high sensitivity to base slope of the solution presented by Knight et al. (2005) for sloping base aquifers, and aquifer head response under reduced recharge conditions. These issues are addressed in this report.

Objectives of the current report are:

- Investigate the temporal variation of aquifer transmissivity under large irrigation developments and its subsequent effect on discharge to rivers.
- Compliment the study of aquifer heterogeneity conducted by Rassam et al. (2004) to include low conductivity barriers spanning in the vertical direction.
- Investigate the effect of aquifer base slope on the URE predictions.
- Show how various parts of the aquifer may respond differently to reductions in recharge.

Key findings of the current report are:

The temporal variation of aquifer transmissivity at Loxton was shown to increase by about 40% during a 100-year period; this only resulted in a 10% increase in discharge to the river, which is well within the expected range due to aquifer parameter uncertainty as outlined by Rassam et al. (2004).

Low conductivity vertical barriers were found to speed up the flux response to the river when they are situated behind the recharge source; as their hydraulic conductivity becomes extremely low, they function as no flow boundaries. Low conductivity vertical barriers located between the recharge source and the river slow down the flux response to the river; a modified form of the URE is proposed to estimate the discharge flux response under such conditions.

The high sensitivity of flux response to the aquifer base slope is due to existing head gradients and not to the slope angle per se; for a sloping base aquifer with no head gradient, the basic URE is still applicable provided a suitable aquifer thickness that accounts for the slope effect is used; in the presence of head gradients, the criteria outlined by Rassam et al. (2004) should be followed.

The analytical functions for predicting pressure heads presented by Rassam et al. (2004) may be used under reduced recharge conditions; when recharge is reduced in a high-transmissivity aquifer, the water table between the recharge source and the river drops quickly while it continues to rise behind the recharge source long after recharge had been reduced. This demonstrates that different parts of the aquifer may respond differently to recharge reduction.

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1 Introduction:

This report follows CSIRO Technical Report 35/04 (Rassam et al., 2004), which involved a detailed investigation of the unit response equation (URE) presented by Knight et al. (2002 and 2005) and its application in the SIMRAT model (URS, 2005). SIMRAT is a GIS based model, which is currently being used to assess the salinity impacts of irrigation development in the Mallee region, in South-East Australia. Rassam et al. (2004) addressed many technical assumptions associated with SIMRAT and more specifically the Unit Response Equation, which had been previously thought to be violated for many areas of the Mallee Region. This had led to masking of these areas, where the model could not be used with high confidence. There were 3 underlying concerns. There were doubts:

- about the basic underlying theory of the URE regarding basic concepts such as linearity and superposition,
- whether this simple formula is capable of producing accurate results comparable to those obtained from more sophisticated models such as MODFLOW,
- about the model applicability in the real world where the underlying assumptions might be violated (such as different boundary conditions, geometry, heterogeneity, etc).

Since the publication of Technical Report 35/04, further questions were raised regarding the applicability of the URE, they mainly related to the following issues:

The formation of a groundwater mound under such large irrigation developments leads to increased aquifer thickness and hence to increased transmissivity. This would superficially violate linearity assumptions of the URE. Previously, this was considered a good reason for the URE not to be applied to simulate areas with large groundwater mounds.

Given that some irrigation developments cover a large area, it is more likely that these areas would include heterogeneities. Once again, these would violate some of the underlying assumptions of the URE. However, there may be some simplifying relationships that would enable the simpler URE to continue to be applied within some constraints.

There has been previously some confusion relating to the high sensitivity of the discharge response to aquifer base slope; it was thought that this phenomenon would grossly undermine the applicability of the URE because many regions of the study area had steep aquifer bases.

Improvements in water use efficiency are thought to lead to reductions in root zone drainage and hence reductions in aquifer recharge. There is a need to consider appropriate design of monitoring to detect such changes in the background of increased recharge due to increased irrigation development. From a mathematical perspective, there is hence a need to show that different parts of the aquifer may respond differently to recharge reduction.

In this supplementary report, we address those issues. The objective of the report is that for these 4 issues to:

Test the range of applicability of the unit response equation,

Test whether simplifying assumptions can enable the URE to be extended in those cases, where the URE does not apply, and

Test whether alternative formulations can be developed where it is not feasible to extend the URE.

2 Temporal variation of aquifer transmissivity:

Increased recharge under large irrigation developments leads to the formation of groundwater mounds. The increased thickness of the aquifer in the vicinity of the mound leads to an increase in aquifer transmissivity. This violates the assumptions of linearity and potentially could lead to errors when applying the URE for large irrigation developments. The objective of this section is to test the applicability of the URE for estimating groundwater discharge to a stream following a large irrigation development by using a case study with Loxton data.

2.1 Modelling experiment:

The objective of the modelling is to estimate the difference discharge to stream between using the URE assuming no changes in aquifer thickness and using analytical theory allowing for changes in aquifer thickness, estimate the mound development at Loxton, investigate the temporal variation of transmissivity and its impact on discharge to river

Here, we re-visit the case study of the mound at Loxton (outlined in Section 10.2.2 of Rassam et al., 2004); we refer the reader to Figure 43 of Rassam et al. (2004) for flow domain details.

Figure 1 shows how the groundwater mound builds up with time; these are cross sections through the centre of the irrigation development running perpendicular to the river (i.e., through the peak of the mound). The water table levels between the centre of the irrigation development and the river rise dramatically during the first 30 years then slowly creep up; steady-state analysis has shown that the peak water level is about 33 m (occurs at 2660 m from the river). Figure 1 shows that the water level behind the centre of the irrigation development continues to rise at large times and results in shifting the peak of the groundwater mound there.

In order to assess the impact of the increased transmissivity on discharge to the river, we estimate the effective aquifer thickness based on the water table levels shown in Figure 1; it is the average water table height between the centre of the irrigation development and the river calculated on a weighted mean basis (by integrating the areas under each of the curves of Figure 1).

