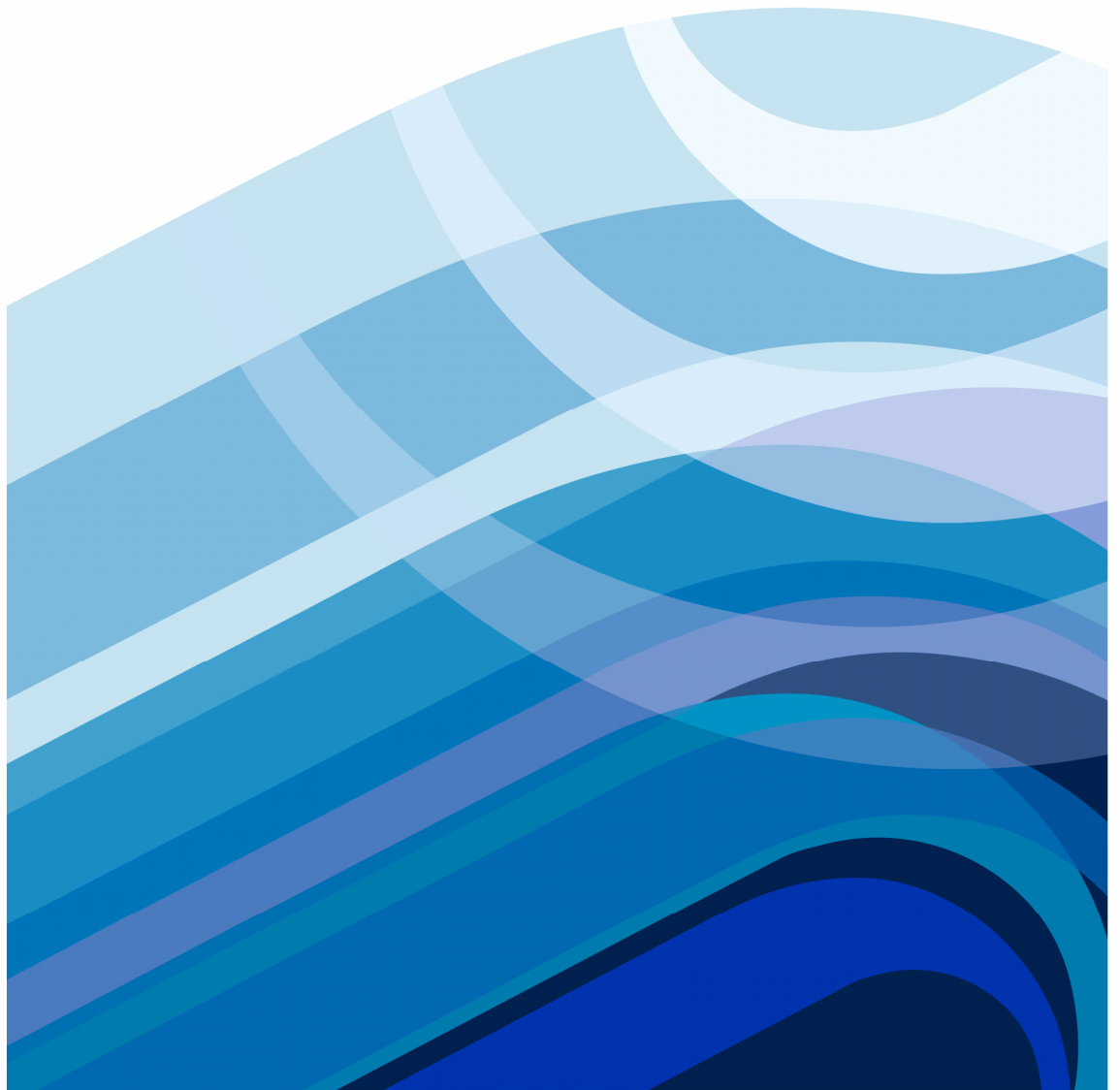




Confined Pumping Response



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EXECUTIVE SUMMARY

Increased abstraction from the confined Leederville and Yarragadee aquifers for public water supply has raised some concerns regarding the impacts and sustainability of continued confined abstraction at a high rate. To provide a better understanding of the aquifer system behaviour, a number of confined abstraction scenarios were developed and simulations using the Perth Regional Aquifer Modelling System (PRAMS) model were undertaken. Results were analysed to assess the response of the aquifer system to confined pumping. The major findings of this study are summarised as follows.

- Impacts of pumping in the confined aquifer propagate through the confined aquifer system rapidly and confined heads should approximately stabilise within 2 years after a change in abstraction in the areas where the Corporation confined bores are located.
- The Superficial aquifer responds to the confined abstraction slowly. Response function analysis shows that full impacts on the Superficial aquifer of a simulated step pumping can be delayed up to 5 years for abstraction in the Yarragadee aquifer and up to 4 years for abstraction in the Leederville aquifer. The delay of full impacts of current abstraction is also dependent upon how long the aquifer has been pumped. Since both the Leederville and Yarragadee aquifers have been pumped for many years, the delay of maximum impacts of confined abstraction on the Superficial aquifer is estimated to be about 1-2 years.
- Over the total area of the Gngangara Mound, about 38% of the abstraction from the Yarragadee propagates to the Superficial aquifer while about 50% of the Leederville abstraction propagates back to the Superficial aquifer. The remainder of the water balance is initially derived from storage, but as heads equilibrate and gradients steepen, water is captured from north and south of the mound and from offshore discharge.
- Near the crest of the Gngangara Mound, abstraction from the Yarragadee aquifer has a greater drawdown impact on the Superficial aquifer than pumping from the Leederville aquifer. About 30% of the abstraction from the Yarragadee propagates to the Superficial aquifer in the Pinjar and Yeal areas while only about 16% of the Leederville abstraction propagates back to the same area. Abstraction of 100 GL/a from the confined aquifers (55 GL/a from the Yarragadee and 45 GL/a from the Leederville) will induce about 0.2 m/yr drawdown impacts on the crest of the Gngangara Mound.
- Abstraction of 10 GL/a from the Yarragadee aquifer will cause a 10 m head drop in the Yarragadee aquifer around the area where the Corporation confined bores are located whereas Abstraction of 10 GL/a from the Leederville aquifer will cause a 5 m head drop in the Leederville aquifer.
- The Leederville aquifer recovers more quickly than the Yarragadee aquifer after reduction in abstraction. It takes 3 years for the Leederville aquifer to recover 90% of the drawdown whereas it takes about 5 years for the Yarragadee aquifer to achieve the same level of recovery.

Results of this analysis indicate that both Yarragadee and Leederville aquifers can hydraulically sustain increased abstraction and aquifer heads around the Corporation borefields will stabilise at lower levels within a short period (1-2 years). Major constraints will be capacity of the existing infrastructure and water quality consideration (temperature, TDS and iron etc) and environmental impacts, particularly in the Yeal and Pinjar areas. Further work is required to incorporate these considerations in determining the optimal abstraction strategy to maximise the use of Gngangara Mound groundwater resources while minimising impacts on groundwater dependant ecosystems (GDEs).

Introduction

Groundwater from Gnangara Mound is a major source for Perth and is critical to maintaining the reliability of the Integrated Water Supply System (IWSS). Low storage levels in the hills reservoirs due to prolonged drought have led to an increased dependence upon Gnangara Mound groundwater for public water supply to IWSS. Since 1997, groundwater abstraction from the Gnangara Mound for public water supply has increased from about 100 GL per annum to 150 GL per annum to meet growth and to avoid the imposition of a total ban on use of sprinklers on lawns and gardens. To minimise the risk of environmental impacts, the Corporation has reduced abstraction from the Superficial aquifer and has increased abstraction from the confined aquifers. Abstraction for public water supply from the confined aquifers, namely the Leederville and Yarragadee aquifers, has increased from about 45 GL/a in 1996/1997 to 95 GL/a in 2004/2005.

Increased abstraction from the confined aquifers has accelerated the decline in the potentiometric heads in the Leederville and Yarragadee aquifers. Impacts of the confined abstraction also propagates back to the Superficial aquifer via increased leakage in areas where the major confining beds, the Kardinya Shale (an aquiclude that separates the Superficial aquifer and the Leederville aquifer) and the South Perth Shale (an aquiclude that separates the Leederville aquifer and the Yarragadee aquifer), are absent (Davidson and Yu, 2004). The increase in leakage to the confined aquifers may cause water table decline in the Superficial aquifer which may affect groundwater dependent ecosystems (GDEs) in some areas.

Propagation of impacts from confined abstraction to the Superficial aquifer (and hence the GDEs) can take many years, and may be greatly attenuated by the hydraulic properties of the aquifer system (Davidson and Yu, 2004). Understanding the conceptual hydrogeology and response of the aquifer system to confined abstraction is an important step in developing strategies to best utilise the groundwater resources and manage environmental impacts.

Questions often asked by resource managers and water infrastructure planners include:

- How long does it take for the confined pumping response to propagate to the Superficial aquifer?
- How long does it take for the head in the confined aquifer to stabilise?
- What is the magnitude of impacts on the water table, particularly around the crest of the Gnangara mound, from pumping the Leederville and Yarragadee aquifers?
- Which areas are affected by the confined pumping?
- Can we continue current abstraction from the confined aquifers?
- What are the limits to increasing abstraction from the confined aquifer?
- If the confined abstraction is reduced, how quickly will the aquifer system, particularly the confined aquifers, recover?
- Where is water sourced from to meet the confined abstraction requirements?

To address these questions, a number of abstraction and modelling scenarios were developed and simulations using the Perth Regional Aquifer Modelling System (PRAMS) model (Barr et al. 2003, CyMod 2004, Davidson and Yu 2004, Silberstein et al. 2004, Xu et al. 2004) have been undertaken. The concept of a transient response function was used to quantify the temporal impacts of the confined abstraction on the water table on the Gnangara Mound. Water balance analysis was also used to determine the spatial and temporal distribution of leakage to the confined aquifers.

Response Functions for Impacts of Confined Abstraction on the Gngangara Mound

General Concept of Response Functions

Abstraction from a confined aquifer initially draws water from aquifer storage around the bores creating a cone of depression which enables groundwater flow toward the bore. The effects of pumping continue propagating radially as an evolving change in the water pressure head until they reach a boundary condition such as a discharge or recharge boundary. Reduction in the confined aquifer heads may result in reduction in groundwater discharge and induce more recharge via leakage. The confined heads will progressively stabilise when aquifer discharge or recharge is modified to compensate for this change. The time required for near-stabilisation of groundwater-level evolution can be evaluated from:

$$t = \frac{L^2 S}{CT} \quad (1)$$

Where S and T are aquifer storage coefficient and transmissivity respectively; L is the characteristic length of the aquifer, C is a constant ranging from 0.5-4 [PUWB used 3, in well function $w(u)$, $C=4$, in others, e.g., Manga (1999), $C=2$; Custodio (2002), $C=0.5-2.5$]. For the Yarragadee aquifer, $S \approx 10^{-4} \sim 10^{-3}$, $T \approx 1500 \text{ m}^2/\text{d}$ (Davidson and Yu 2004), $L \approx 30 \text{ km}$, the distance from the G series Yarragadee bores (G7, G17 and G27) to the North of Pinjar Lake where the confined aquifers have hydraulic connection with the Superficial aquifer. For $C = 1 \sim 2$, the time scale of the Yarragadee aquifer will be in the order of one month to two years, indicating the time required for the regional Yarragadee aquifer to come to a 'new' equilibrium after a disturbance is relatively rapid, in comparison with the Superficial aquifer which has a time scale greater than 40 years (Xu 2005a).

For equation (1), if the parameters C, T and L are similar for an unconfined and confined aquifer, the difference in response to abstraction is due to the difference in storage coefficients. In general, the storage coefficient (specific yield) in unconfined aquifers is much greater (up to a thousand times) that of the confined aquifers. The response to a disturbance in the confined aquifers is therefore more rapid than the response of the unconfined aquifers.

The effects of the abstraction in the Yarragadee aquifer will continue to propagate into the Leederville aquifer and then propagate up to the Superficial aquifer through the leakage in areas where there is good hydraulic connection between the aquifers. This inter-aquifer propagation is complex and controlled by the distribution of confining beds and intra-aquifer shales and the hydraulic properties of the aquifer system. Response functions can be used to describe the spatial and temporal propagation of impacts.

Response functions are mathematical descriptions of the relationship between a unit stress to an aquifer at a specified location and an impact elsewhere in the aquifer system. The shape of the response function will depend on aquifer characteristics (aquifer transmissivity, storativity and leakage, etc) and how proximal the point of stress is to the location. A response function can be generated using either analytical techniques or a numerical model. Analytical techniques are typically subject to restrictive or simplifying assumptions whereas generating a response function using a numerical groundwater model enables the resolution of complex system heterogeneities and anisotropies.

One of the most powerful features of response functions is that they can be combined using the theory of superposition to approximate aquifer behaviour at any point in time under complex scenarios of groundwater recharge and discharge. The theory of superposition applies to linear systems and states that the solution to a large complex problem with linear inputs is equal to sum of the solution of the individual linear components of the problem. If the aquifer system can be represented as a linear system, the effects of individual stresses that have occurred at different times and in different locations, can be summed to estimate the net impacts of total abstraction.

Similarly, individual responses may be scaled to reflect any magnitude of response, retaining the linear property. This property of scalability can be used to estimate the magnitude of the impact according to the magnitudes of the stress without regeneration the response functions.

In a confined aquifer, the relationship between the head and pumping is linear and the response function is an exact representation of the aquifer hydraulics. In an unconfined aquifer (nonlinear system), the response function can only be used as an approximation of the true aquifer hydraulic response. Nevertheless, the response function approach has been widely used in optimising groundwater planning, development and management, e.g., Fredericks et al. (1998), Cosgrove and Johnson (2004), and Merrick (OPTIMAQ model, Pers. Comm.).

Applications

The PRAMS model was used to generate the transient response functions at some locations of interest, particularly the centre of the impacts of the confined pumping on the Gngangara Mound in this study (Figure 1). The transient response function is determined by the difference between a simulation with a given stress (pumping) and one with the stress absent.

The Yarragadee and Leederville aquifers have enormous storage capacity that provides a buffer to attenuate the effects of pumping from the confined system. In order to obtain a reasonably accurate response function, the stress on the aquifer system must be sufficiently large over one stress period to minimise effects of numerical error. For the Yarragadee aquifer, a total abstraction of 50 GL was applied to a one month stress period (equivalent to 600 GL/year) and a stress of 35 GL/mth (420 GL/year) was applied for the Leederville aquifer. These stresses were applied to the Yarragadee and Leederville aquifers separately. A unit transient response function was obtained by dividing the simulated response by the magnitude of the stress applied to one stress period. This unit response can then be scaled to reflect any magnitude of response.

Locations of the confined abstraction also have effects on the aquifer transient response. In this study, the confined bores that operate under the DoE 165 GL/a scenario are considered as pumping points. To avoid the numerical problem of dry cells due to the large volume at the point of abstraction, the abstraction is evenly distributed to surrounding cells. The response functions derived in this way can be considered as a good approximation.

The baseline scenario assumes that no confined abstraction occurs. The PRAMS model is run for 10 years to establish initial conditions before applying the stress, and continues for another 15 years after the stress period to obtain the aquifer response. To minimise the numerical error in the simulation process, a very small convergence criterion for aquifer heads (10^{-3} m as opposed to 10^{-1} m in normal simulations) is used.

Several locations were selected to extract the simulation results for examining the aquifer system response to step pumping. For the confined aquifers, heads at monitoring bores, AM36, AM32, AM21 and AM17 were analysed and for the Superficial aquifer, an arbitrary location around the centre of the impacts from confined abstraction was selected for illustration purposes (Figure 1).

Response to Step Pumping in the Yarragadee Aquifer

Figure 2 shows the head response to the step pumping in the Yarragadee aquifer at the selected location. Modelling results show that the drawdown impacts are propagated rapidly through the Yarragadee aquifer. Figure 3 shows that except for AM17, the maximum drawdown impacts at AM36, AM32 and AM21 occur almost immediately after the step pumping is applied due to their proximity to the abstraction points. It takes about 6 months for the maximum impacts to propagate to AM17. Modelling results also show that whilst the aquifer heads near the pumping bores (AM36 and AM32) recover reasonably quickly after pumping stops, it takes much longer for the aquifer to recover in the area far from the abstraction points. Figure 3 shows that it takes about 2 years for the aquifer heads at AM36 and AM32 to recover 90% of the drawdown impacts but it takes longer than 5 years for the aquifer head at AM17 to achieve a similar recovery.

The propagation of drawdown impacts in the Yarragadee aquifer to the Leederville aquifer in the area where the confining bed (the South Perth Shale) is absent is quite rapid. Figure 4 shows the drawdown response in the Yarragadee and Leederville aquifers at AM17. Results indicate that the maximum impacts in the Leederville aquifer is delayed about 2 months compared with that in the Yarragadee aquifer and the impacts are significantly attenuated during propagation.

The propagation of the impacts of the Yarragadee abstraction to the Superficial aquifer is much slower compared with that in the confined aquifers. Figure 5 shows the response of the Superficial aquifer at the centre of impacts to step pumping of 50 GL in the Yarragadee aquifer. The modelling results show that whilst the impacts start to accumulate shortly after the step pumping, it takes about 5 years for the maximum impact to develop in the Superficial aquifer. The results also indicate that the impacts can last for decades, and more than half of the impacts remain at the end of simulation (15 years after the step pumping applies).

A fourth order polynomial function was used to fit the simulation result as shown in Figure 5. This function was then scaled by dividing the response by the magnitudes of step pumping to generate unit response functions (e.g., response for one GL or 10 GL abstraction). Figure 6 shows the response function for the impacts on the Superficial aquifer of step pumping of 10 GL/mth from the Yarragadee or Leederville aquifer.

To determine if the impacts of abstraction in the Yarragadee aquifer on the Superficial aquifer can be adequately described by a linear system, a further simulation using only half of the stress (25 GL/mth) was performed to obtain the corresponding response. This response is then scaled to obtain the 50 GL/mth responses. The scaled response is then compared with the actual simulation result using the 50 GL/mth step pumping. Results are illustrated in Figure 7. Clearly, the scaled response from the response to a 25 GL/mth step pumping agrees well with the simulated response to the 50 GL/mth step pumping. This means that the response of the Superficial aquifer to abstraction in the Yarragadee aquifer can be approximately considered as linear and hence the theory of superposition can be applied.

Figure 8 illustrates how the theory of superposition can be used to estimate the total impact of continued pumping at 40 GL/a from the Yarragadee aquifer on the Superficial aquifer. The response function to annual abstraction of 40 GL is first developed. The responses for individual abstraction for year 1, 2, and 3 are the same but differ in time as shown in Figure 8. Total impacts of this pumping at a particular time can be obtained by simply adding the individual impacts from the corresponding response curves.

By using the theory of superposition, impacts of various abstraction scenarios from the Yarragadee aquifer on the Superficial aquifer can be explored without the need to carry out a large number of full simulations of the aquifer system. Figure 9 illustrates the temporal impacts on the Superficial aquifer by pumping the Yarragadee aquifer at a rate of 40 GL/a. It is interesting to note that the maximum impact (timing and magnitude) of the pumping is affected by the length of the previous pumping. Figure 10 shows the delay in the maximum impact on the Superficial aquifer versus how long the pumping has been applied. Delay in the maximum impacts decreases as the length of continuous pumping increases. The increments in the maximum impacts also decrease as the length of continued pumping increases as shown in Figure 11.

Response to Step Pumping in the Leederville Aquifer

Figure 12 shows the head response at selected locations to step pumping in the Leederville aquifer. Modelling results show that the drawdown impacts are propagated rapidly through the Leederville aquifer. Figure 13 shows that the maximum drawdown impacts at all the selected bores occur almost immediately after the step pumping is applied. Modelling results also show that whilst the aquifer heads around the pumping bores (AM36 and AM32) recover reasonably quickly after pumping stops, it takes much longer for the aquifer to recover in the area further from the abstraction points (Figure 13). It takes less than one year for the aquifer heads at AM36 and AM32

to recover 90% of the drawdown impacts but longer than 2.5 years for the aquifer head at AM17 to achieve a similar recovery.

The drawdown impacts in the Leederville aquifer are also propagated rapidly into the Yarragadee in the area where the confined bed (the South Perth Shale) is absent as shown in Figure 14. Results indicate that the maximum impact in the Yarragadee aquifer are attenuated to some extent and are slightly delayed.