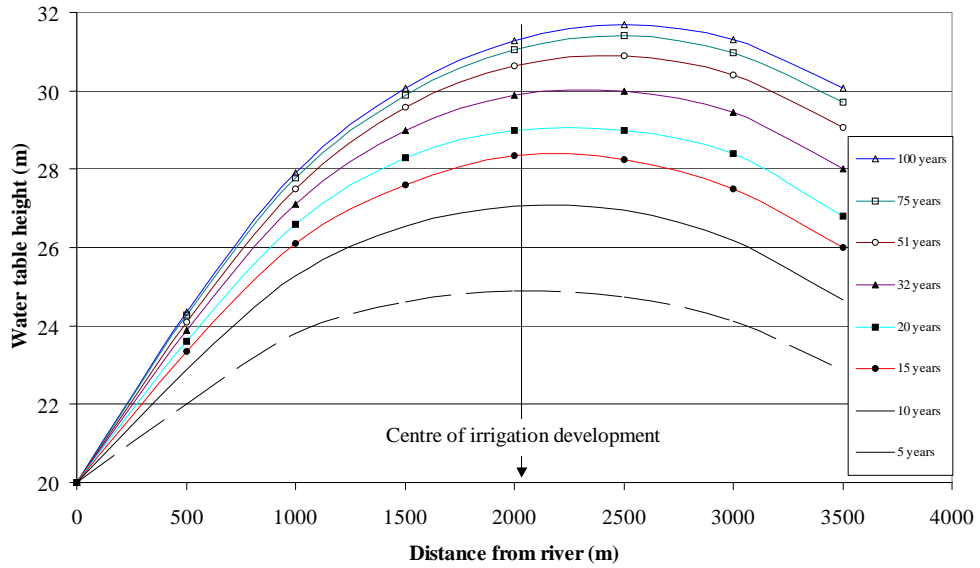


Figure 1: Mound development at Loxton

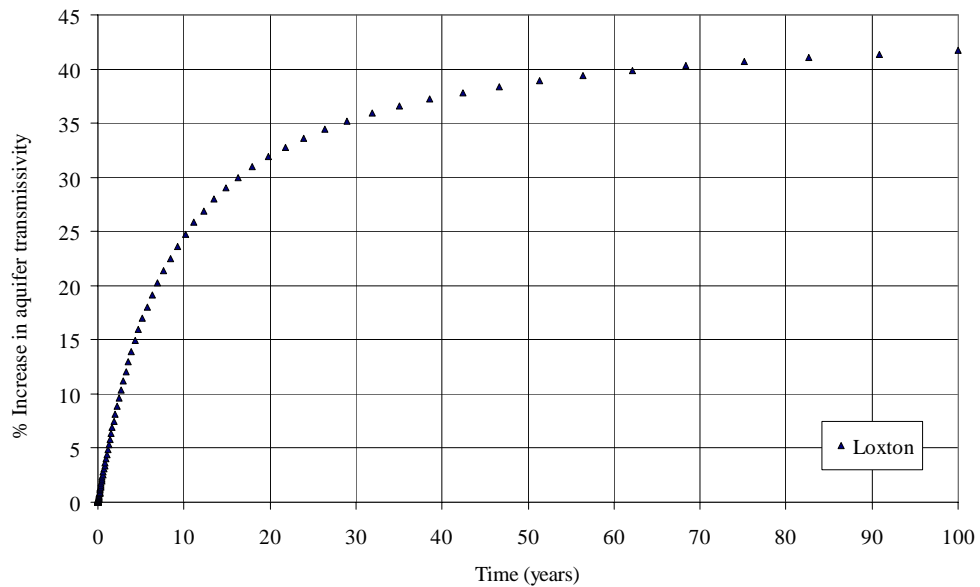


Figure 2: Variation of average aquifer transmissivity under the irrigation development

Figure 2 shows that the average aquifer transmissivity has increased by about 40% after 100-year period.

The increase in stream discharge is estimated by the basic URE equation; Figure 3 shows that a 50% increase in aquifer transmissivity increases discharge by only about 10%. A 40% increase in transmissivity leads to about a 20% decrease in the time for the same impact to occur at the river. As the transmissivity increases slowly over time, this time lag also increases slowly. Because the discharge function begins to flatten, an error in the time lag of 20% is unlikely to lead to more than a 10% error in the discharge function.

2.2 Summary:

The introduction of large irrigation developments leads to the formation of their own groundwater mounds; the increased saturated aquifer thickness leads to a higher aquifer transmissivity. The groundwater mound requires a long time to reach to steady state (this happens when the applied recharge becomes equal to the discharge to the river, at that time the water table reaches a stable level) so one expects that during the mound build-up, aquifer transmissivity gradually increases. The temporal variation of aquifer transmissivity at Loxton was shown to increase by about 40% during a 100-year period; this only resulted in a 10% increase in discharge to the river, which is well within the expected variations due to aquifer parameter uncertainty outlined by Rassam et al. (2004).

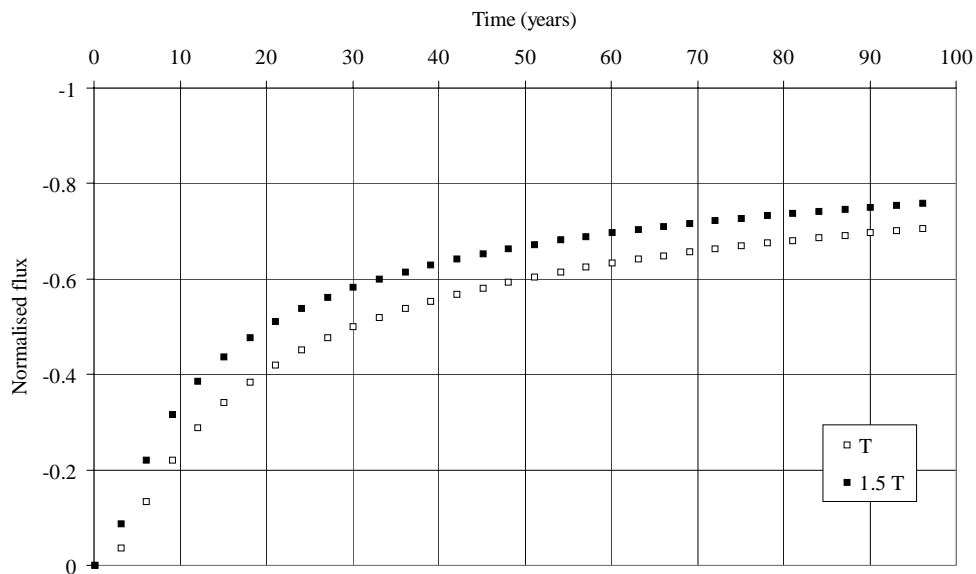


Figure 3: Impact of increase in transmissivity on discharge to river

3 Response of a heterogeneous aquifer; low-conductivity barriers spanning in the vertical direction:

The formulation of the URE is based on the assumption that the aquifer is homogenous. It is more likely that we encounter lateral aquifer heterogeneities with large irrigation developments and when the distance between the development and the river is large. In Section 10.3 of Rassam et al. (2004) the implications of having vertically layered aquifers were discussed; i.e., low conductivity layers spanning in the x-direction. In this section, we discuss the effects of barriers that span in the orthogonal direction; i.e., low conductivity barriers spanning in the y-direction (see shaded areas in Figure 4). We investigate the implications of having such barriers located behind the recharge source as well as those located between the recharge source and the river (Cases 1 and 2, Figure 4).

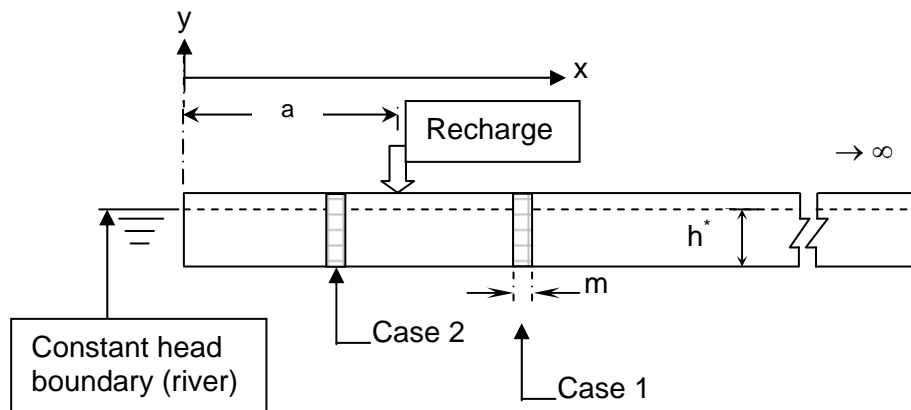


Figure 4: Recharge to a semi-infinite aquifer with a semi-impervious layer

3.1 Modelling experiment

The presence of the low-conductivity (low-K) barrier is represented by a retardation factor (α), which was defined by Hantush (1965) as the effective thickness of aquifer required to cause the same head loss as the low-K barrier; it is equal to mK/K^* where K is the hydraulic conductivity of the aquifer, m is the width of the low-K barrier (see Figure 1), and K^* is its hydraulic conductivity.

We compare results from the analytical solution of Hantush (1965) with outputs from numerical simulations using MODFLOW (McDonald and Harbaugh, 1988).

3.1.1 Case 1: Low conductivity barrier behind the recharge source

For this case, we placed a low-K barrier 800 m from the river; domain width 3,000m; $a=410$ m; $K=5$ m/day; $h=10$ m; and $\phi=0.05$; where 'a' is the distance between the recharge source and the river, 'K' is the hydraulic conductivity, 'h' is the average saturated aquifer thickness, and 'phi' is the specific yield. We used $w=100$ m and vary the hydraulic conductivity to obtain various retardation factors (α); we conducted MODFLOW simulations using $\alpha=1E2$, $1E3$, $1E4$, and $1E7$.

Figure 5 shows that when α is as low as 100, the low-K barrier has virtually no effect and the response is identical to that provided by the URE (Equation 4 of Knight et al., 2005; distance to no-flow boundary $c=3,000$ m). When α attains a value high as $1E7$, the low-K barrier acts as a no-flow boundary and significantly speeds the flux response to the river (see Figure 5); we get excellent agreement with the URE results (Equation 4 of Knight et al., 2005; $c=800$ m). Intermediate cases lie in between. This case is similar to the leaky aquifer situation

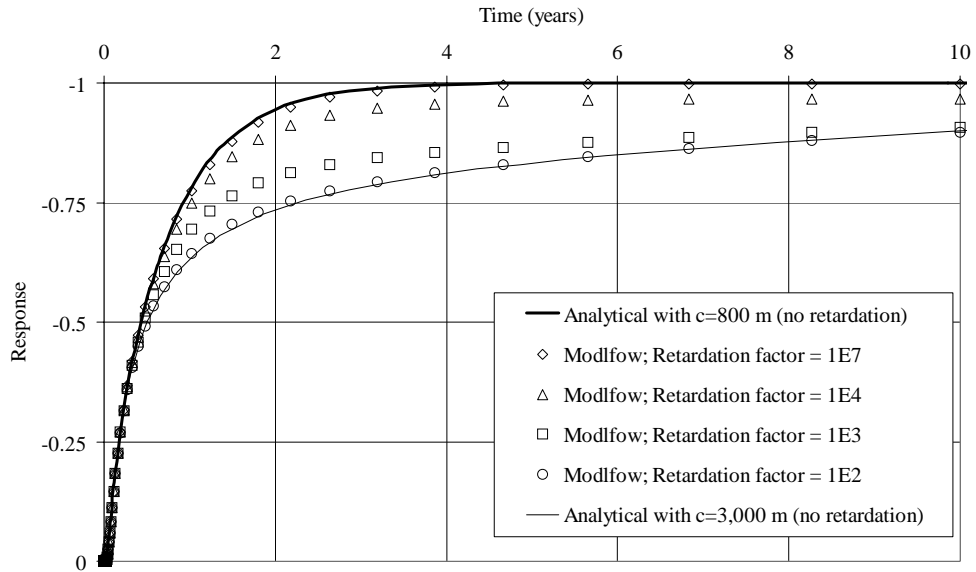


Figure 5: Low-K barrier behind recharge source; effect on flux response

presented in Section 10.3.2 of Rassam et al. (2004) where the URE can provide upper and lower bound solutions for the problem.