The propagation of the impacts of the Leederville abstraction to the Superficial aquifer is much slower compared to within the confined aquifers. Figure 15 shows the response of the Superficial aquifer on the top of the Gnamptara Mound to the step pumping of 35 GL in the Leederville aquifer. The modeling results show that whilst the impacts start to accumulate shortly after the step pumping, it takes about 4 years for the maximum impacts to develop in the Superficial aquifer. The results also indicate that the impacts can last for a very long time and more than half of the impacts remain at the end of simulation (15 years after the step pumping applies). A fourth order polynomial function was used to fit the simulation result as shown in Figure 15. This function was then scaled by dividing the response by the magnitudes of step pumping to generate unit response functions (e.g., response for one GL or 10 GL/mth abstractions). Figure 6 shows the response function for the impacts on the Superficial aquifer of step pumping of 10 GL/mth from the Leederville aquifer.

Comparison of the Superficial responses to the step pumping in the Leederville and Yarragadee aquifers indicates that at the selected location on the top of the Gnamptara Mound impacts of abstraction from the Yarragadee aquifer is greater than that from the Leederville aquifer. This may be because the Leederville aquifer is more 'open', with a large area where the confining bed is absent, and has good hydraulic connection with the Superficial aquifer. In comparison, the Yarragadee aquifer is tightly confined by the South Perth shale over most of the area, leading to a more concentrated propagation of the impacts toward the 'window' where both the South Perth Shale and Kardinya Shale are absent.

A further simulation using about two thirds of the stress (23 GL/mth) was performed to determine if the impacts of abstraction in the Leederville aquifer on the Superficial aquifer can be adequately described by a linear system. This response was then scaled to obtain the 35 GL/mth responses. The scaled response is then compared with the actual simulation result using the 35 GL/mth step pumping. Results are illustrated in Figure 16. Clearly, the scaled response from the response to 23 GL/mth step pumping agrees well with the simulated response to the 35 GL/mth step pumping. This means that the response of the Superficial aquifer to abstraction in the Leederville aquifer can be approximately considered as linear and hence the theory of superposition can also be applied.

Summary of results

Simulation and analysis of the aquifer response to the step pumping in the confined aquifers indicates that:

- Impacts of pumping in the confined aquifer propagate through the confined aquifer system rapidly and confined heads should approximately stabilise within one year after a change in abstraction in most of the area where the Corporation confined bores are located.
- The Superficial aquifer responds to the confined abstraction slowly. Response function analysis shows that full impacts on the Superficial aquifer induced by step pumping can be delayed up to 5 years for abstraction in the Yarragadee aquifer and up to 4 years for abstraction in the Leederville aquifer. It was found that the delay of full impacts of current abstraction is also dependent upon how long the aquifer has been pumped. Given that both the Leederville and Yarragadee aquifers have been pumped for many years, the delay of maximum impacts of confined abstraction on the Superficial aquifer is likely to be less than two years (Figure 10).

- At a centre of the impacts by confined abstraction, analysis of the response functions shows that impacts of Leederville abstraction on the Superficial aquifer are smaller than that of Yarragadee abstraction (Figure 6).

Spatial Distribution of Leakage into the Confined Aquifer

Impacts of confined abstraction at any location on the Superficial aquifer can be assessed by using the response function approach as described previously. Alternatively the overall spatial impact of a particular abstraction scenario can be described explicitly by plotting the drawdown at a particular time on a map as shown in Figure 1. Figure 1 shows the spatial extent of drawdown impacts on the Superficial aquifer in 2003 of the confined abstraction since 1985. This pattern of impacts is consistent with the conceptual hydrogeology. The impacts of the confined abstraction are propagated upward to the Superficial aquifer in the area where the confining beds are known to be absent. The maximum impacts of confined abstraction are centred in the north Pinjar and Yeal area where the South Perth Shale and Kardinya Shale were removed by erosion and hence there is strong hydraulic connection between the aquifers.

The hydraulic connection between the Superficial aquifer and the confined aquifers can also be described by the leakage between the aquifers. In order to obtain the magnitudes of interflows between the superficial and confined aquifers, a water balance analysis was undertaken for the period 1997-2003 for each of the groundwater subareas defined by DoE. Results are presented in Figure 17. Clearly, the confined aquifer system receives recharge from a very broad area, and most are outside the Gnangara Mound area. In the central area of impacts, the leakage into the confined system is estimated to be around 50 mm/a, about 6% of the annual rainfall (~800 mm/a). Increased abstraction in the confined aquifers will steepen the hydraulic gradient between the Superficial and Leederville aquifers and induce additional groundwater recharge to the confined aquifer system.

Aquifer System Response to Increased Confined Abstraction

Scenario development

Water balance analysis (Xu, 2005b) indicates that because of heterogeneity and anisotropy of the aquifer system, the impacts of confined abstraction propagate over a broad area with only about one third of the abstraction being derived from the Gnangara Mound. The balance is met by storage depletion (short term) then increased throughflow from outside the Gnangara Mound area. Based on that result, it was concluded that increased confined abstraction to meet demand during drought periods is the best strategy to minimise environmental impacts. However, many questions remain regarding whether high rates of abstraction in the confined aquifers can be sustained and how the depletion of the confined aquifer may affect the future drought security of the Perth Integrated Water Supply System (IWSS).

To investigate the aquifer response under increased abstraction in the confined aquifers, several modelling scenarios with double and treble abstraction from the confined aquifers are developed. The baseline for comparing the results of different simulation scenarios is the 165 GL/a case, (54 GL/a from the Yarragadee aquifer, 42 G/a from the Leederville aquifer and 69 GL/a from the Superficial and Mirrabooka aquifers). Table 1 summarises the modelling scenarios developed for this analysis. Abstraction for a particular aquifer in a scenario is obtained by scaling up the abstraction in the baseline scenario.

Scenario		Comments
Baseline		Abstraction of 42 GL/a and 54 GL from the Leederville and Yarragadee
Leederville response	Leed_D	Double Leederville abstraction to 84 GL/a
	Leed_T	Treble Leederville abstraction to 126 GL/a
	Leed_T_R	Treble Leederville abstraction to 126 GL/a for 10 years then reverse back to 42 GL/a
Yarragadee response	Yarra_D	Double Yarragadee abstraction to 108 GL/a
	Yarra_T	Treble Yarragadee abstraction to 162 GL/a
	Yarra_T_R	Treble Yarragadee abstraction to 162 GL/a for 10 years then reverse back to 54 GL/a

Table 1 Abstraction scenarios

The first two scenarios for each aquifer are designed to examine the aquifer response under increased abstraction whilst the third scenario aims to assess the recovery of the aquifer after a prolonged period of high abstraction. As demonstrated earlier, the aquifer system responses to the confined abstraction can be considered as linear. Results from the analysis can be used to interpolate or extrapolate for other pumping scenarios provided the abstraction pattern is similar to that used here.

The PRAMS model was set up to start in January 2003 and finish in June 2019. Prior to July 2004, actual abstraction by the Corporation was used in the model. Scenario abstraction applies after June 2004. Figure 18 and Figure 19 show the abstraction pattern for the Leederville and Yarragadee aquifer respectively. The median climate of 1978-2003 (Canci, 2004) was used for all the simulations. Due to the large volume of output data associated with each simulation, only results for the late part of the simulations were recorded and analysed.

Simulation results

Confined aquifer responses to increased confined pumping were assessed by examining the aquifer heads at the location of bores AM36 and AM 17. AM36 was selected as it is located at the centre of the Corporation’s confined bores and AM17 was selected because of its greater distance from abstraction and in the area where there is strong hydraulic connection between the aquifers. The response of the Superficial aquifer is assessed at the centre of the confined pumping impacts (Centre), which is about 4 km east to AM17 (Figure 1).

Responses to Increased Yarragadee Abstraction

Figure 20 and Figure 21 show the Yarragadee heads at AM36 and AM17 under various abstraction scenarios from the Yarragadee aquifer. The heads at AM36 show reasonably steady trends indicating the even under a high abstraction of 162 GL/a, the confined heads around the bores will stabilise after initial drawdown at around -140 m AHD. At AM17, the heads show a slightly declining trend even at the end of the simulation period, indicating that heads in the Yarragadee aquifer are still evolving in response to the increased pumping and are yet to reach a new equilibrium.

The Leederville heads at AM36 and AM17 are shown in Figure 22 and Figure 23. The Leederville heads at both bores show a slightly declining trend, indicating the Leederville aquifer is still responding to the increased abstraction in the Yarragadee aquifer. The strong seasonal response at AM36 is due to the seasonal variation in the Leederville abstraction, which was not changed in this scenario. Figure 24 shows the relationship between the aquifer heads (close to steady) and the abstraction in the Yarragadee aquifer. In the area where the Corporation’s Yarragadee bores are located (AM36), abstraction of one GL/a from the Yarragadee aquifer will cause one metre drop in the aquifer heads. However, increase in the Yarragadee aquifer has very limited impacts on the pumping heads of the Leederville bores as shown in the Figure 24 (AM36L). This is due to the presence at AM36 of confining bed of the South Perth Shale that prevents the direct propagation of the impacts of Yarragadee abstraction to the Leederville aquifer.

Figure 25 shows the response of the Superficial aquifer at the crest of the Gngangara Mound to increased Yarragadee abstraction. Using the results shown in Figure 25 at the end of the simulation, the relationship between abstraction in the Yarragadee aquifer and drawdown impacts at the crest of the Gngangara Mound can be established as shown in Figure 26. The result indicates that continued abstraction of 54 GL/a from the Yarragadee aquifer for 15 years would have about 2 m drawdown impacts on the Mound. This would occur at an approximate drawdown rate of 13 cm/yr. The spatial distribution of impacts from abstracting 54 GL from the Yarragadee aquifer for 15 years on the Superficial aquifer is shown in Figure 27.

A water balance analysis was undertaken to identify volumes and sources of water to meet the abstraction from the Yarragadee aquifer. Three water budget zones as shown in Figure 28 were used for analysis of the Superficial, Leederville and Yarragadee aquifers. Figure 29 shows the trace of water for additional abstraction of 54 GL/a from the Yarragadee aquifer at the end of the simulation period. The results show that about half (27 GL/a) of the 54 GL/a is sourced from increased leakage from the Leederville aquifer in the central area with another half sourced from increased through flows from the Northern and Southern areas. Only a small proportion comes from aquifer storage in the central area. Continued depletion in the aquifer system, particularly the Superficial aquifer indicates that the system is still evolving and is yet to reach a new equilibrium. Increased leakage into the Yarragadee aquifer in turn reduces the discharge from the Leederville aquifer into the ocean and induces more leakage from the Superficial aquifer. About 23 GL/a of the 27 GL/a leakage into the Yarragadee aquifer is propagated back to the Superficial aquifer at the central area. Overall, of the 54 GL/a abstraction from the Yarragadee aquifer, about 10% is from the confined storage depletion, 30% from storage depletion in the Superficial aquifer, 40% from reduction in groundwater discharge and 20% from induced recharge into the Superficial aquifer due to the storage depletion and reduction in evapotranspiration.

Note that the central budget zone covers a larger area than the Gngangara Mound, and includes outcropping Mesozoic sediments east of the Gingin Scarp (Figure 28). Analysis indicates that increased abstraction in the Yarragadee aquifer by 54 GL/a will induce 21 GL/a leakage from the Gngangara Mound area, i.e. about 38% of the abstraction. About 15 GL or about 30% of the 54 GL/a abstraction from the Yarragadee aquifer is derived from the Pinjar and Yeal areas.

Investigation was carried out to evaluate the time taken for the Yarragadee aquifer to recover when abstraction from the aquifer is reduced. As shown in Figure 20 and Figure 21, the recovery is still in progress at the end of the simulation (4 years after reduction in the abstraction). In order to obtain a broad view of the aquifer recovery, a water balance approach based on the storage depletion in the Yarragadee aquifer in the central area is adopted for analysis of the recovery process. The annual storage depletion after abstraction is reduced was obtained by zone budget analysis and results are plotted in Figure 30 and Figure 31. This indicates that the Yarragadee storage (heads) will recover about 35% after one year, ~75% after three years and ~90% after 5 years, with close to full recovery after 8 years. There will, however, be some residual effects that the aquifer may never recover to. Analysis also indicates that abstraction of 10 GL/a will cause a total of about 20 GL storage depletion in order to induce more throughflow and leakage to balance the abstraction.

Figure 25 shows that the impacts of the abstraction in the Yarragadee aquifer on the Superficial aquifer continue to the end of the simulation. Previous analysis (Xu, 2005a) indicated that the time scale for the Superficial aquifer on the Gngangara mound is greater than 40 years. It is anticipated that drawdown impacts will persist for a long time unless increased recharge (via increased burning frequency of vegetation or natural increase in rainfall) occurs to offset the impacts.

Responses to Increased Leederville Abstraction

Figure 32 and Figure 33 show the Leederville heads at AM36 and AM17 under various abstraction scenarios from the Leederville aquifer. The heads at both AM36 and AM17 show steady trends indicating the even under high abstraction of 126 GL/a, the Leederville heads will stabilise at

around -80 m AHD at AM36 and -2 m AHD at AM17. The strong seasonal response at AM36 is due to its proximity to abstraction bores and the seasonal variation in the Leederville abstraction. Figure 34 shows the relationship between the aquifer heads (close to steady) and the abstraction in the Leederville aquifer. In the area with Water Corporation Leederville bores and greatest drawdown impacts (around AM36), abstraction of one GL/a from the Leederville aquifer will cause about a half metre drop in the aquifer heads.

Figure 35 shows the response of the Superficial aquifer on top of the Gngangara Mound to increased abstraction in the Leederville aquifer. Using the results shown in Figure 35 at the end of simulation, the relationship between abstraction in the Leederville aquifer and drawdown impacts on top of the Gngangara Mound can be established as shown in Figure 36. The result indicates that continued abstraction of 42 GL from the Leederville aquifer for 15 years would have about 0.8 m drawdown impact on the Mound, with an approximate drawdown rate of 6 cm/yr. The spatial distribution of impacts from abstracting 42 GL from the Leederville aquifer for 15 years on the Superficial aquifer is shown in Figure 37.

Water balance analysis using budget zones as shown in Figure 28 was undertaken to identify sources of water to meet the abstraction from the Leederville aquifer. Figure 38 shows the water sources for an additional abstraction of 42 GL/a in Leederville aquifer at the end of the simulation period. The results show that about 70% (29 GL/a) of the 42 GL/a is sourced from increased leakage from the Superficial aquifer in the central area with rest from throughflow, reduction in discharge to the ocean and reduced vertical leakage to the Yarragadee aquifer. Only a small part is from aquifer storage in the central area. The continued depletion in the aquifer system, particularly the Superficial aquifer indicates that the system is still evolving and yet to reach a new equilibrium. Overall, of the 42 GL/a abstraction from the Leederville aquifer, about 5% is from confined storage depletion, 24% from storage depletion in the Superficial aquifer, 45% from reduction in groundwater discharge and 16% from induced recharge into the Superficial aquifer due to the storage depletion and reduction in evapotranspiration.

An increase in abstraction in the Leederville aquifer by 42 GL/a will induce about 21 GL/a leakage from the Gngangara Mound area, i.e. about 50% of the abstraction. Analysis also shows that about 7 GL/a of this leakage occurs in the Pinjar and Yeal areas. That is, about 16 % of the 42 GL/a abstraction from the Leederville aquifer is derived from the Pinjar and Yeal areas. This result is consistent with the response function analysis which shows that the drawdown impact on top of the Gngangara Mound of abstraction from the Yarragadee aquifer is greater than that from the Leederville aquifer.

Investigation was carried out to evaluate the time taken for the Leederville aquifer to recover when the abstraction from the aquifer is reduced and results are shown in Figure 38 and Figure 39. Results indicated that the Leederville storage (heads) will recover about 50% after one year, 80% after two years and more than 90% after 3 years, with close to full recovery after 5 years. There will, however, be some residual effects that the aquifer may never recover to. Analysis also indicates that abstraction of 10 GL/a will cause about 10 GL storage depletion in order to induce more throughflow and leakage to balance the abstraction.

Figure 35 shows that the impacts of abstraction in the Leederville aquifer on the Superficial aquifer continue to the end of the simulation. Previous analysis (Xu, 2005a) indicated that the time scale for the Superficial aquifer on the Gngangara mound is greater than 40 years. It is anticipated that drawdown impacts will likely persist for a long time unless increased recharge (via burning or natural increase in rainfall) occurs to offset the impacts.

Summary of Analysis Results

Major conclusions from the analysis of the aquifer response to increased confined abstraction are summarised in Table 2.

Aquifer being abstracted	Impact propagation	Drawdown around WC bores and storage depletion in the central area by abstraction of 1 GL/a	Time to recovery after reduction in abstraction	Leakage (Gnangara Mound area)	Leakage (Pinjar and Year areas)	Source of water (Overall water balance) (close to steady state)
Leederville	<ul style="list-style-type: none"> • Heads around WC bores should stabilise within 1 year. • Slow propagation back to the Superficial aquifer • 70% of abstraction from induced leakage in the central area and the rest from throughflow and reduction in discharge 	<ul style="list-style-type: none"> • Head drop of 0.5 m • Storage depletion of 1 GL in Leederville before stabilised 	<ul style="list-style-type: none"> • 1st year 50% • 2nd year 80% • 3rd year 90% • 5th year 99% 	50% of the abstraction	<ul style="list-style-type: none"> • 16% of the abstraction • Drawdown of 6 cm/yr at centre of impacts for 42 GL/a abstraction 	<ul style="list-style-type: none"> • 5% - Confined storage depletion • 24% -Superficial storage depletion • 55% - Reduction in discharge • 16%- Induced recharge
Yarragadee	<ul style="list-style-type: none"> • Heads around WC bores should stabilise within 1-2 years. • Rapid propagation to Leederville aquifer • Slow propagation back to the Superficial aquifer • Half abstraction from leakage from Leederville in central area and another half from throughflow 	<ul style="list-style-type: none"> • Head drop of 1 m • Storage depletion of 2 GL in Yarragadee before stabilised 	<ul style="list-style-type: none"> • 1st year 35% • 3rd year 75% • 5th year 90% • 7th year 99% 	38% of the abstraction	<ul style="list-style-type: none"> • 30% of the abstraction • Drawdown of 13 cm/yr at centre of impacts for 54 GL/a abstraction 	<ul style="list-style-type: none"> • 11% - Confined storage depletion • 30% -Superficial storage depletion • 36% - Reduction in discharge • 23%- Induced recharge

Table 2 Summary of the aquifer response to increase in confined abstraction

Conclusion

Groundwater modelling and analysis has demonstrated that:

1. Impacts of pumping in the confined aquifer propagate through the confined aquifer system rapidly and confined heads should approximately stabilise within 2 year after a change in abstraction in areas where the Water Corporation confined bores are located.
2. The Superficial aquifer responds to the confined abstraction slowly. Response function analysis shows that full impacts on the Superficial aquifer of step pumping can be delayed up to 5 years for abstraction in the Yarragadee aquifer and up to 4 years for abstraction in the Leederville aquifer. The delay of full impacts of current abstraction is also dependent upon how long the aquifer has been pumped. Since both the Leederville and Yarragadee aquifers have been abstracted for some time, the delay of maximum impacts of confined abstraction on the Superficial aquifer is estimated to be about 1-2 years.
3. The Superficial aquifer response to confined abstraction can be considered as a linear function.
4. About 38% of the abstraction from the Yarragadee aquifer propagates to the Superficial aquifer in the Gngangara Mound area whereas about 50% of the Leederville abstraction propagates to the same area.
5. Abstraction from the Yarragadee aquifer has greater impact on the Superficial aquifer near the crest of the Gngangara Mound than that from the Leederville. About 30% of the abstraction from the Yarragadee propagates to the Superficial aquifer in the Pinjar and Yeal areas while only about 16% of the Leederville abstraction propagates to the same area. Abstraction of 100 GL/a from the confined aquifers (55% from the Yarragadee and 45% from the Leederville) will induce about 0.2 m/yr drawdown impacts near the top of the Gngangara Mound.
6. Abstraction of 10 GL/a from the Yarragadee aquifer will cause a 10 m head drop in the Yarragadee aquifer in the area where Corporation confined bores are located. Abstraction of 10 GL/a from the Leederville aquifer will cause a 5 m head drop in the Leederville aquifer in this area.
7. The Leederville aquifer recovers more quickly than the Yarragadee aquifer after reduction in abstraction. It takes 3 years for the Leederville aquifer to recover 90% of the drawdown whereas it takes about 5 years for the Yarragadee aquifer to achieve the same level of recovery.

Recommendation

Results of this analysis indicate that both the Yarragadee and Leederville aquifers can hydraulically sustain increased abstraction and aquifer heads around the Corporation borefields will stabilise at lower levels in a short period. Major constraints will be capacity of the existing infrastructure and water quality consideration (temperature, TDS and iron etc) and environmental impacts, particularly in the Yeal and Pinjar areas. Further work is required to incorporate these considerations in determining the optimal abstraction strategy to maximise the use of Gngangara Mound groundwater resources while minimising the impacts on GDEs.

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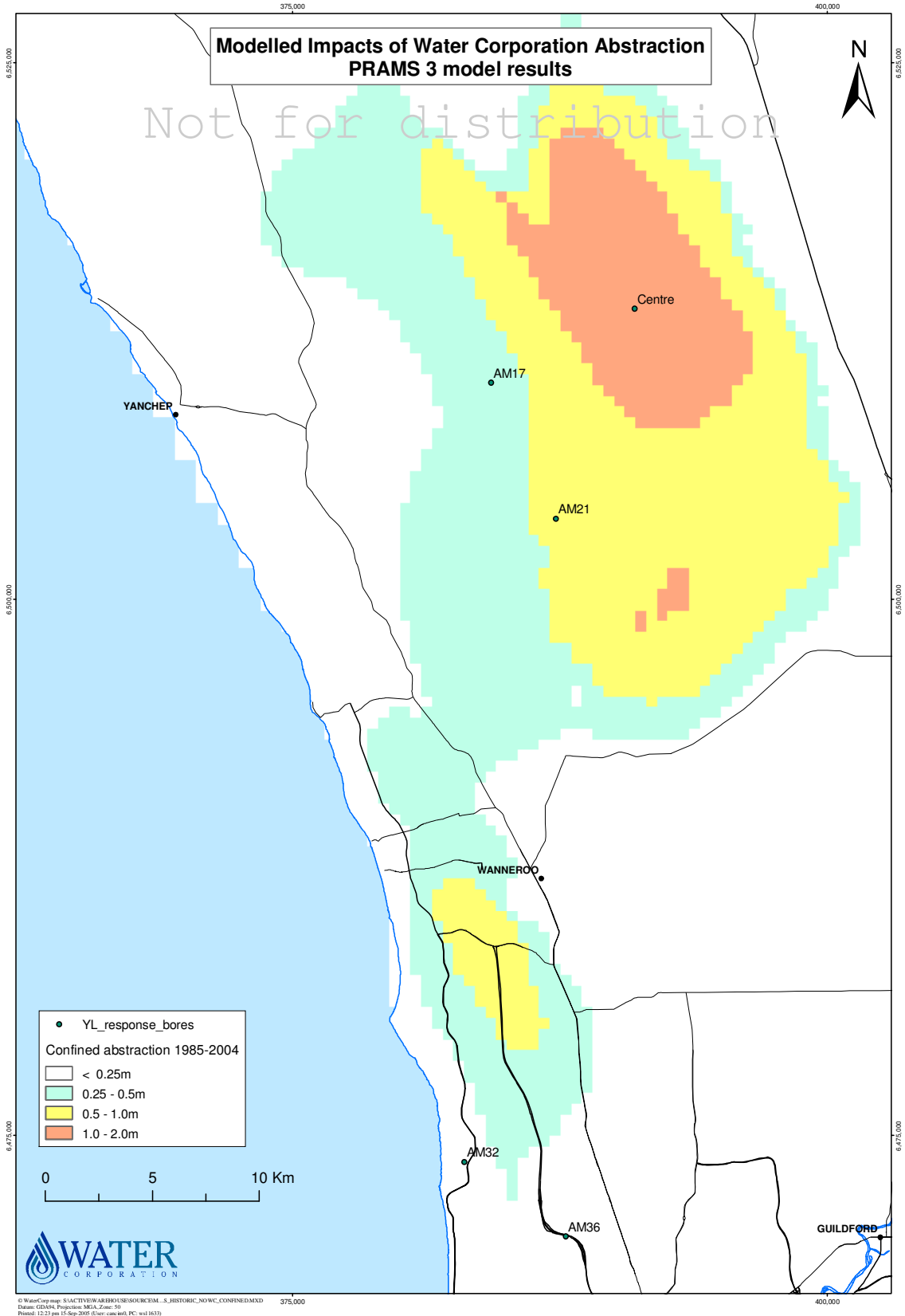


Figure 1 Gngangara Mound and simulated impacts of Corporation's confined abstraction since 1985

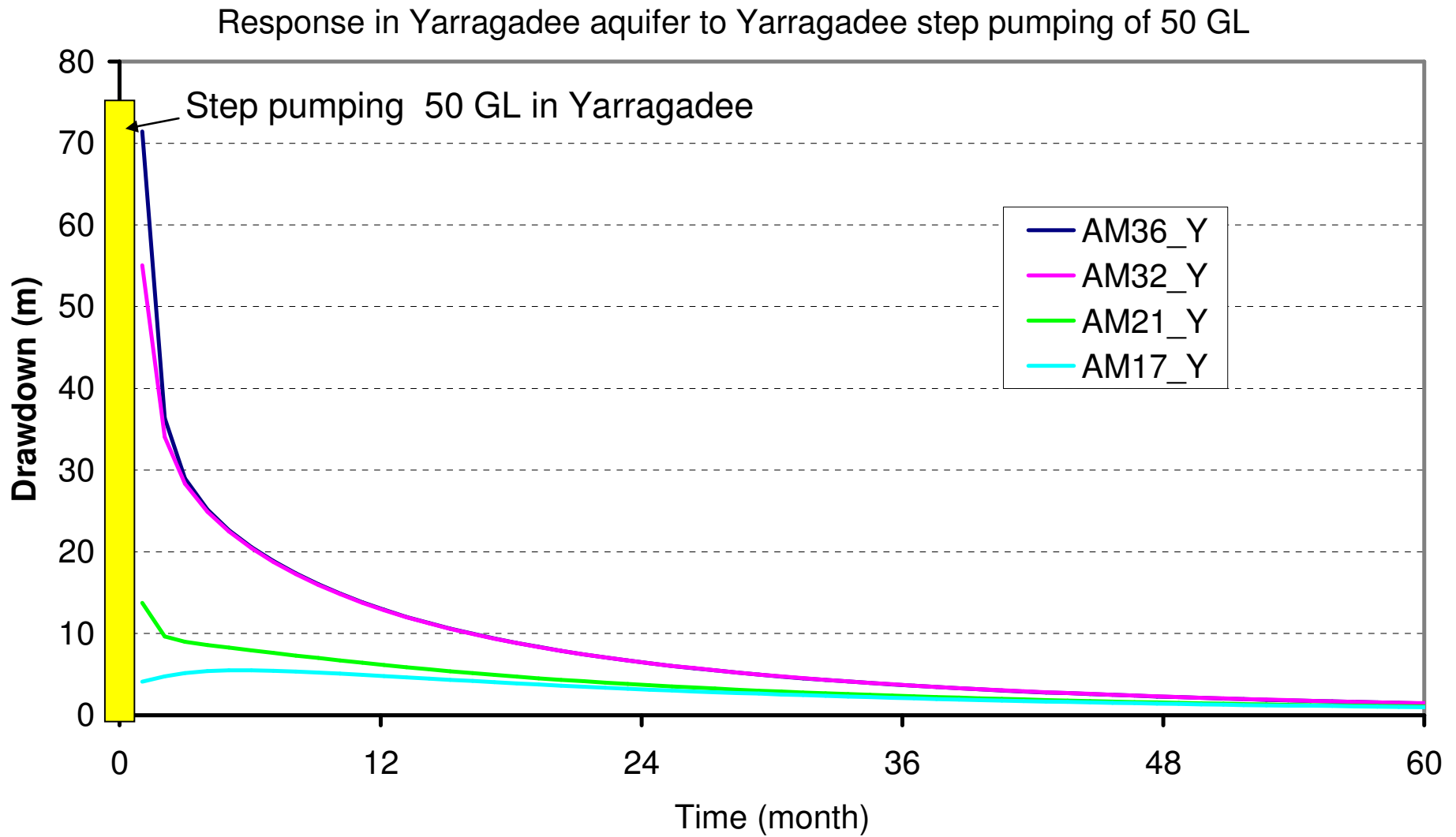


Figure 2 Yarragadee head response to Yarragadee step pumping

Response in Yarragadee aquifer to Yarragadee step pumping of 50 GL

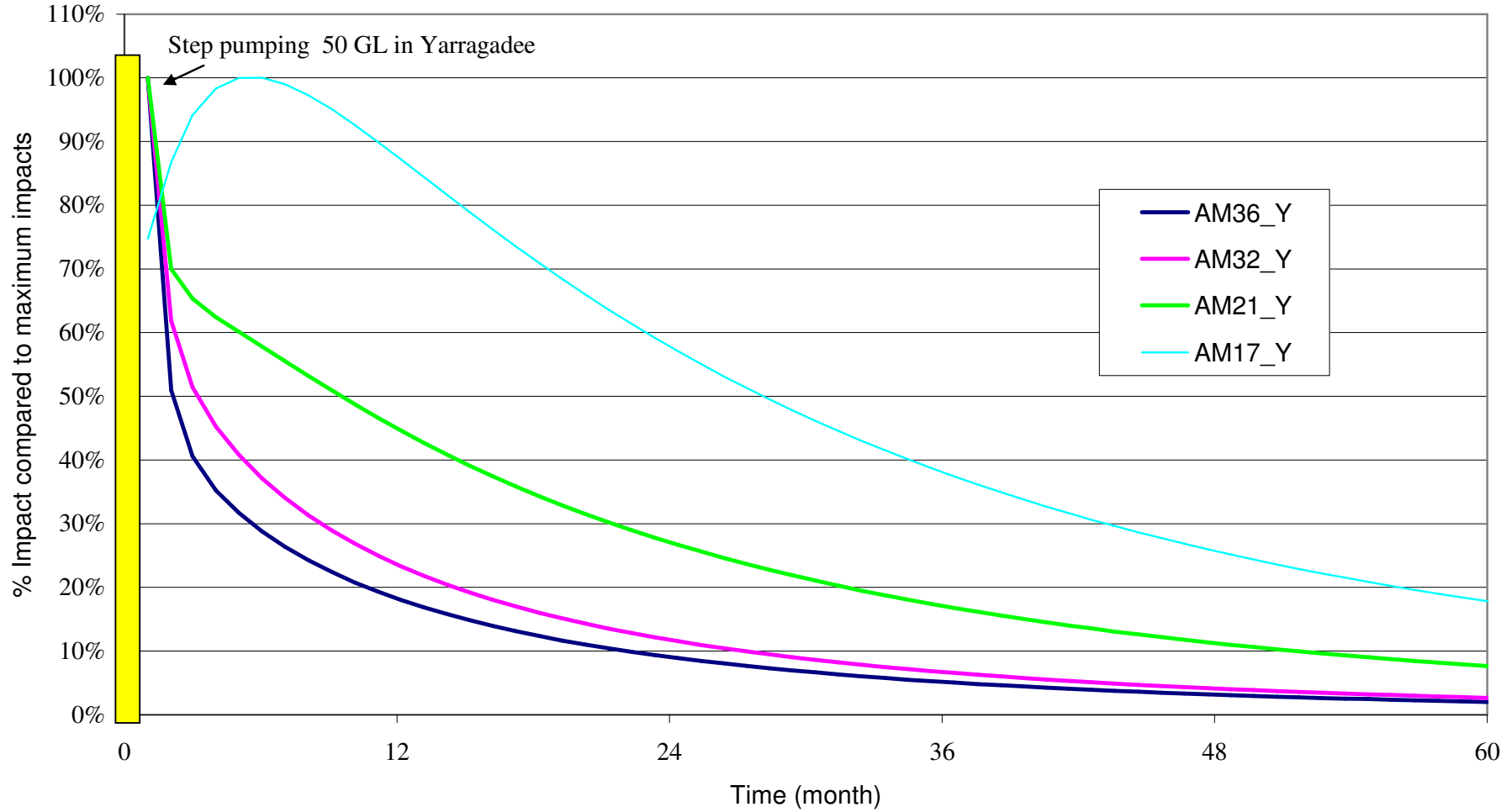


Figure 3 Yarragadee head recovery after step pumping

Drawdown response at AM17 to Yarragadee step pumping

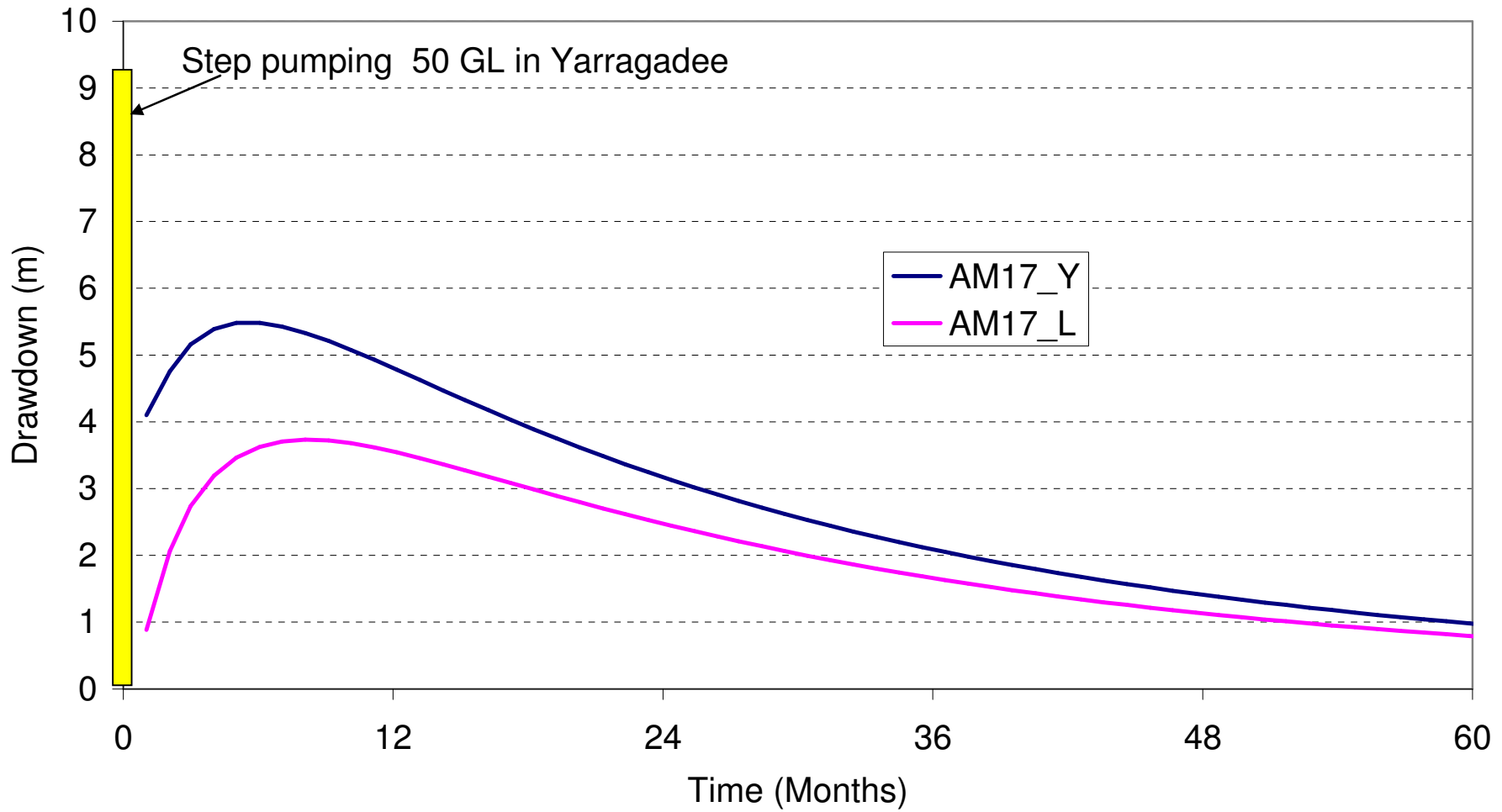


Figure 4 Drawdown response at AM17 to Yarragadee step pumping

Superficial response to Yarragadee step pumping (stress = 50 GL/m)
(at centre of impacts)

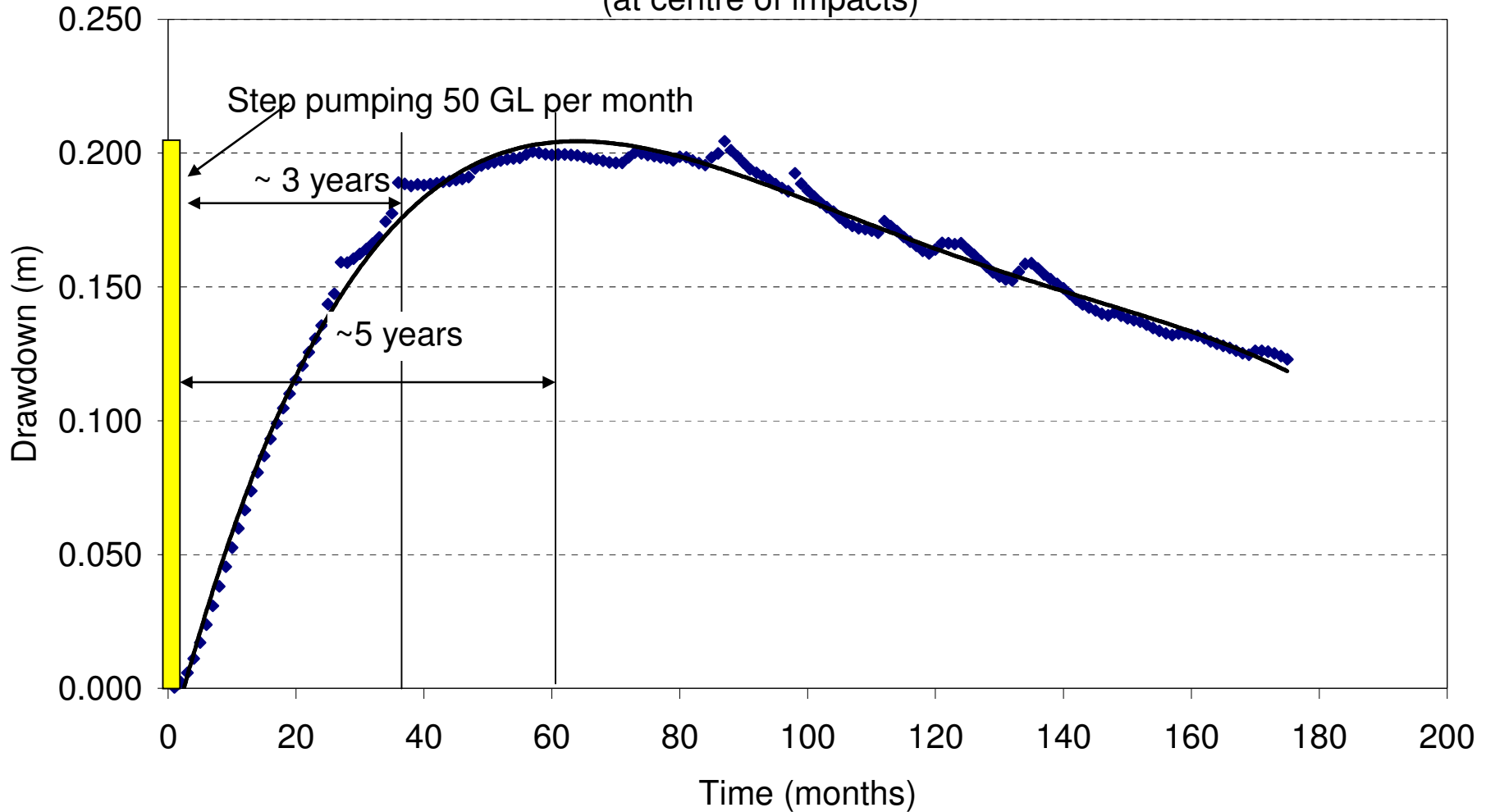


Figure 5 Superficial aquifer response to Yarragadee step pumping

Superficial response to a step pumping of 10 GL/m from Yarragadee or Leederville (Centre of confined pumping impacts)