3.1.2 Low conductivity barrier between the recharge source and the river

We use the solution of a radiation boundary problem given by Carslaw and Jaeger (1959; reported by Hall and Moench, 1972) to define the flux response in the presence of a vertically oriented low-conductivity barrier located between the recharge source and the river; it is given by:

$$F(a, t, \alpha) = \operatorname{erfc}\left(\frac{a}{2\sqrt{Dt}}\right) - \exp\left(\frac{a}{\alpha} + \frac{Dt}{\alpha^2}\right) \operatorname{erfc}\left(\frac{a}{2\sqrt{Dt}} + \frac{\sqrt{Dt}}{\alpha}\right) \quad (1)$$

where (a) represents the distance separating the recharge source from the river (the constant head boundary), (t) is a time variable, and (D) is the diffusivity ($D=Kh^*/\phi$, where K is the saturated hydraulic conductivity, h^* is the average height of the water table, ϕ is the specific yield of the layer where the water table exists, and α is the retardation factor (defined in the previous section). The first term in Equation (1) is the basic form of the URE (Equation 1 of Knight et al., 2005; and Equation 4 of Rassam et al., 2004); the second term accounts for the effect of aquifer heterogeneity as represented by a finite vertical barriers (or barriers) having a hydraulic conductivity lower than that of the aquifer. Note that the location of the low conductivity barrier is not explicitly represented in Equation (1), however, it is implicit that that the low-K barrier is located between the recharge source and the river (Case 2, Figure 4) since the original formulation of Equation 1 was for an semi-pervious stream bank; its effect is

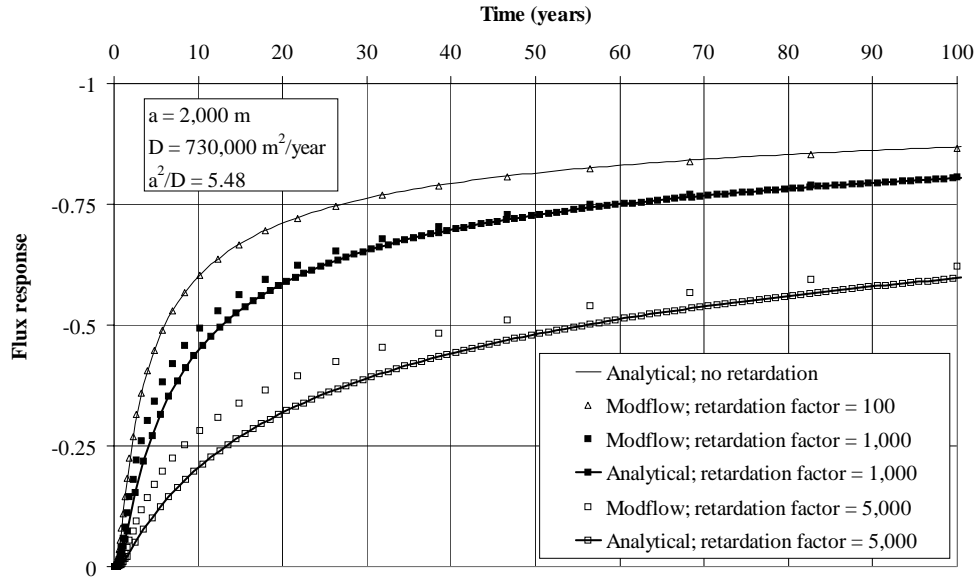


Figure 6: Low-K barrier between recharge source and river; effect on flux response

the same regardless of its location, which also implies that the effects of multiple barriers are additive. Note that we cannot evaluate the second term of Equation 1 using ordinary arithmetic because it contains the product $\text{exp}() \times \text{erfc}()$ where the former is a very large value and the latter is a very small value; this is a limitation of computer arithmetic. We use the method proposed by van Genuchten and Alves (1982) to write an Excel VBA function that calculates the flux response (see Appendix I). We use a very wide domain spanning 25,000 m in the x-direction to eliminate any no-flow boundary effects; a recharge source is placed 2,000 m away from the river; $D=730,000 \text{ m}^2/\text{year}$. We introduce a low-K vertical barrier with α values ranging from 100 to 5,000; note that the location of this barrier is irrelevant (as long as it is between the recharge source and the river); α is the result of any combination of K^* and w ; that is, for an aquifer having a hydraulic conductivity K , a barrier w wide with a hydraulic conductivity $0.1K$ located next to the river has the same effect as a barrier $2w$ wide with hydraulic conductivity $0.2K$ located next to the recharge source.

Figure 6 shows that when α is as low as 100, the low-K barrier has virtually no effect and the response is identical to that provided by the basic URE (Equation 1 of Knight et al., 2005); for higher α values, the response slows down more significantly. Figure 6 shows that Equation 1 provides good estimates for the flux response for α values of up to 1,000; for α values of 5,000 Equation 1 underestimates the response by a maximum of 10% at early times and the discrepancy diminishes at large times (compared to MODFLOW predictions). Figure 7 shows how the time (dimensionless time, τ) required to reach 50% response varies with nonlinearly with α .

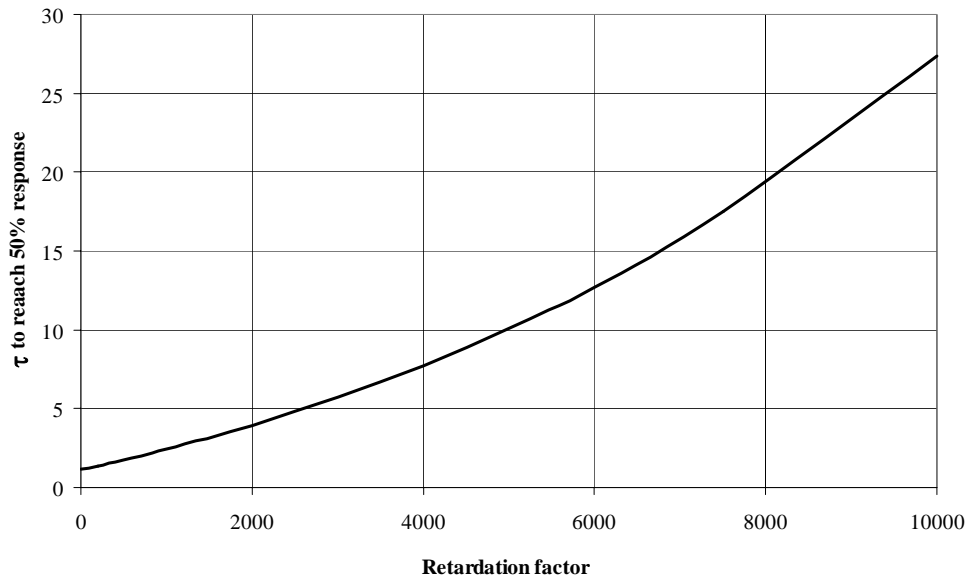


Figure 7: Low-K barrier between recharge source and river; effect of retardation factor on flux response