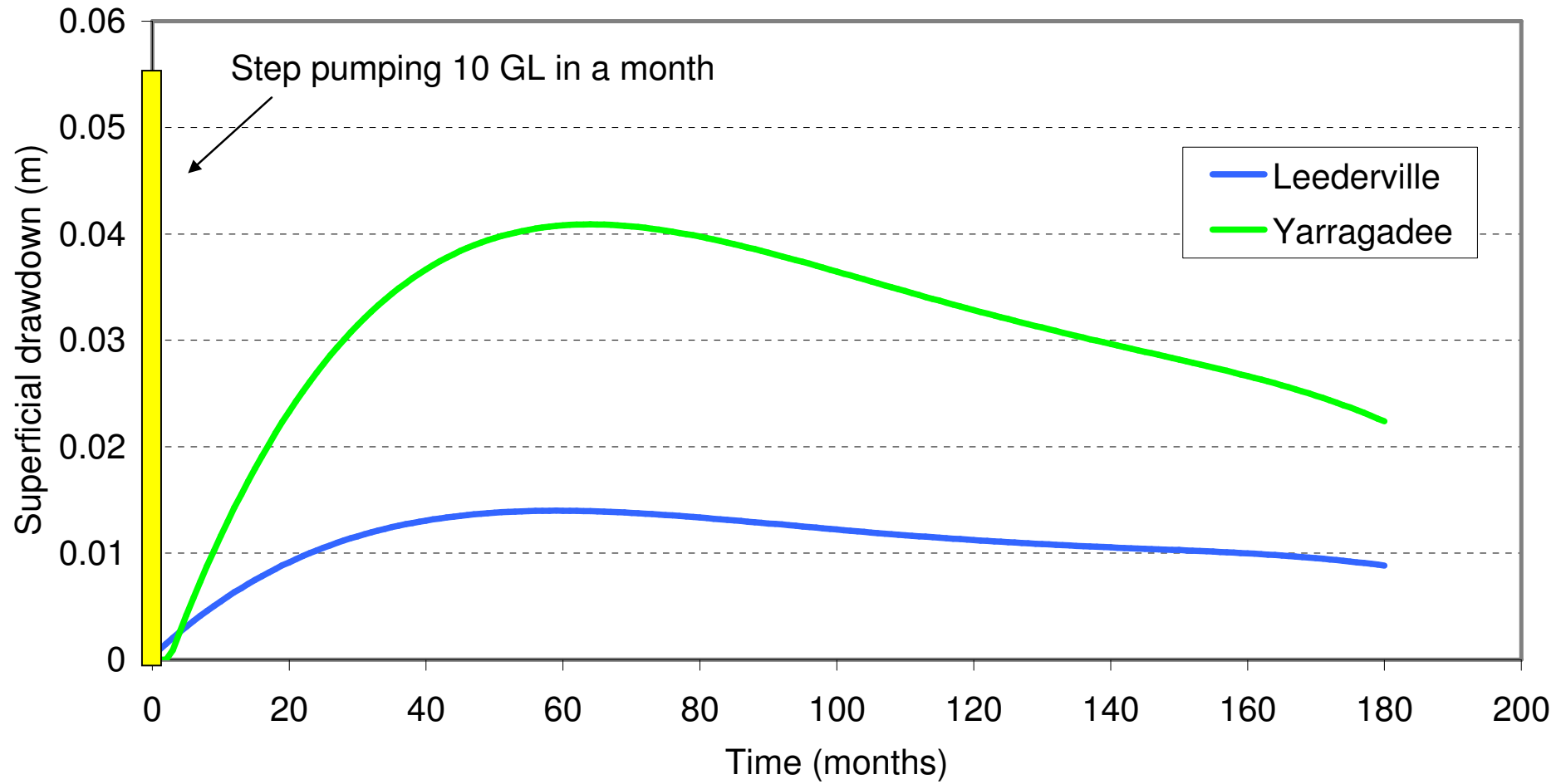


Figure 6 Drawdown impacts on the Superficial aquifer by abstracting 10 GL/m from Yarragadee or Leederville aquifer

Response of Superficial aquifer to step pumping in Yarragadee aquifer
(at centre of impacts)

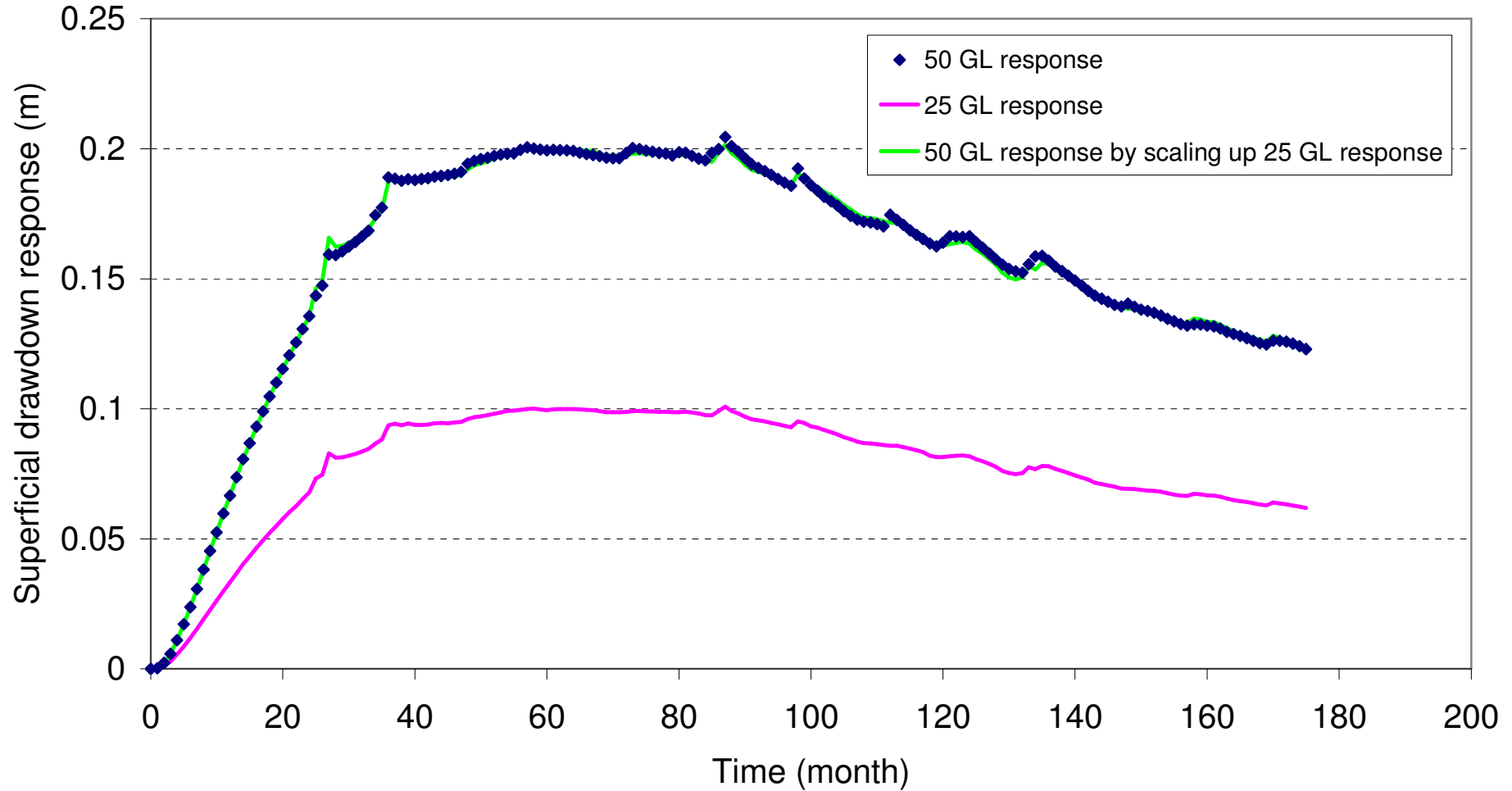


Figure 7 Test of linearity of the superficial response to Yarragadee abstraction

Principle of superposition of pumping impacts

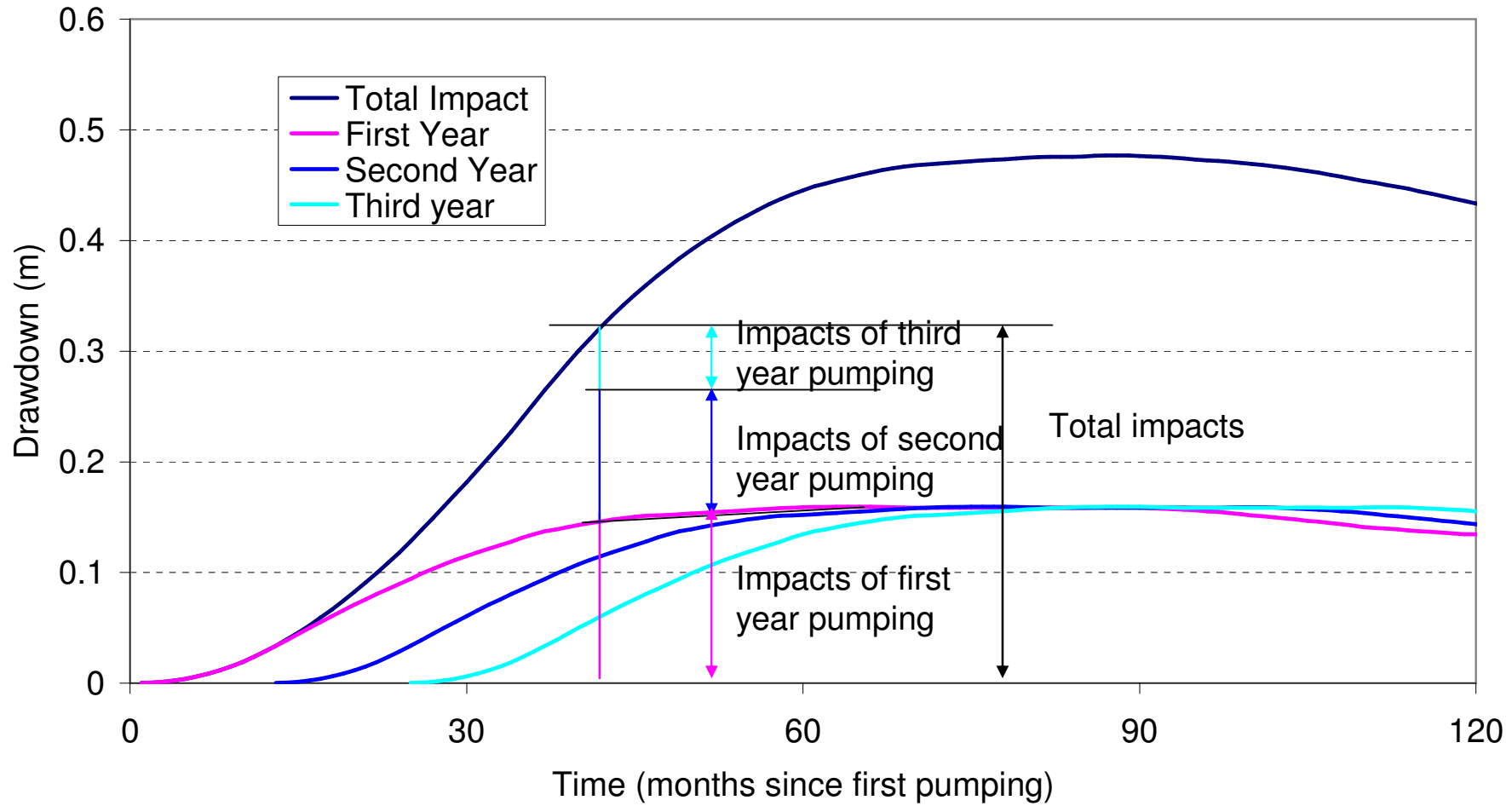


Figure 8 Illustration of superposition principle

Superficial response to continued Yarragdee pumping (40GL) up to X years
(at the centre of impacts)

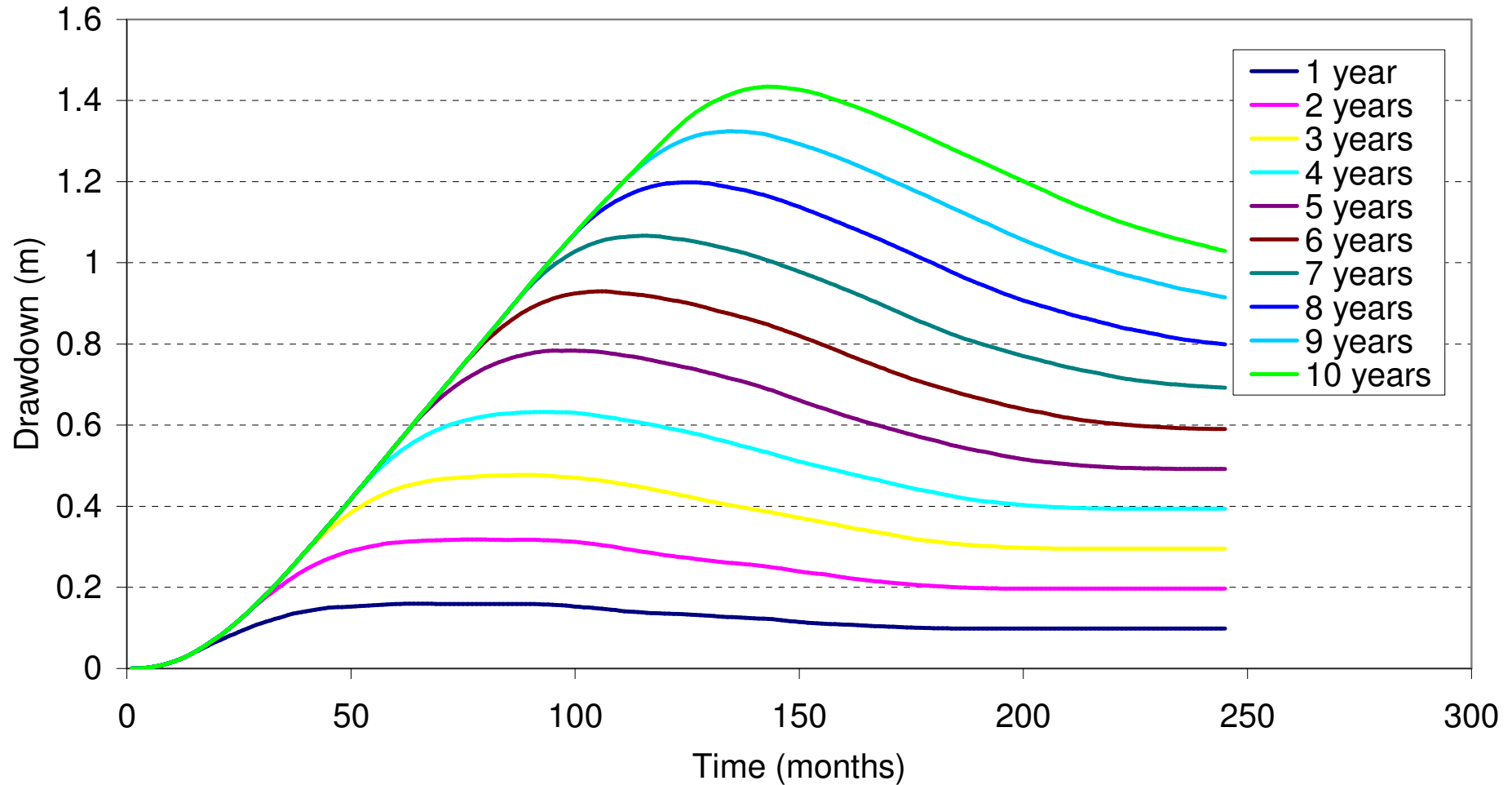


Figure 9 Application of superposition principle to determine the impacts of Yarragadee abstraction

Delay in maximum impacts on Superficial aquifer of Yarragadee Pumping
(40 GY/a)

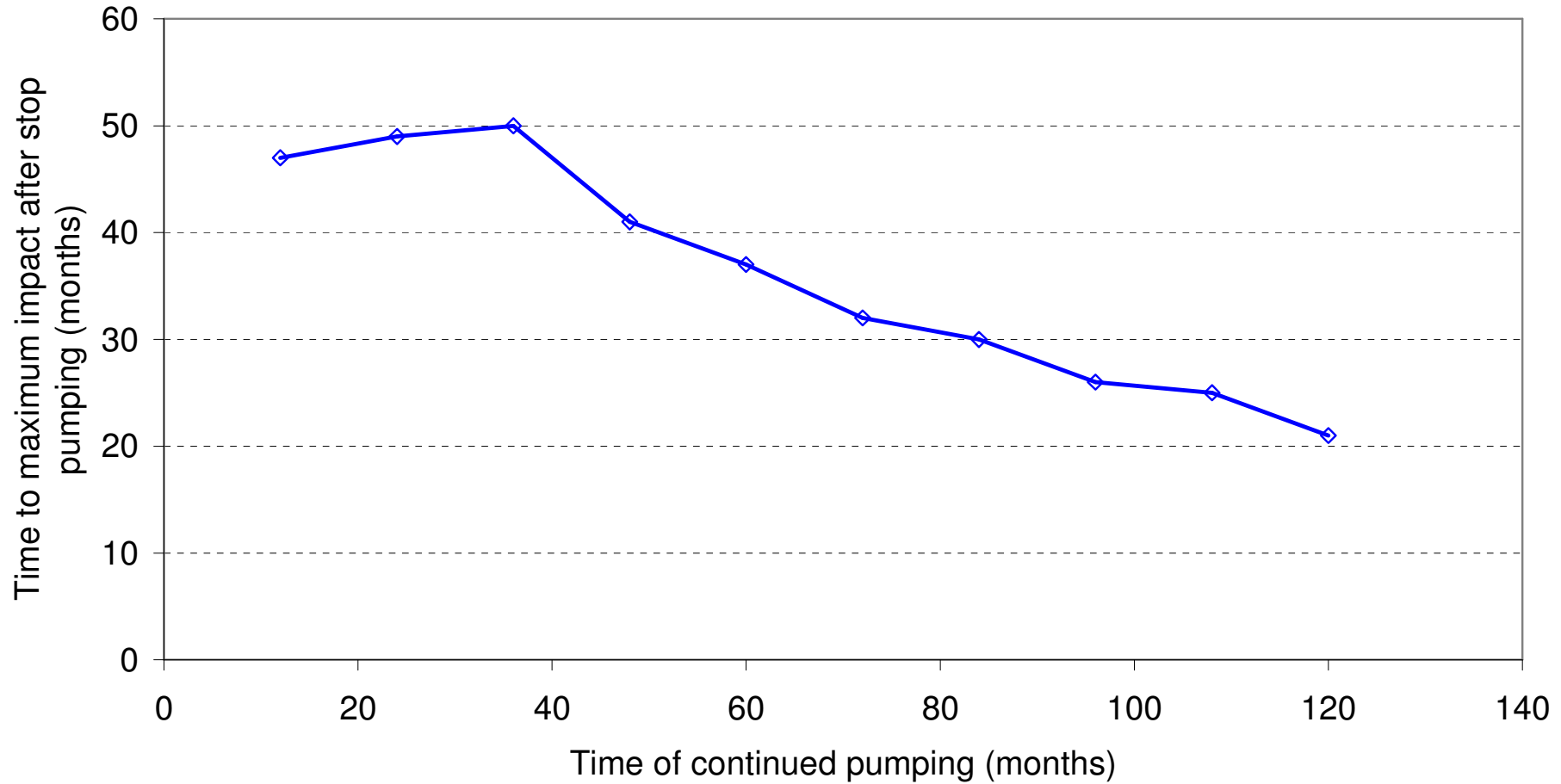


Figure 10 Delay of maximum impacts on Superficial aquifer by the Yarragadee abstraction

Maximum impacts on Superficial aquifer vs continued pumping time
at rate of 40 GL/a

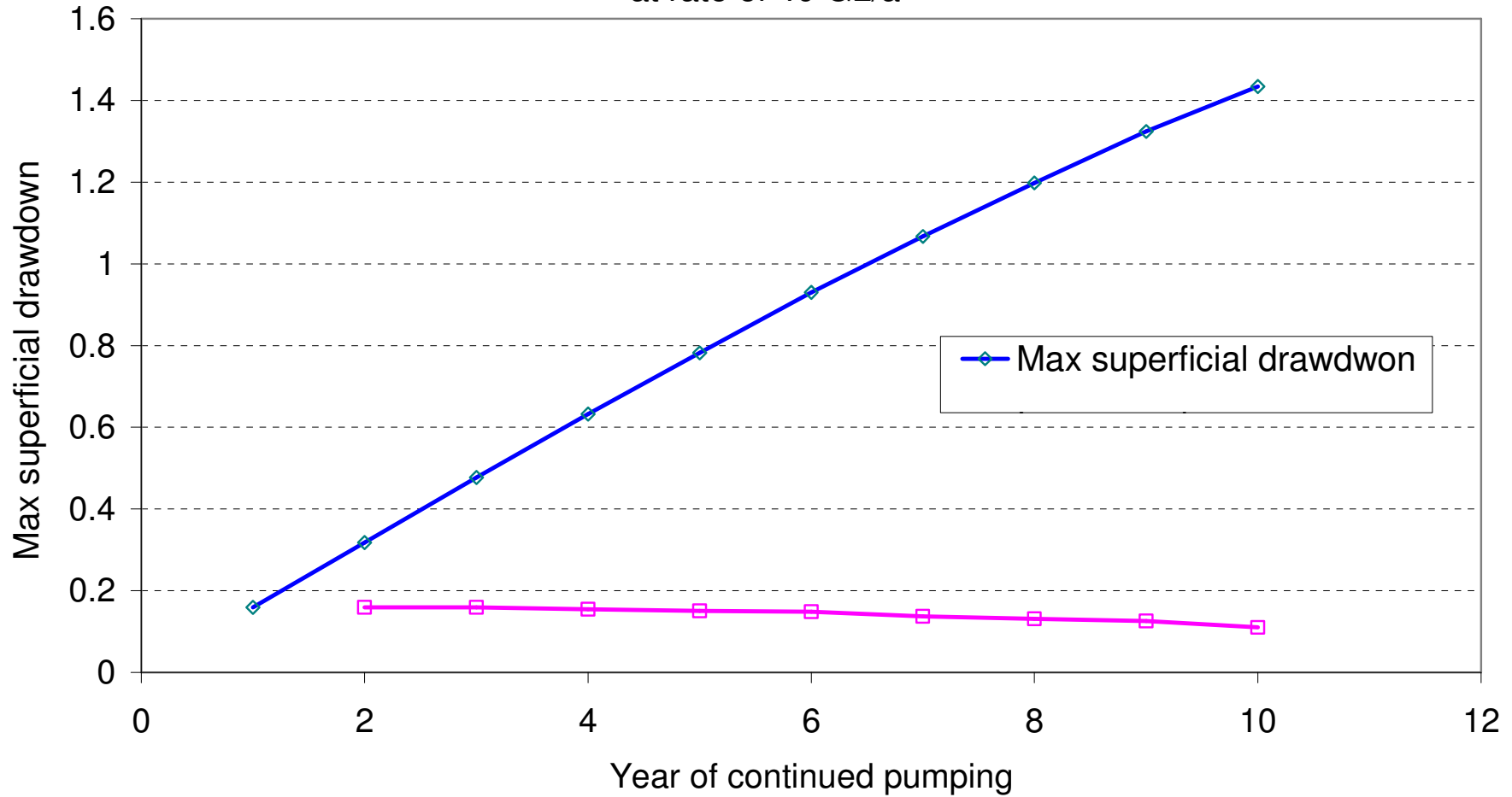


Figure 11 Maximum impacts on Superficial aquifer vs abstraction duration from the Yarragadee aquifer

Head response in Leederville aquifer to step pumping in Leederville aquifer

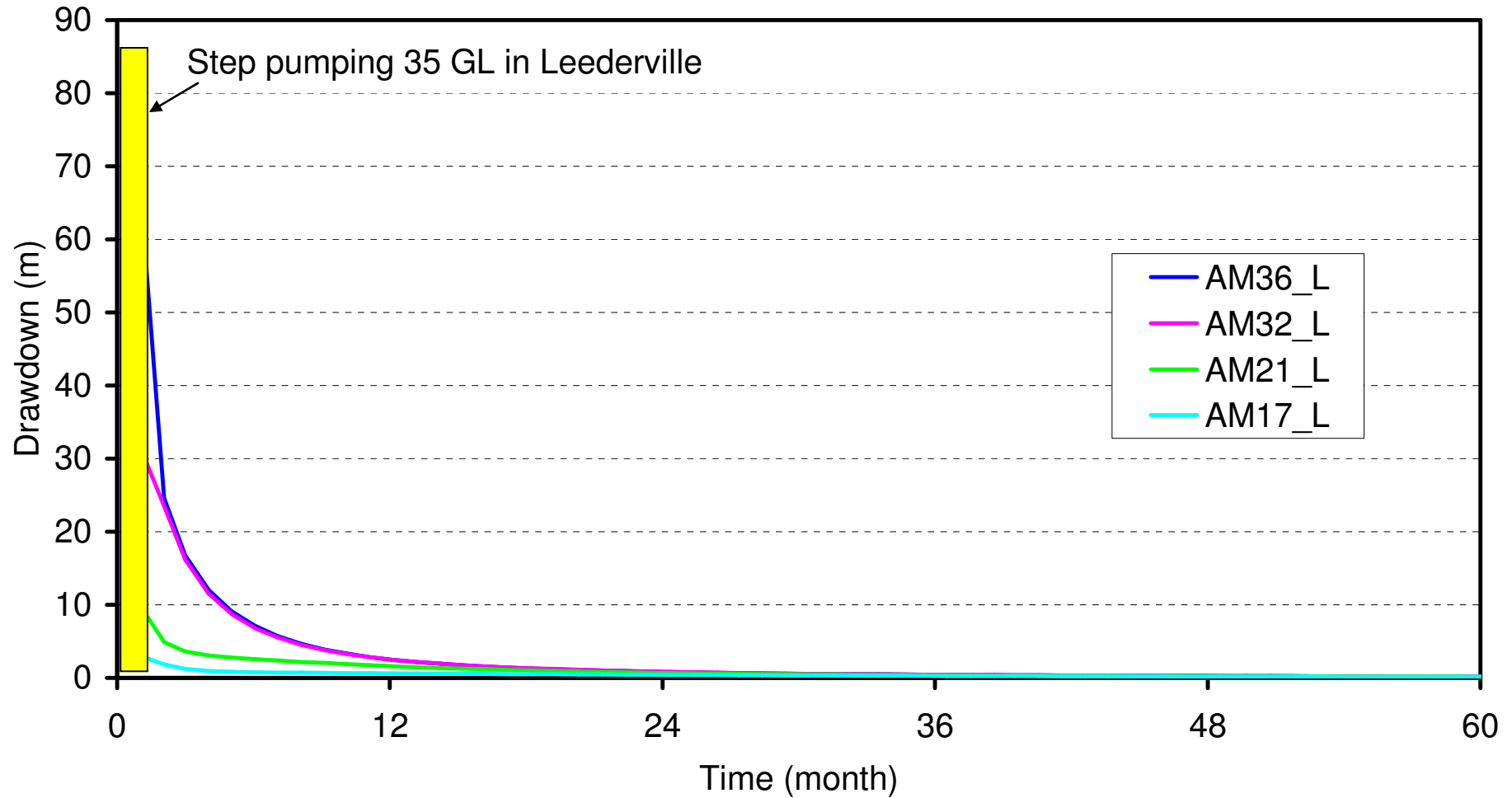


Figure 12 Leederville head response to step Leederville pumping

Head response in Leederville aquifer to step pumping in Leederville aquifer

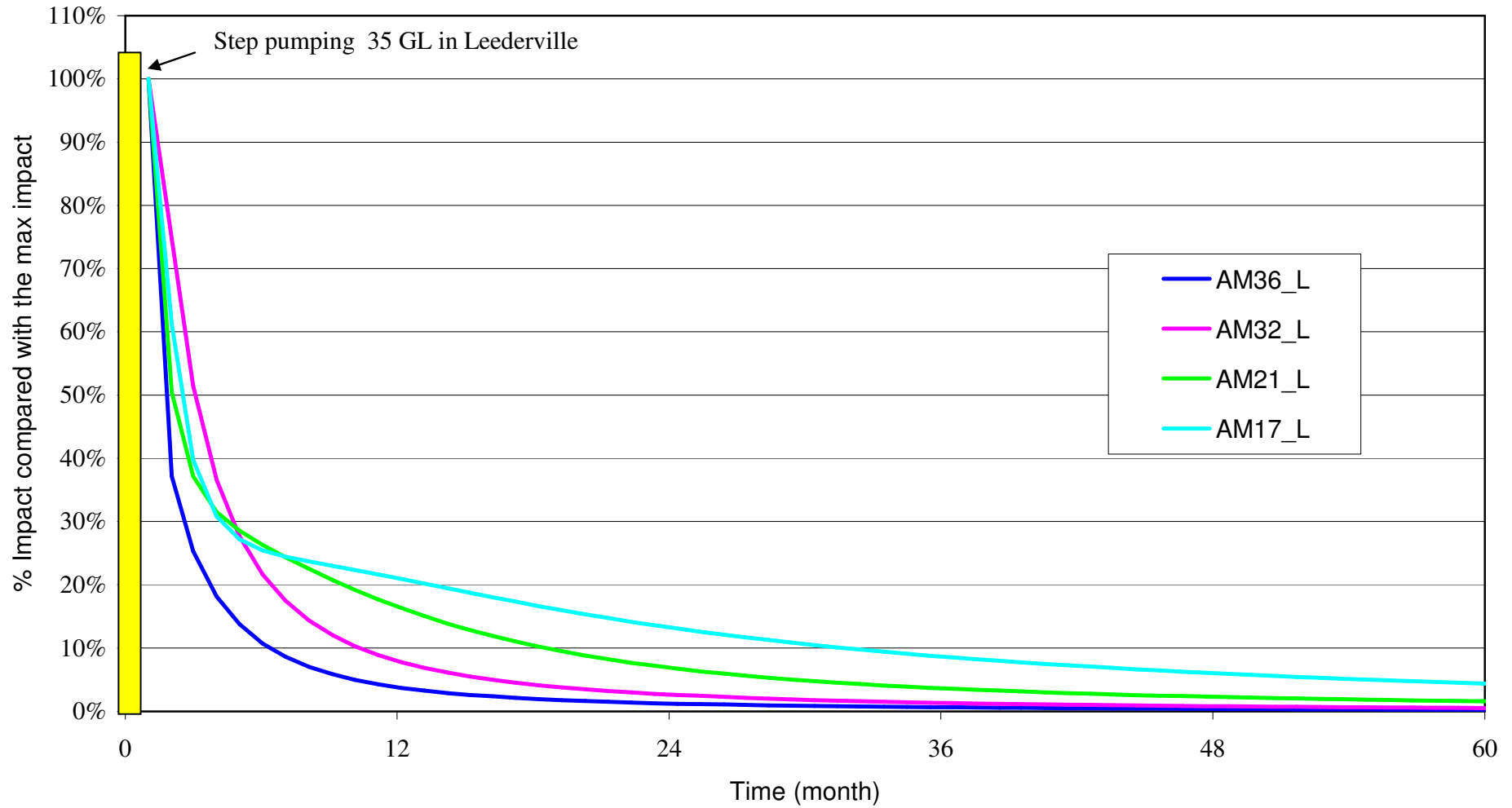


Figure 13 Leederville head recovery after step pumping

Drawdown response at AM17 to step pumping in Leederville

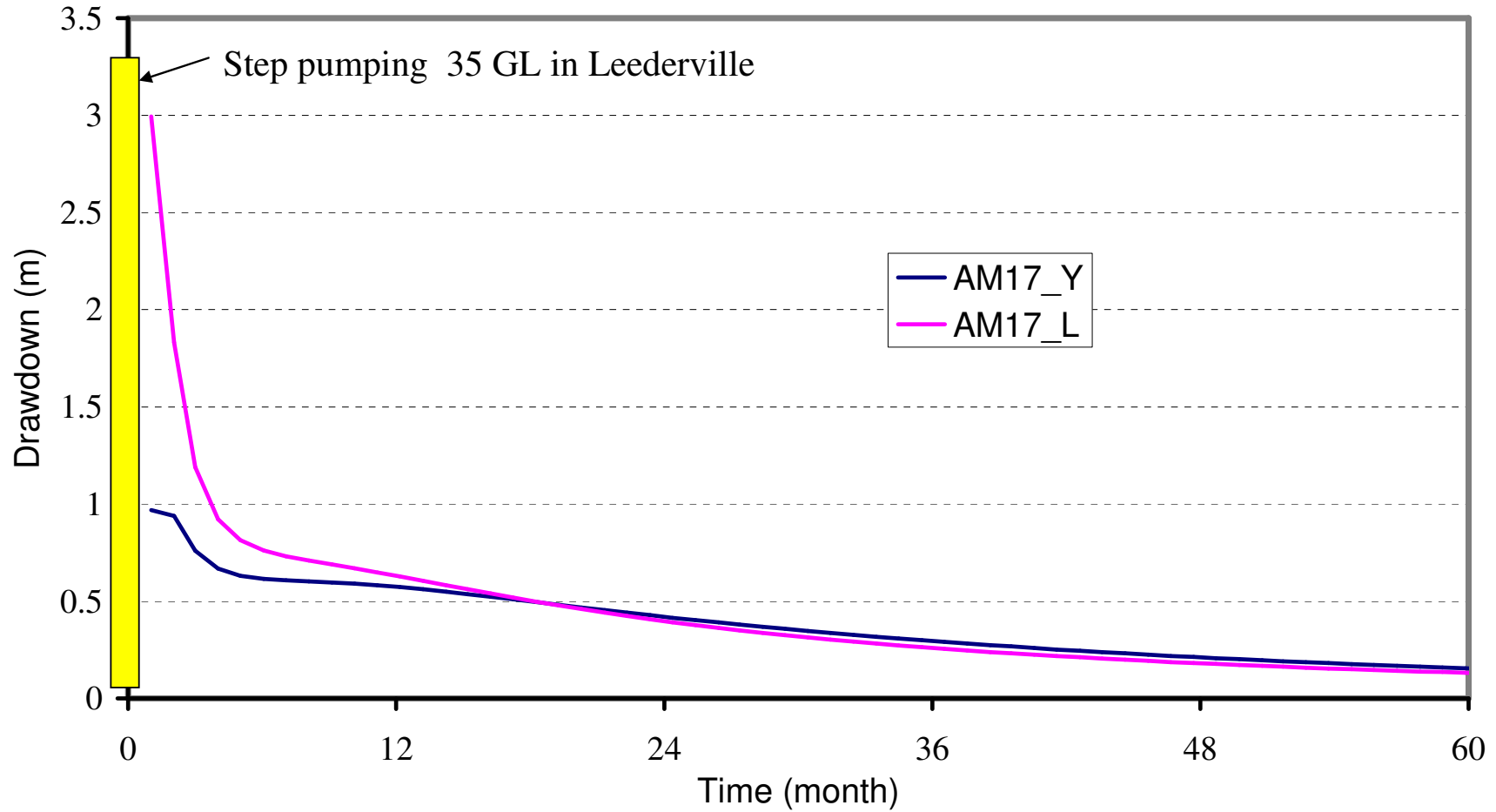


Figure 14 Drawdown response at AM17

Superficial aquifer response to step pumping in Leederville

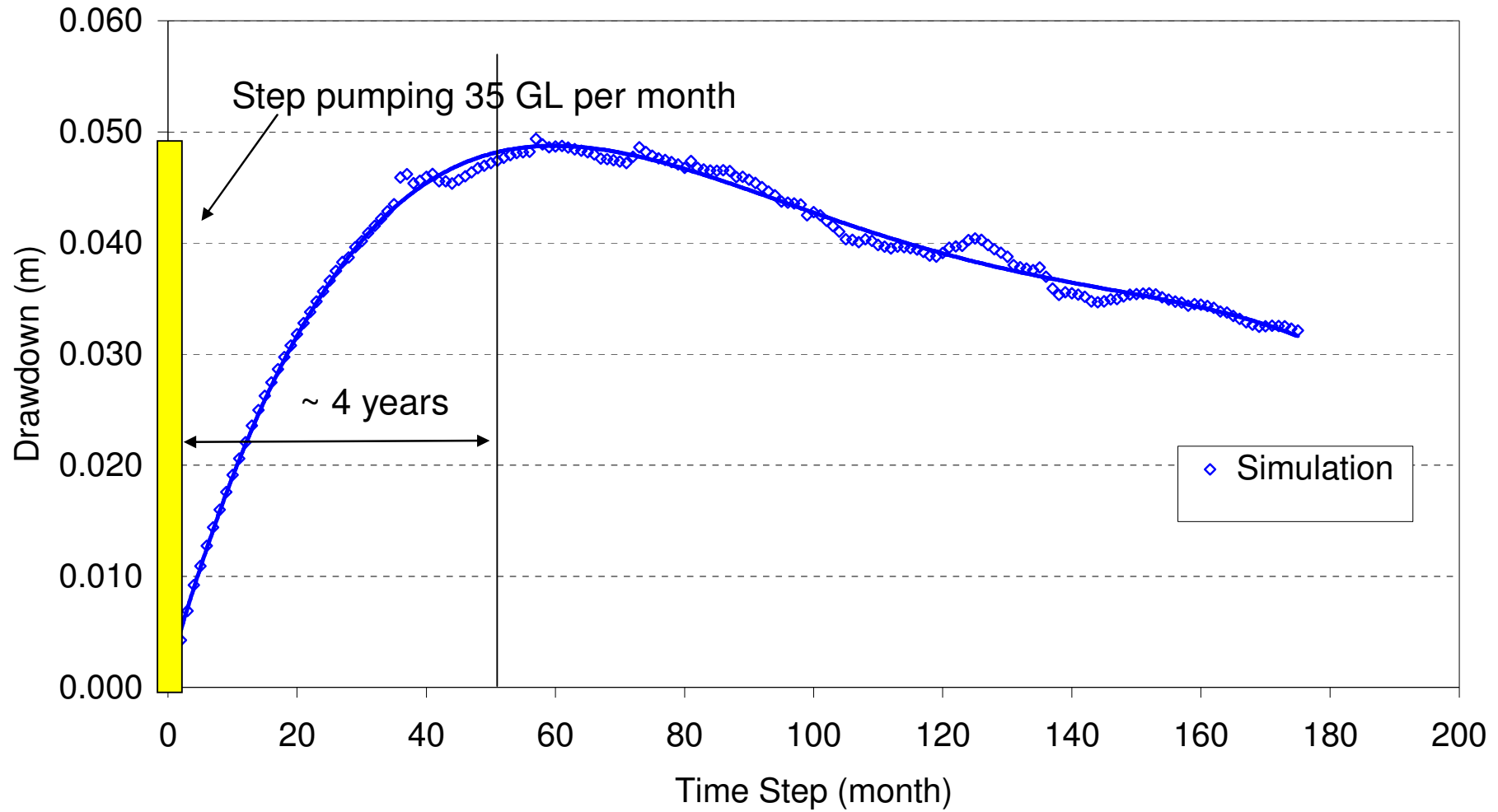


Figure 15 Superficial aquifer response to Leederville step pumping

Reponse of Superficial aquifer to step pumping in the Leederville aquifer test of linearity