3.2 Summary:

The formulation of the URE is based on the assumption that the aquifer is homogenous. However, when the URE is used predict flux responses resulting from large irrigation developments or when the distance to the river is large, there is a high likelihood of encountering aquifer heterogeneities. This section dealt with the effects of having low conductivity barriers that spans in the y-direction of the aquifer (i.e., parallel to aquifer thickness). The presence of the low-K barrier was represented by the retardation factor presented by Hantush (1965); the effect of this barrier depends on whether it is located in front or behind the recharge source. When the low-K barrier is behind the recharge source, it speeds up the flux response to the river because it aids in rebounding the recharge water by acting as a no-flow boundary; its effect becomes more pronounced as the hydraulic conductivity decreases and the thickness increases. When the low-K barrier is between the recharge source and the river, it delays the flux response to the river. The mathematical formulation reported by Hall and Moench (1972) is used to estimate the flux response in the presence of such a barrier; the estimates were found to agree with those obtained from MODFLOW for retardation factors of up to 1,000. The time required to reach 50% response was found to vary non-linearly with the retardation factor.

4 Effect of aquifer base slope

Knight et al. (2005) presented a modified form of the URE that accounts for a sloping base aquifer; it was shown that the flux response is highly sensitive to the slope of the aquifer base. Since some areas of the Mallee region have aquifers with sloping bases, there were serious concerns regarding the applicability of the basic form of the URE in these areas. In this section, we will demonstrate that it is the head gradient that is responsible for the high sensitivity to slope and not the base slope per se.

4.1 Modelling experiment

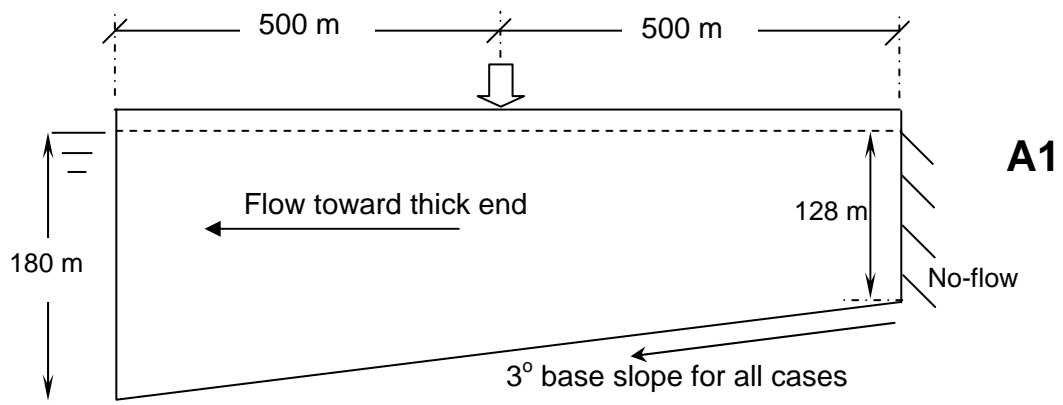
We simulate two aquifers of different thicknesses both with sloping bases. A pulse recharge is applied at the middle ($a=500$ m for all cases); for each aquifer thickness, the location of the no-flow boundary condition is changed as shown below such that flow is reversed (in one simulation flow is towards the thick aquifer end and in the other flow is towards the thin aquifer end). Aquifer properties are as follows: $K=0.5$ m/day; specific yield=0.05; aquifer base slope = 3° for all cases; aquifer thicknesses as displayed in Figure 8.

The formulation of the sloping aquifer presented by Knight et al. (2005) assumed an aquifer with a sloping base and a uniform saturated thickness to maintain linearity (i.e., aquifer base is parallel to the phreatic surface). The URE for the sloping base aquifer is highly sensitive to changes in head gradients (see Figure 7 of Knight et al., 2005, and Section 9.2 of Rassam et al., 2004). The sensitivity varies inversely with the hydrological response time (a^2/D); i.e., when the flux response is very slow due to either a high 'a' and/or a low 'D' (the hydrological response time is high), then the contribution of the head gradient to speeding the flux response becomes more significant. It is shown here that this high sensitivity is mainly due to the head gradient (slope of the phreatic surface) and not the aquifer base slope per se. The cases discussed in this section relate to an aquifer having a non-uniform saturated thickness (flat water table and a sloping base aquifer as shown in Figure 8).

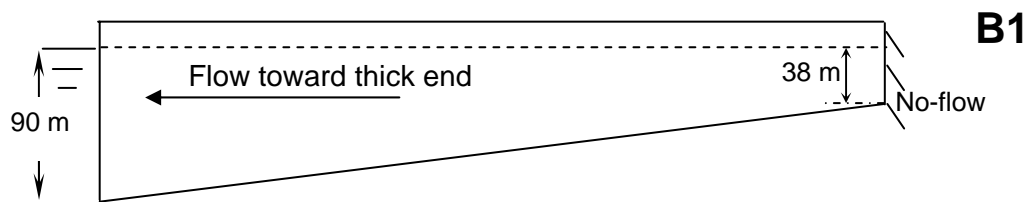
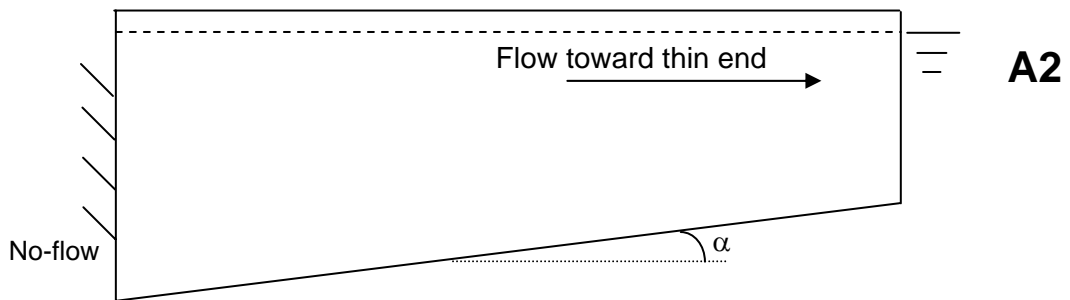
We use the URE for the no-flow boundary case; this is mainly to eliminate any discrepancies when comparing with MODFLOW (where the no-flow boundary is inevitable). Note that we do not use the URE for the sloping case because in the current simulations the head gradient is non-existent.