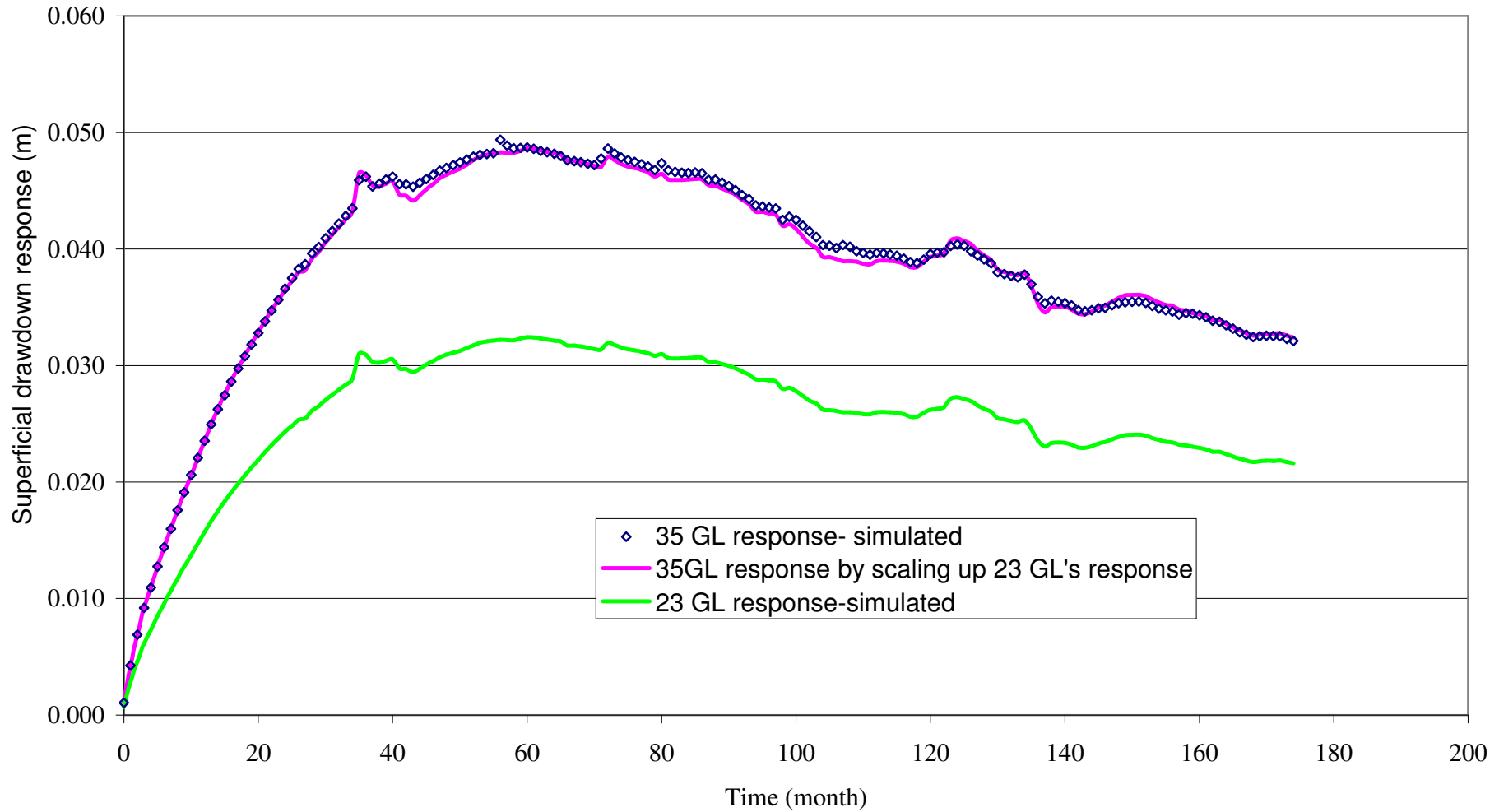


Figure 16 Verification of linear response of superficial aquifer to Leederville step pumping

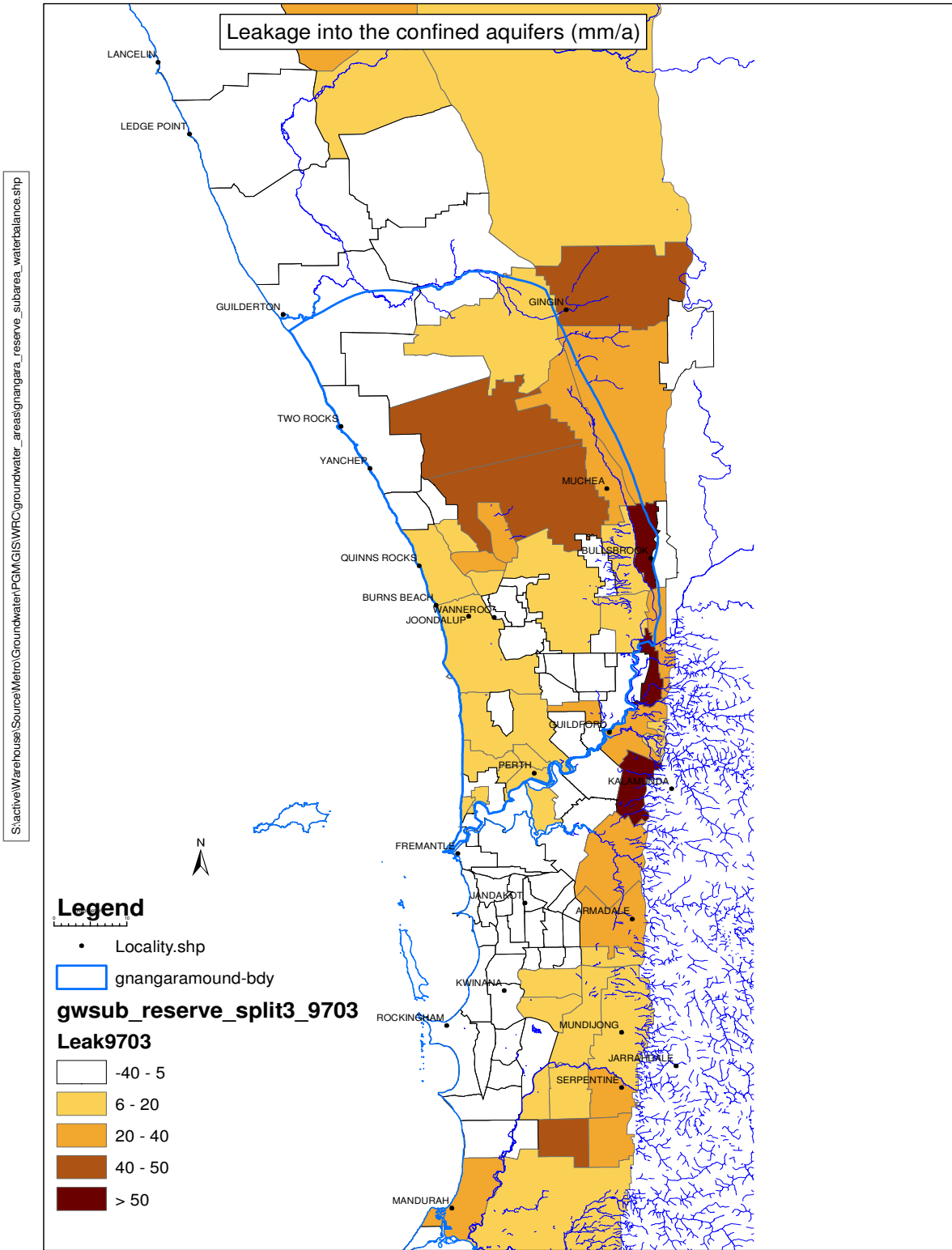


Figure 17 Leakage rate into the confined aquifer (based on water balance for 1997-2003)

**Abstraction scenarios for assessing the response of increased abstraction from the Leederville aquifer
(with abstractions from the superficial and Yarragadee aquifers fixed as the baseline)**

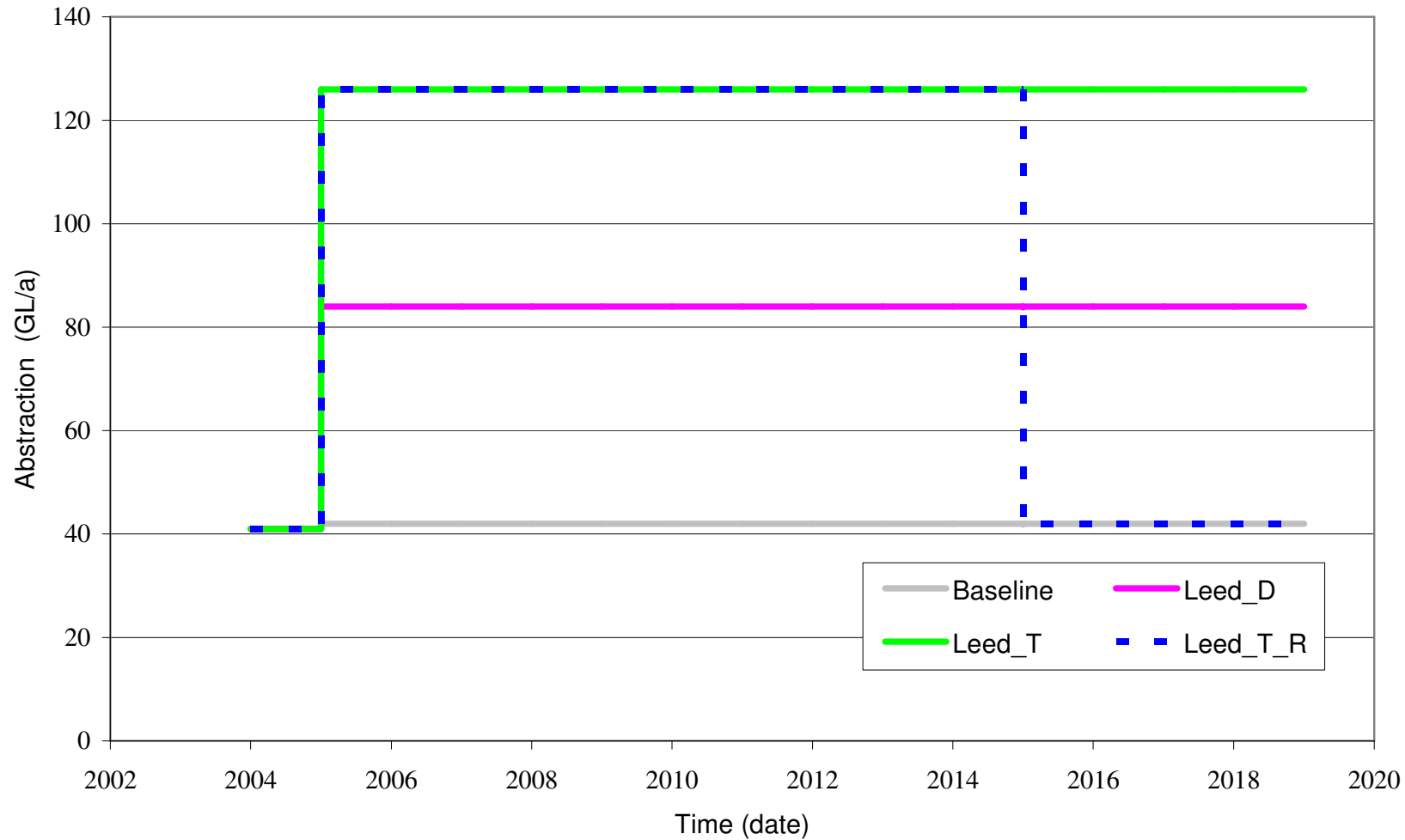


Figure 18 Leederville abstraction scenarios

**Abstraction scenarios for assessing the response of increased abstraction from the Yarragadee aquifer
(with abstractions from the superficial and Leederville aquifers fixed as the baseline)**

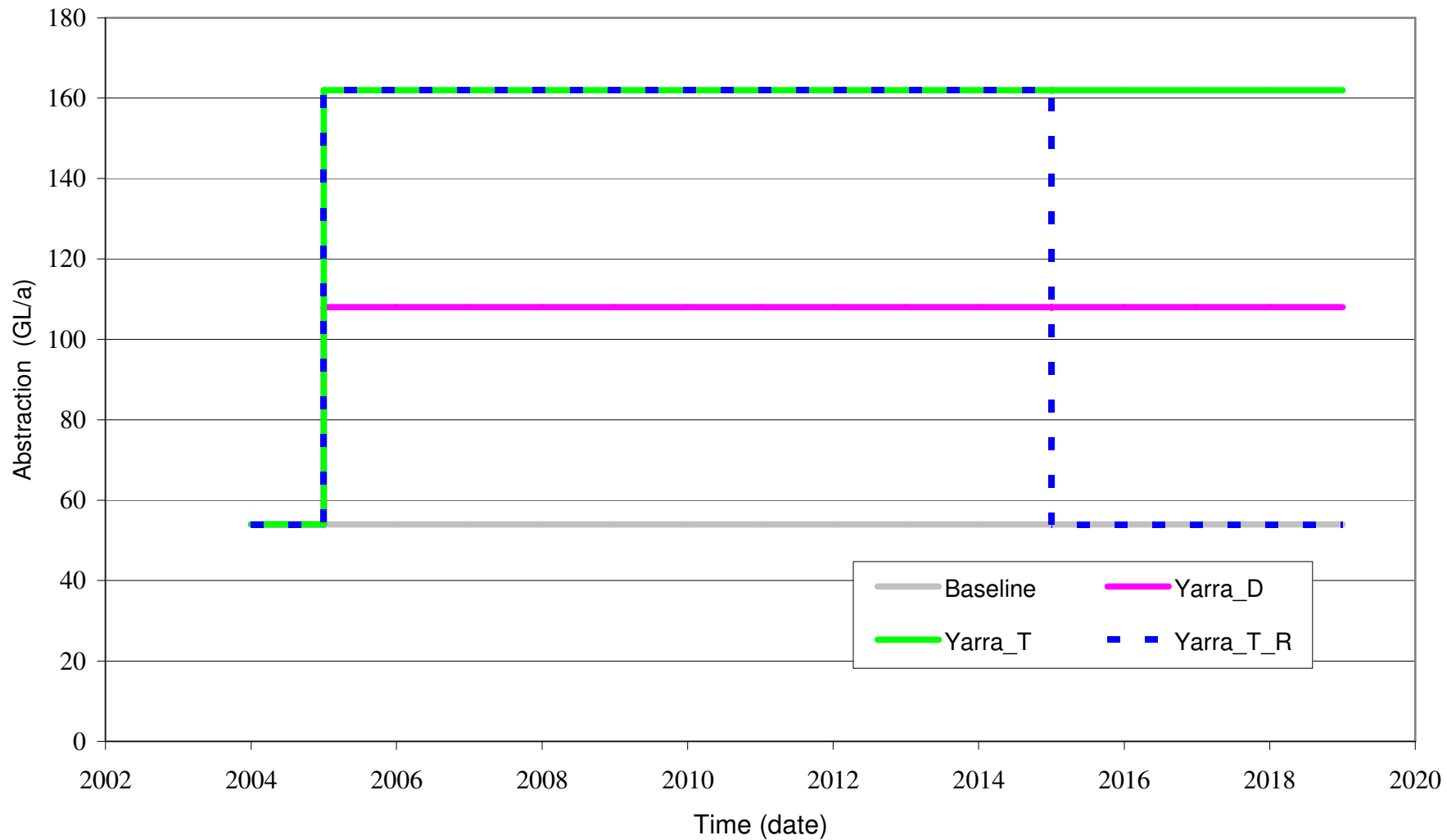


Figure 19 Yarragadee abstraction scenarios

Yarragadee aquifer head response at bore AM36 to increased Yarragadee abstraction

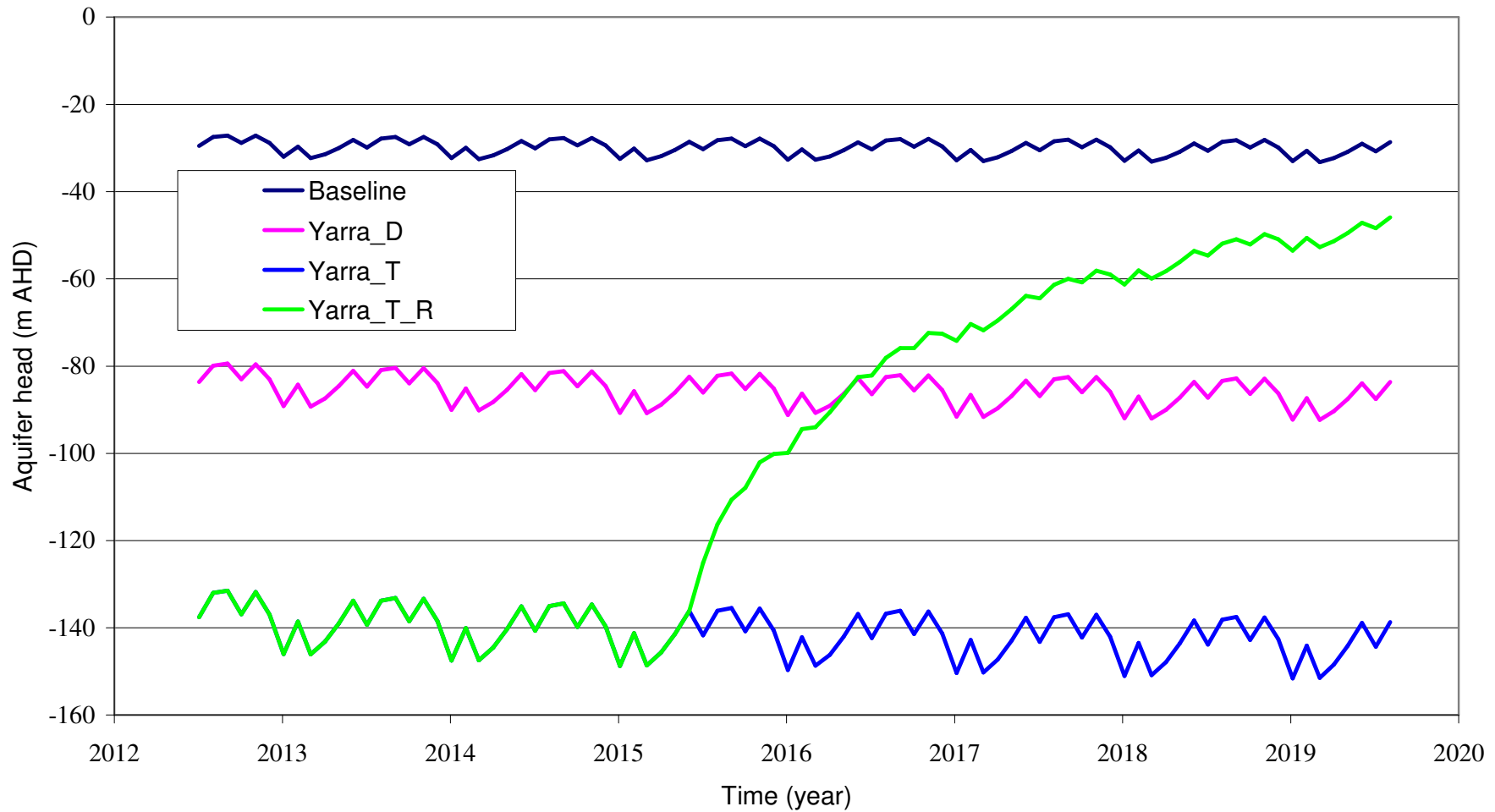


Figure 20 Yarragadee head response at AM36 to change in Yarragadee abstraction

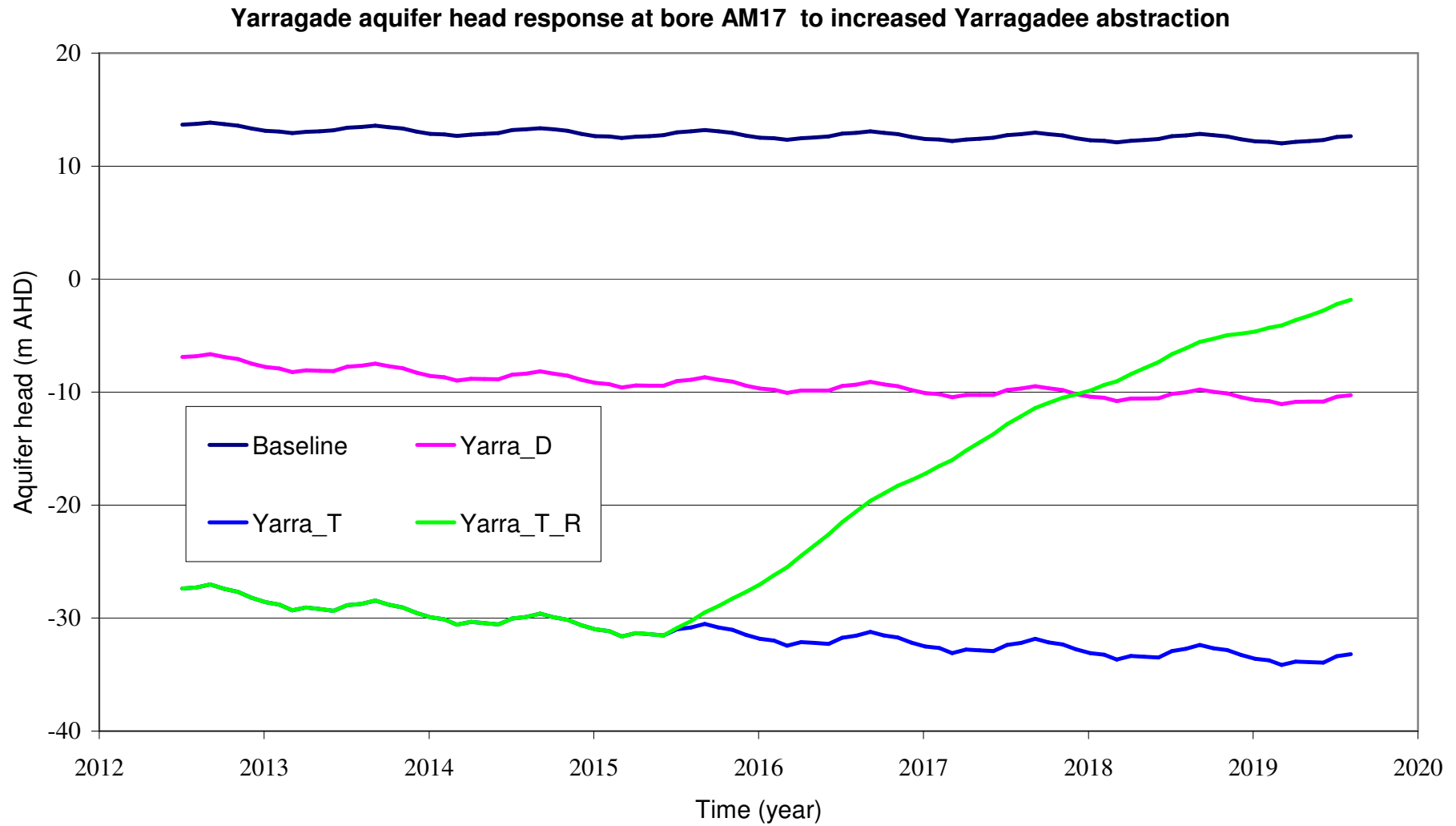


Figure 21 Yarragadee head response at AM17 to change in Yarragadee abstraction

Leerderville aquifer head response at bore AM36 to increased Yarragadee abstraction

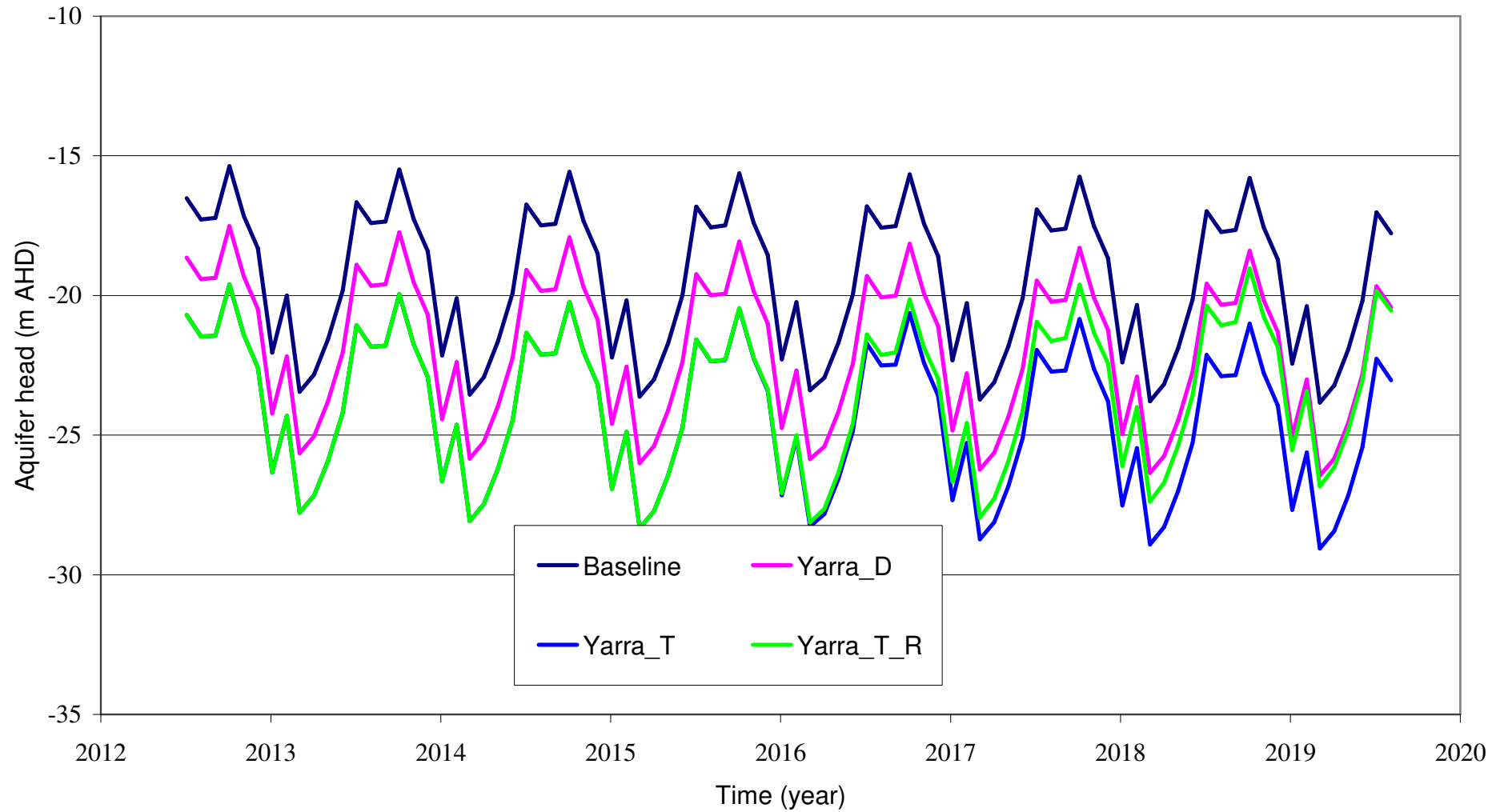


Figure 22 Leerderville head response at AM36 to change in Yarragadee abstraction

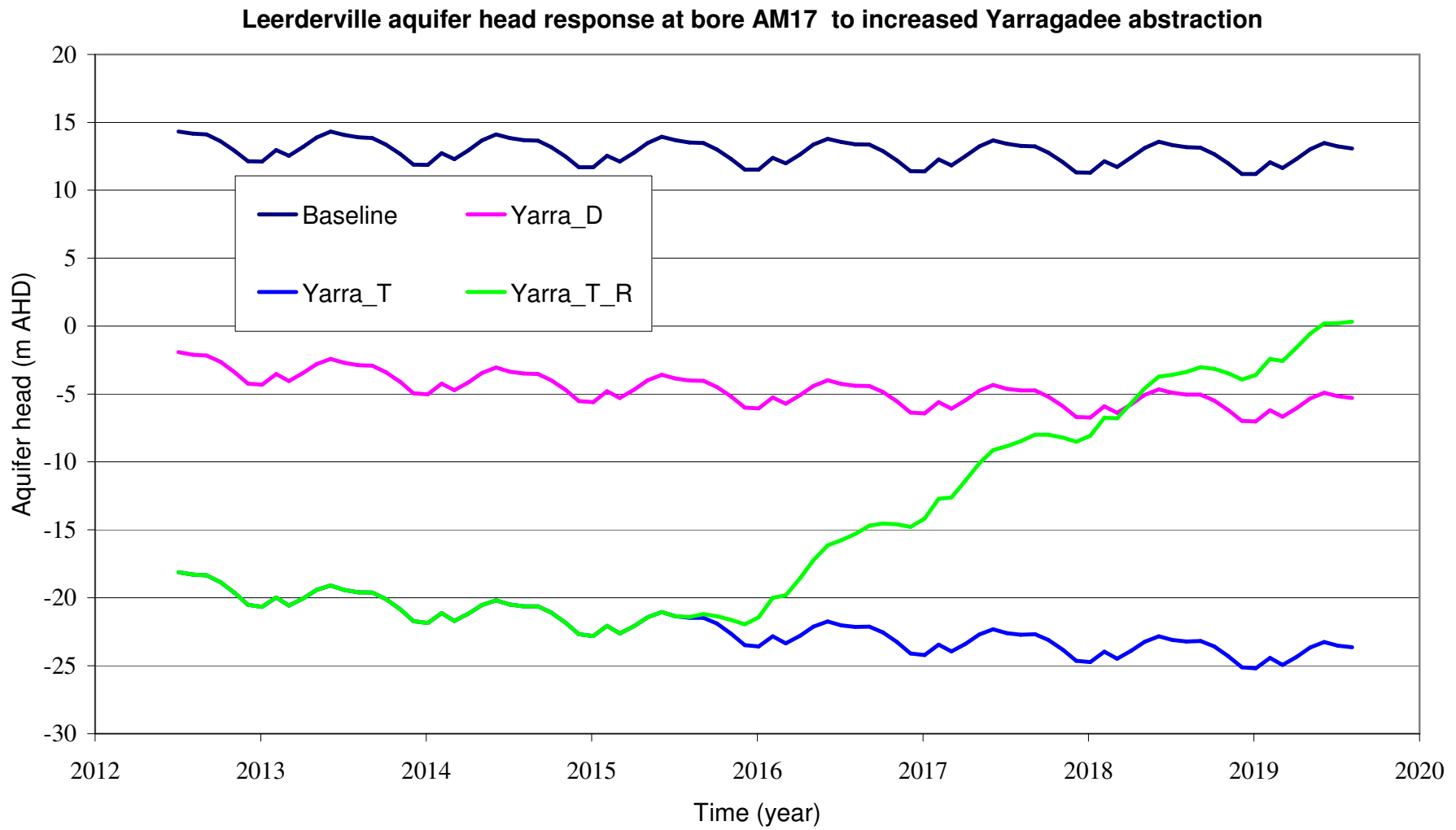


Figure 23 Leerderville head response at AM36 to change in Yarragadee abstraction

Aquifer heads at AM36 and AM 17 vs abstraction from the Yarragadee aquifer

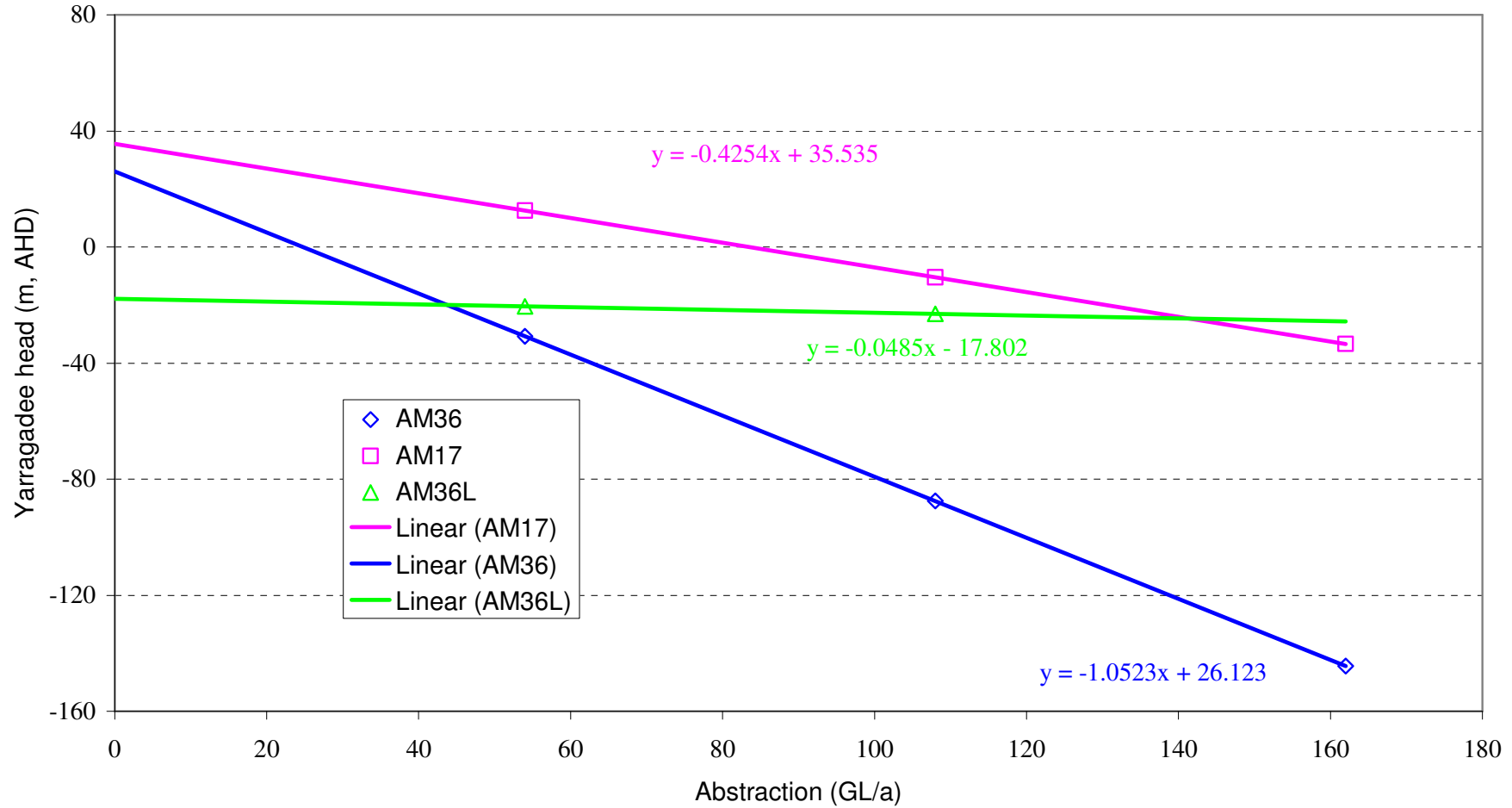


Figure 24 Aquifer heads vs abstraction in Yarragadee aquifer

Superficial aquifer head response to increased Yarragadee abstraction

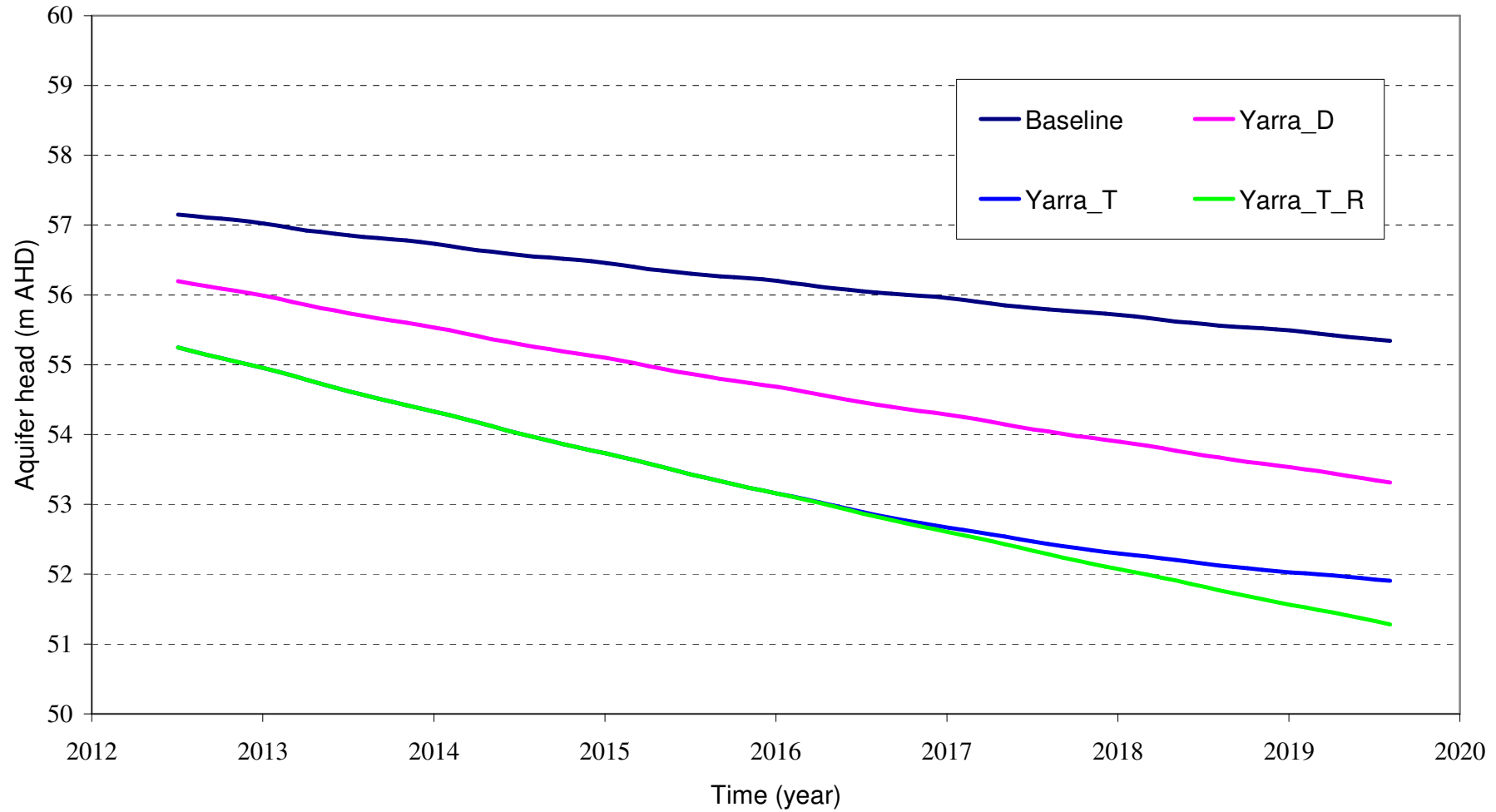


Figure 25 Superficial aquifer response to change in Yarragadee abstraction

**Impacts on the Superficial aquifer on the Gngara Mound by 15 year continued pumping
in the Yarragadee aquifer**

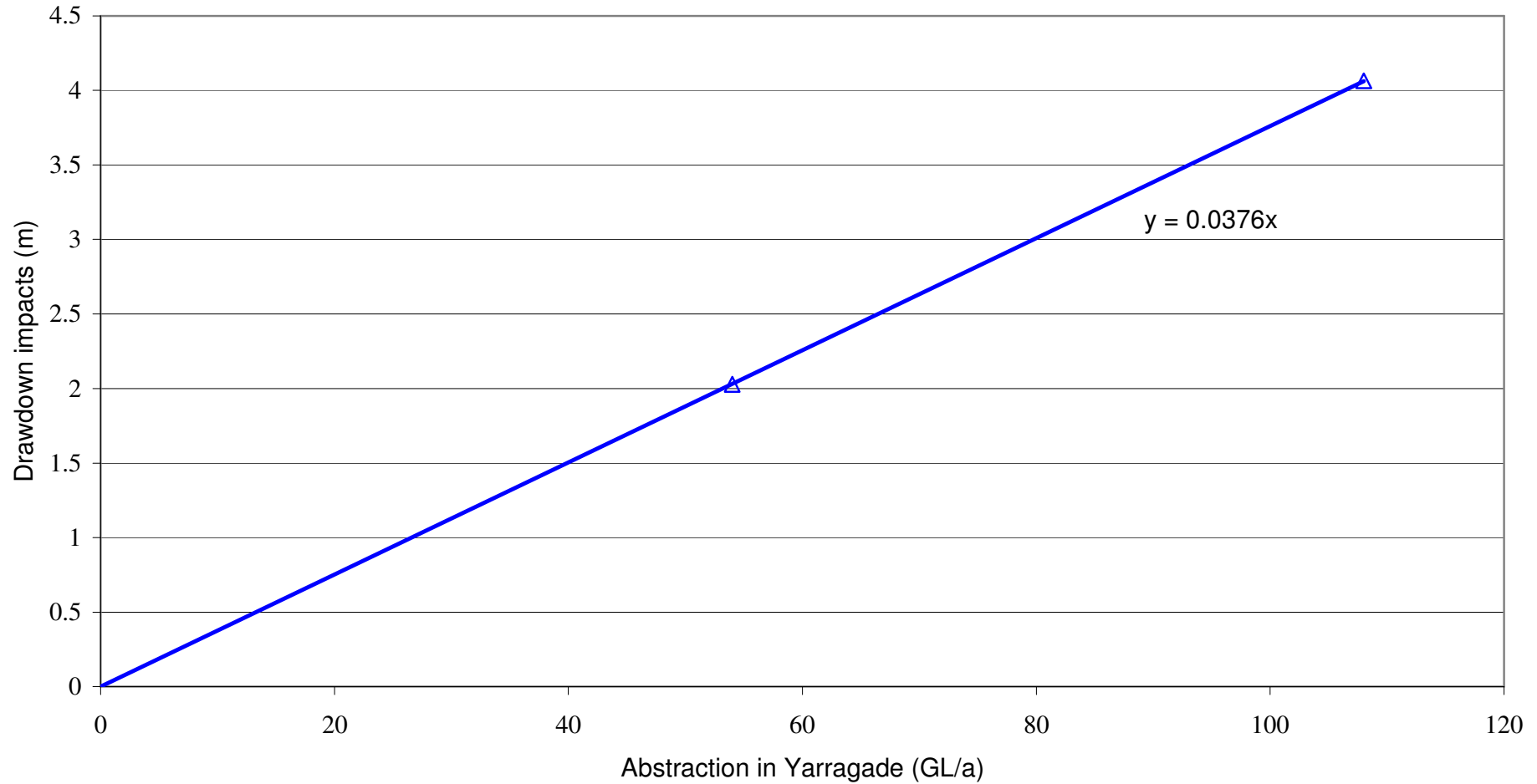


Figure 26 Impacts of Yarragadee abstraction on the Mound after 15 yrs abstraction