Figures 9 and 10 show that the basic URE has produced good agreement with MODFLOW although the aquifer base is sloping at 3° . Once again to minimise errors, the same rules recommended in Rassam et al. (2004) apply; i.e., firstly, the correct effective aquifer thickness must be chosen, and secondly, the differences in transmissivity due to the sloping base should be low relative to the aquifer thickness. This confirms that the sloping base only contributes to an increased transmissivity and thus can be handled with the basic URE provided an effective aquifer thickness is used.

For both simulations A and B the base slope is the same; i.e., the difference in aquifer thickness between the two ends (due to the slope) is equal to 52 m (i.e., from the centre point where the recharge is applied there is a difference of 27 m toward each end). The relative impact of a variable aquifer thickness becomes more and more significant in simulations A1, A2, B1, and B2, respectively (relative increase in transmissivity becomes higher). Compare Figure 9 and 10 (either analytical or numerical); the difference between runs B1 and B2 is much higher than the difference between runs A1 and A2; this is because of the lower aquifer thickness for cases A1 and A2 (the slope effect is more significant).



Thick aquifer



Thin aquifer

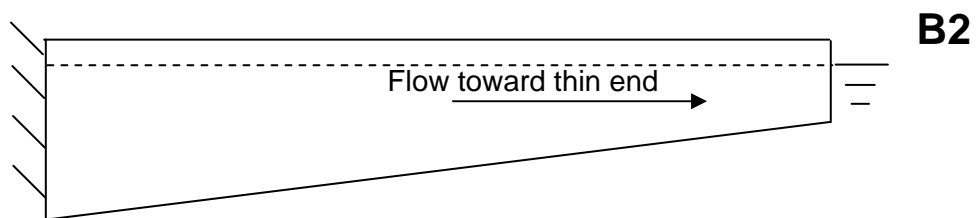


Figure 8: Sloping base aquifers with no head gradient

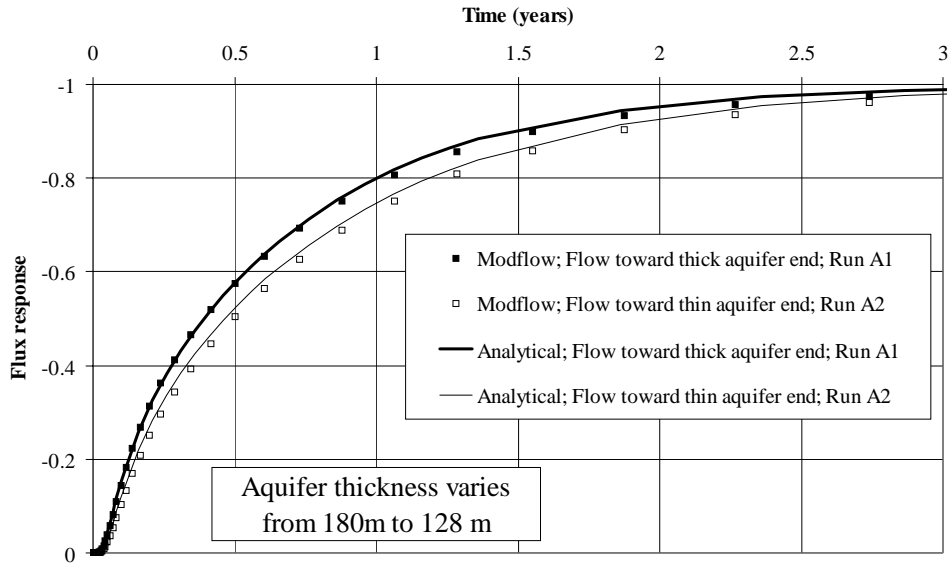


Figure 9: Analytical and MODFLOW simulations for thick aquifer with sloping base

Better agreement with MODFLOW was obtained for series 'A' due to the thicker aquifer. The differences in all case are marginal; it is only when the difference in thickness arising from the slope becomes comparable to the aquifer thickness that we start to get significant discrepancies (i.e., when the thickness doubles due to a sloping base).

Choosing the correct effective aquifer thickness is always critical; in the current simulation an average value was used (average of thickness under the recharge source and thickness at constant head boundary); values were as follows: (A1; $h=167\text{m}$); (A2; $h=141\text{m}$); (B1; $h=77.5\text{m}$); (B2; $h=51.5\text{m}$).

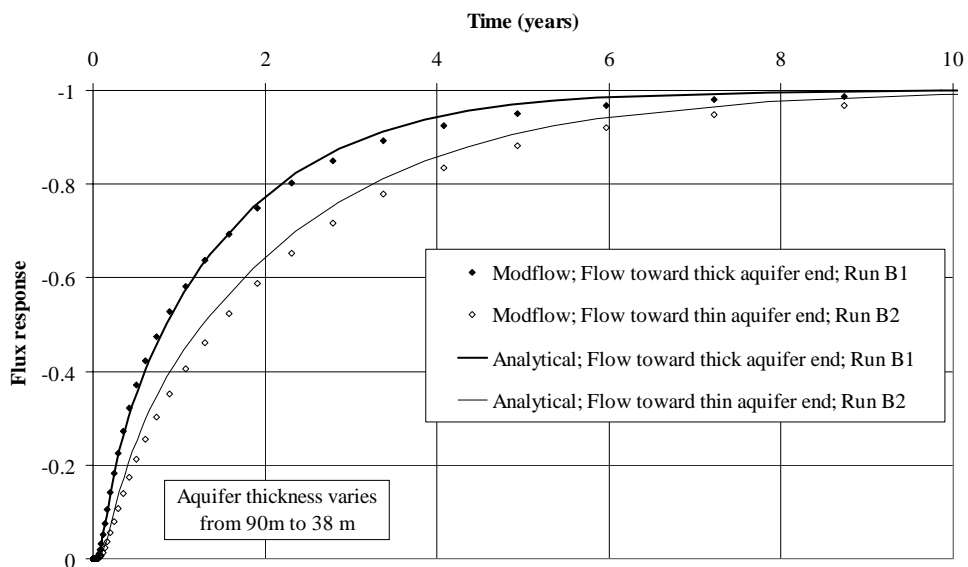


Figure 10: Analytical and MODFLOW simulations for thin aquifer with sloping base

4.2 Summary:

The modified form of the URE for sloping base aquifers proposed by Knight et al. (2005) is highly sensitive to head gradients; this formulation of the URE should only be used if there is a head gradient (as the angle α in Section 2.5 of Knight et al., 2005, actually refers to the head gradient); if the base slope is not parallel to the water surface (non-uniform aquifer thickness; unlike the formulation outlines in Section 2.5 of Knight et al., 2005), the angle must be derived from the head gradient and not from the base slope (the tangent of the angle used in the URE is the head gradient itself); an effective aquifer thickness should be estimated (as the aquifer thickness is non-uniform). If there is no head gradient or if it is less than 1.5% (as recommended in Rassam et al., 2004) and the aquifer base is sloping, we can use the basic URE and adjust the effective aquifer thickness (by taking into account the added thickness due to the sloping base).

5 Pressure heads under reduced recharge conditions:

The favourable effects of reduced recharge are expected to take some time (depending on aquifer properties) until they translate into actual reductions in discharge to the river and to reduced water table levels. The water table levels respond differently to reduced recharge in different parts of the aquifer; this response also varies with aquifer properties. In this section, we will demonstrate this phenomenon.

5.1 Modelling experiment

In this section, we demonstrate how the analytical solution for pressure heads (Equation 6 of Rassam et al., 2004) can be used to predict head changes under reduced recharge conditions.

The aquifer properties used are as follows: specific yield=0.1; aquifer thickness=10 m; $K=1$ m/day; i.e. $T=10$ m²/day. An irrigation development is introduced at ($a=3,000$ m) from the river; initial recharge is 160 mm/year, which was then reduced to 120 mm/year after 20 years.

The results shown in Figures 11 and 12 are due to an irrigation strip 100m-wide per unit length parallel to the river (i.e., the initial total recharge volume is 0.16×100 m³/m length parallel to the river/year); the results scale linearly with the recharge volume, i.e., for a 10m-wide irrigation strip (one tenth), divide the results (on the y-axis of Figures 11 or 12) by 10.

We consider the head rise at 5 locations: 0.25 a, 0.5a, 0.75a, 0.9a, and a; note that during these short time scales (time<50 years for the aquifer properties used here), the head changes in front of, and behind the irrigation development are similar, for example the head changes at 1.25a are similar to the head changes at 0.75a (it is only after 100 years that the head at 0.75a becomes lower than the head at 1.25a, and only after 50 years that the head at 0.25a becomes lower than the head at 1.75a). Hence, the results were restricted to $x \leq a$ (Figure 11).

The solid markers in Figure 11 show the head rise at 5 locations when the recharge remains at the original rate of 160 mm/year; the hollow markers show the head-rise when the recharge is reduced to 120 mm/year after 20 years of starting the development. The response under reduced recharge conditions was obtained using the principle of superposition as follows: obtain a response for a recharge of -40 mm/year (120-160; amount reduced), then add it the response time series starting at 20 years (note that both time series must have the same time step). It is noted that reducing the recharge does not have any effect on water levels close to the river (up to 0.5a). As expected, the maximum reduction in water level occurs under the centre of the irrigation development.

Another scenario is modelled using a much higher aquifer transmissivity ($400 \text{ m}^2/\text{day}$) to demonstrate how various parts of the aquifer respond differently to the reduction recharge conditions.

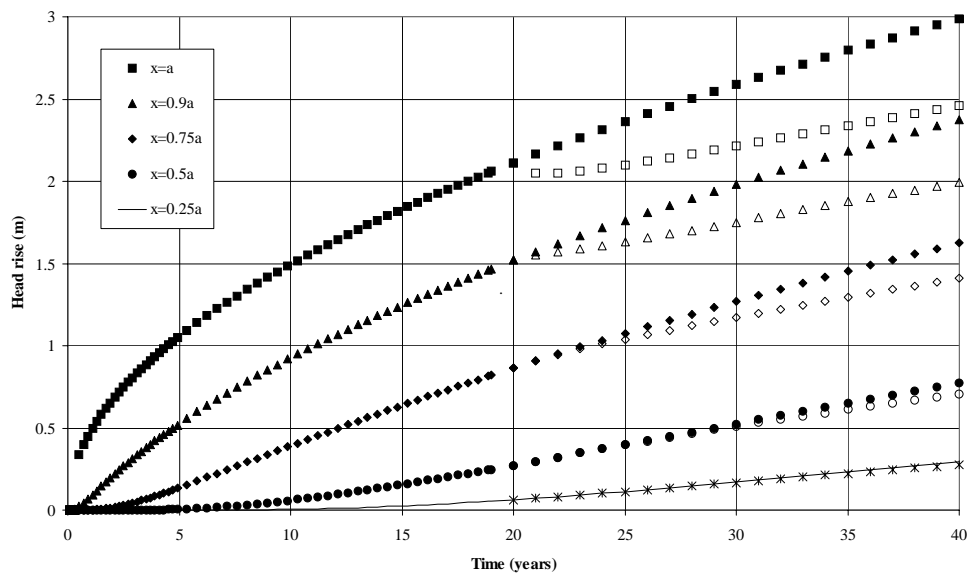


Figure 11: Head rise due irrigation development at 5 locations from the river; low T; solid markers show recharge=160 mm/year and hollow markers show change of recharge to 120 mm/year

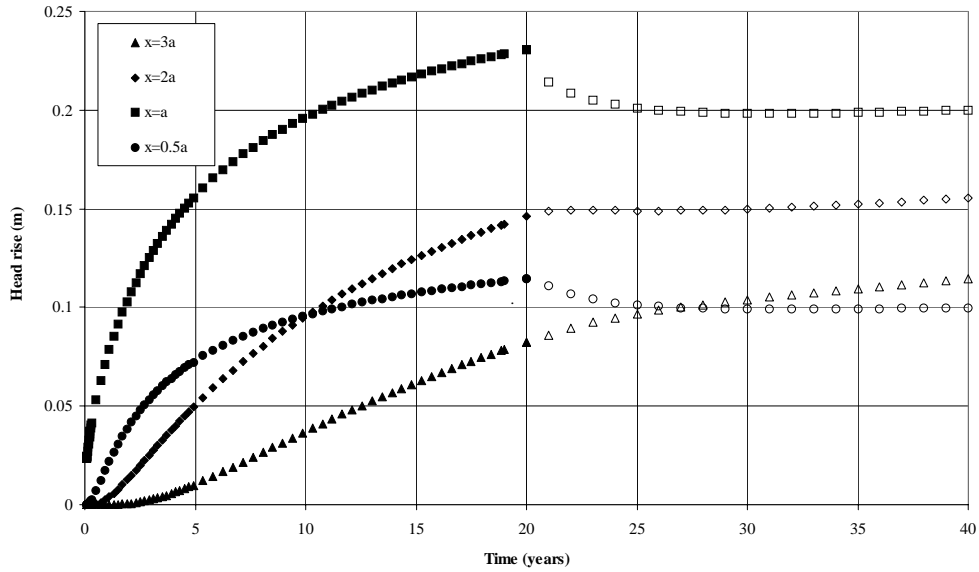


Figure 12: Head rise due irrigation development at 4 locations from the river; high T; solid markers show recharge=160 mm/year and hollow markers show change of recharge to 120 mm/year

The head rise is much lower because the aquifer is draining much faster due to its high transmissivity (compare Figure 11 and 12); the water levels between the recharge source and the river attain a steady state condition after about 25 years. Note that the pressure head does not respond to the reduced recharge behind the recharge source but continues to rise (see Figure 12; triangle and diamond markers); at a distance $3a$ ($2a$ behind the mound), the head continues to rise 20 years after the recharge has been reduced (Figure 12; triangle markers).

5.2 Summary:

The analytical solution for pressure heads presented by Rassam et al. (2004) can be used to predict head changes under reduced recharge conditions through superposition. The response of the water table to a reduction in recharge depends on aquifer properties and on the location (relative to the locations of the recharge source and the river). For an aquifer having a transmissivity of $10 \text{ m}^2/\text{day}$ and within distances closer than $0.5a$ to the river, reducing the recharge by 25% does not have any effect on the water levels. It is shown that when recharge is reduced in a high-transmissivity aquifer, the water table between the recharge source and the river drops quickly while it continues to rise behind the recharge source long after recharge had been reduced.

6 Conclusions:

The introduction of large irrigation developments leads to the formation of groundwater mounds thus leading to non-uniform aquifer transmissivities and violating the underlying linearity assumptions of the URE. Studying the temporal variation of pressure heads resulting from a large irrigation development at Loxton has shown that it increased aquifer transmissivity by about 50%; this increased discharge to the river by only 10%, which is well within the uncertainty limits of aquifer parameters.

Large irrigation developments mean there is a higher likelihood that the aquifer may include heterogeneities; Rassam et al. (2004) investigated the effects of low-conductivity horizontal layers on flux response. The work is extended here to include the effects of low conductivity vertical barriers; it was found that such barriers speed up the flux response to the river when they are located behind the recharge source; as their hydraulic conductivity becomes extremely low (i.e., have a large retardation factor) they eventually function as no flow boundaries. Analytical modelling can develop upper and lower boundary envelopes for the flux response. Low conductivity vertical barriers situated between the recharge source and the river slow down the flux response to the river; an analytical solution that estimates the response was found to produce satisfactory results that compare favourably to MODFLOW predictions.

Knight et al. (2005) presented a solution for sloping base aquifers and a head gradient (the water table is parallel to the base slope), where the flux response was highly sensitive to slope. It is shown here that this high sensitivity is due to the head gradient and not the base slope. The flux response of a sloping base aquifer without a head gradient can be estimated using the basic URE provided an effective aquifer thickness that accounts for the non-uniform saturated thickness is used; in sloping base aquifers the criteria for slope presented by Rassam et al. (2004) should be followed.

The analytical solution for pressure heads presented by Rassam et al. (2004) can be used to predict head changes under reduced recharge conditions. It is shown that when recharge is reduced in a high- transmissivity aquifer, the water table between the recharge source and the river responds to the reduced recharge and drops quickly while it continues to rise behind the recharge source long after the recharge had been reduced. This demonstrates that different parts of the aquifer may respond differently to recharge reduction.

Appendix I

' VBA Functions to evaluate Equation 1.

' Resp is the name of the "User Defined" function;

' a, D, and t are as defined in Equation 1

' Rf is the retardation coefficient (α)

' Activate Microsoft Visual Basic Editor, insert new Module, copy this whole

' appendix and paste it into the module and save.

' In the spreadsheet, Insert/function/User Defined/Resp and identify cells that

' define a, D, t, and α

Function Resp(a, D, t, Rf)

Z1 = a / Sqr(4# * D * t)

Z2 = a / Rf + D * t / Rf ^ 2

Z3 = Z1 + Sqr(D * t) / Rf

Resp = -1 * (exf(0#, Z1) - exf(Z2, Z3))

End Function

Function exf(a, b)

exf = 0#

If (Abs(a) > 170# And b <= 0#) Then GoTo 4

c = a - b * b

If (Abs(c) > 170# And b >= 0#) Then GoTo 4

If (c < -170#) Then GoTo 3

x = Abs(b)

If (x > 3#) Then GoTo 1

t = 1# / (1# + 0.3275911 * x)

y = t * (0.2548296 - t * (0.2844967 - t * (1.421414 - t * (1.453152 - 1.061405 * t))))

GoTo 2

1 y = 0.5641896 / (x + 0.5 / (x + 1# / (x + 1.5 / (x + 2# / (x + 2.5 / x + 1#))))

2 exf = y * Exp(c)

3 If (b < 0#) Then exf = 2# * Exp(a) - exf

3 End Function

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