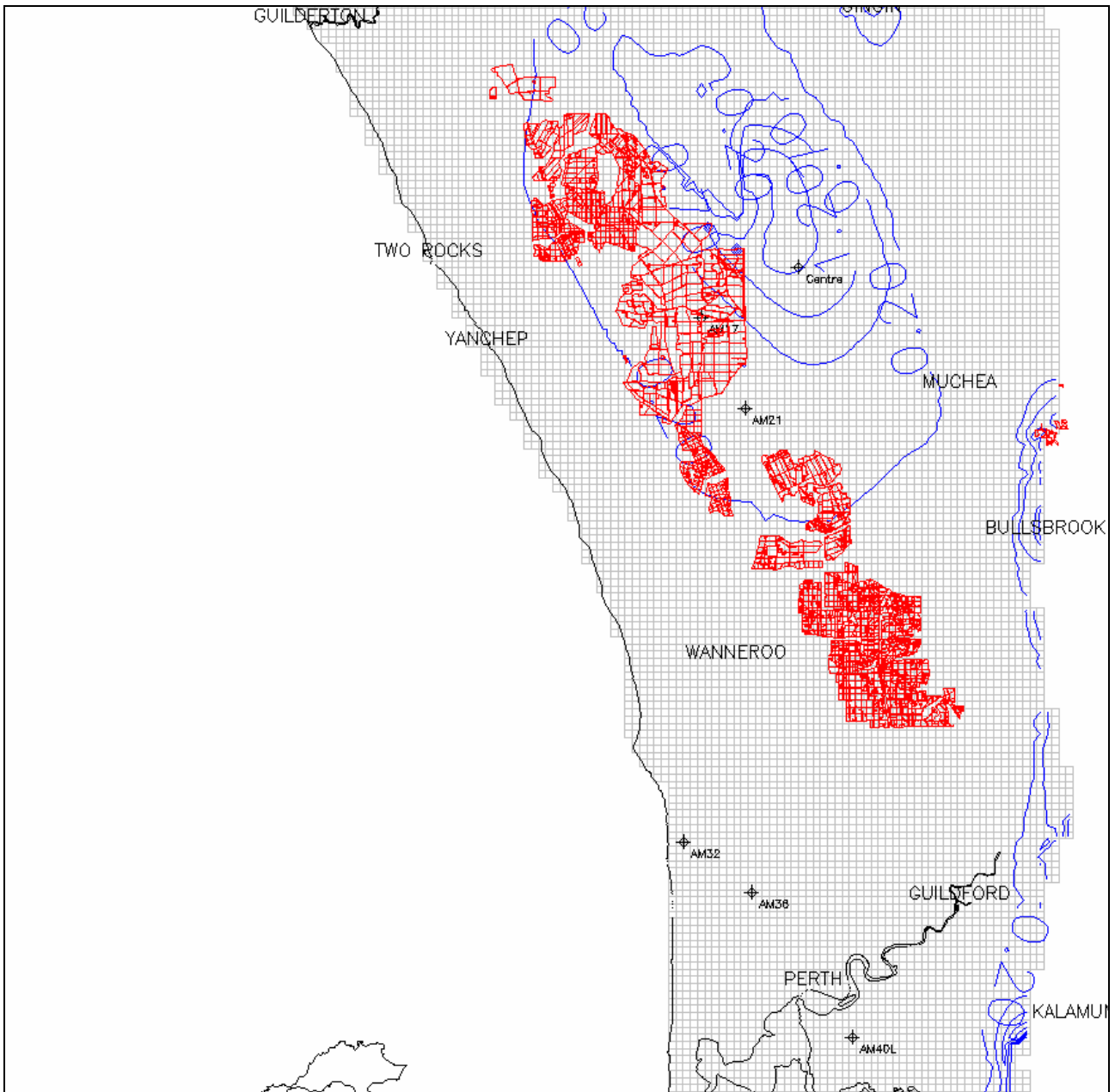


Figure 27 Water table drawdown impacts of abstracting 54 GL from Yarragadee for 15 years

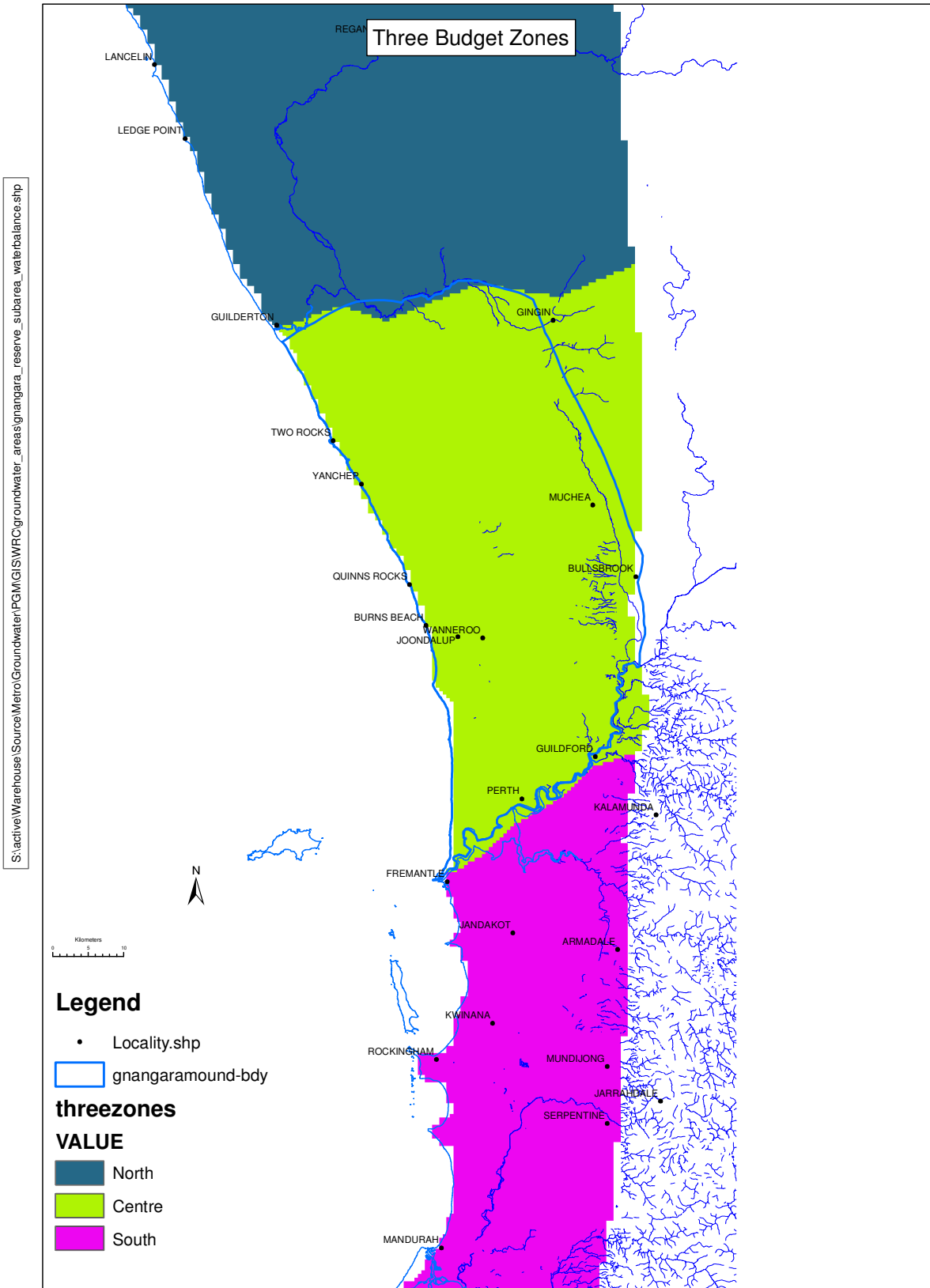


Figure 28 Domain for three budget zones

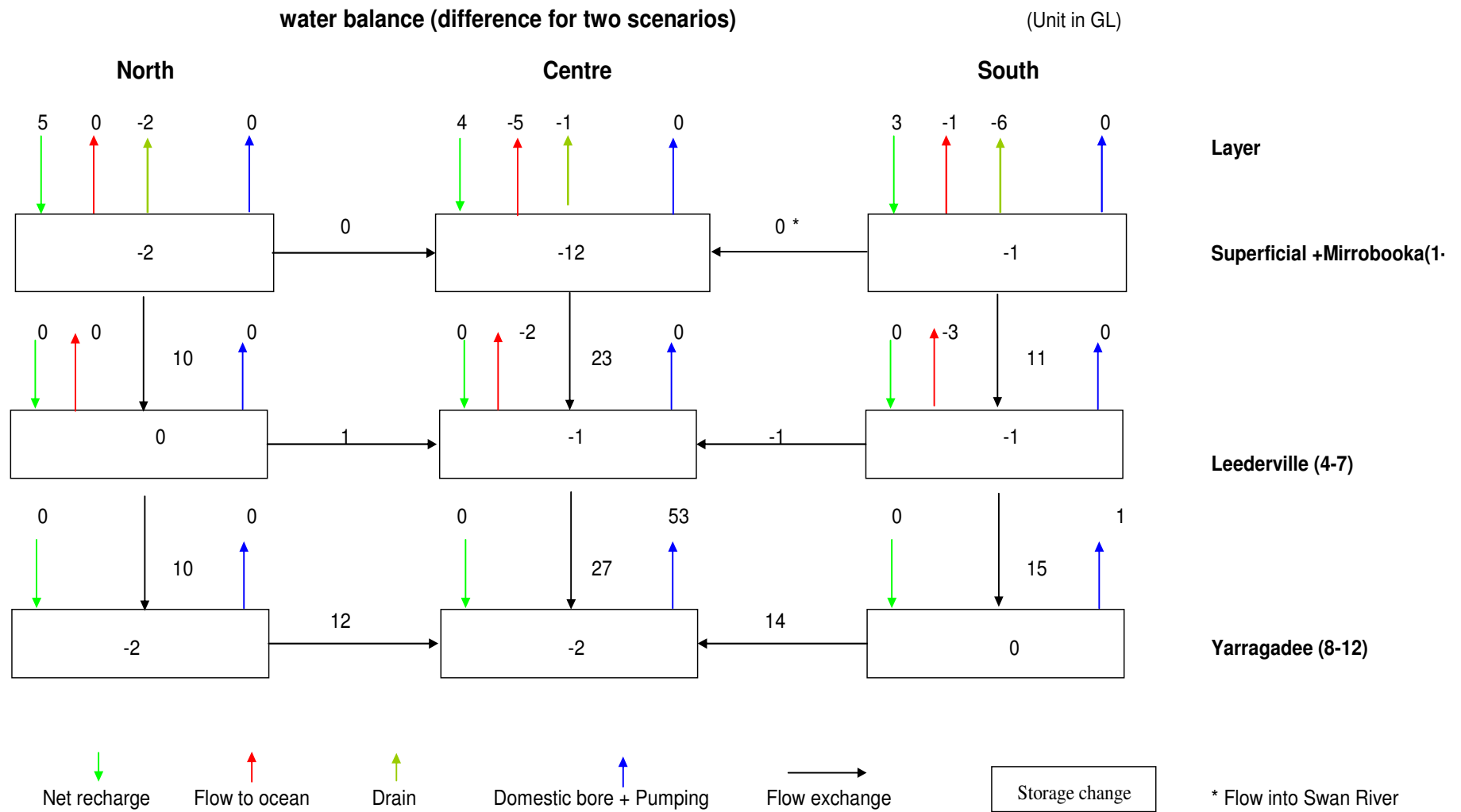


Figure 29 Trace of Yarragadee abstraction at rate of 54 GL/a

**Yarragadee storage recovery
(after 10 yrs pumping of 162 GL/a then reduce to ~ 54 GL/a in 165 basecase)**

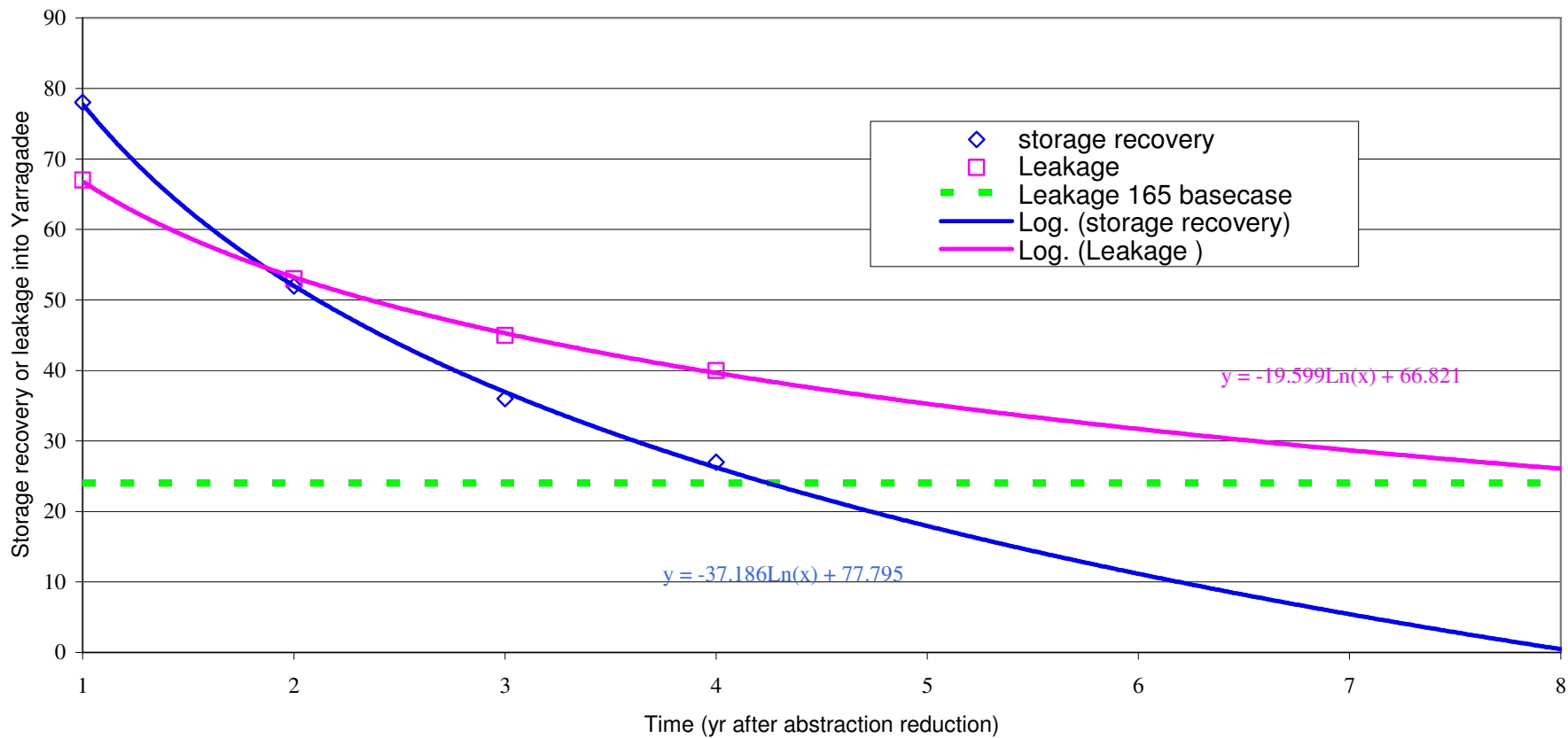


Figure 30 Yarragadee aquifer recovery

**Yarragadee storage recovery
(after 10 yrs pumping of 162 GL/a then reduce to 54 GL/a in 165 basecase)**

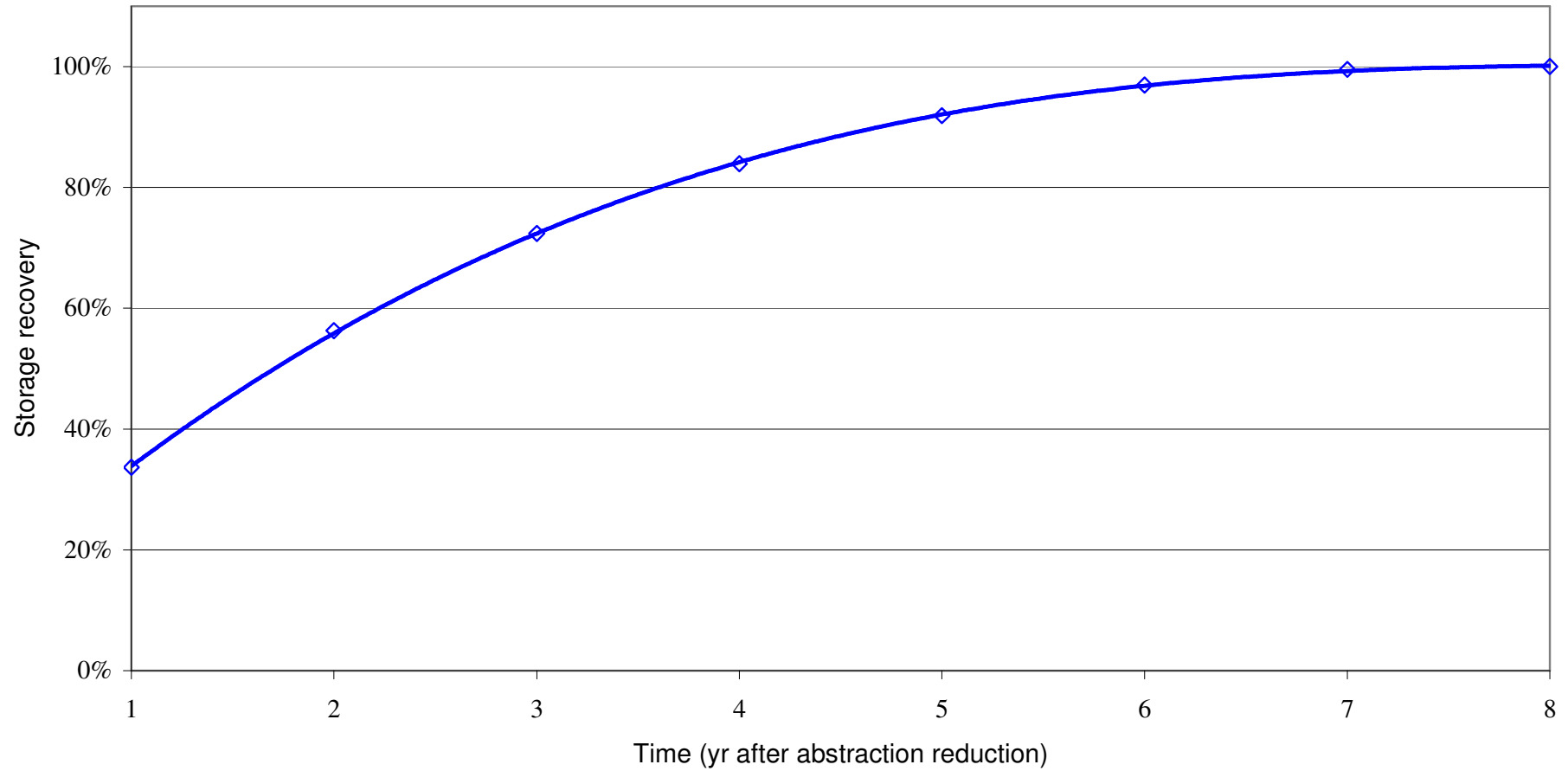


Figure 31 Percentage of Yarragadee recovery vs time

Leederville aquifer head response at bore AM36 to increased Leederville abstraction

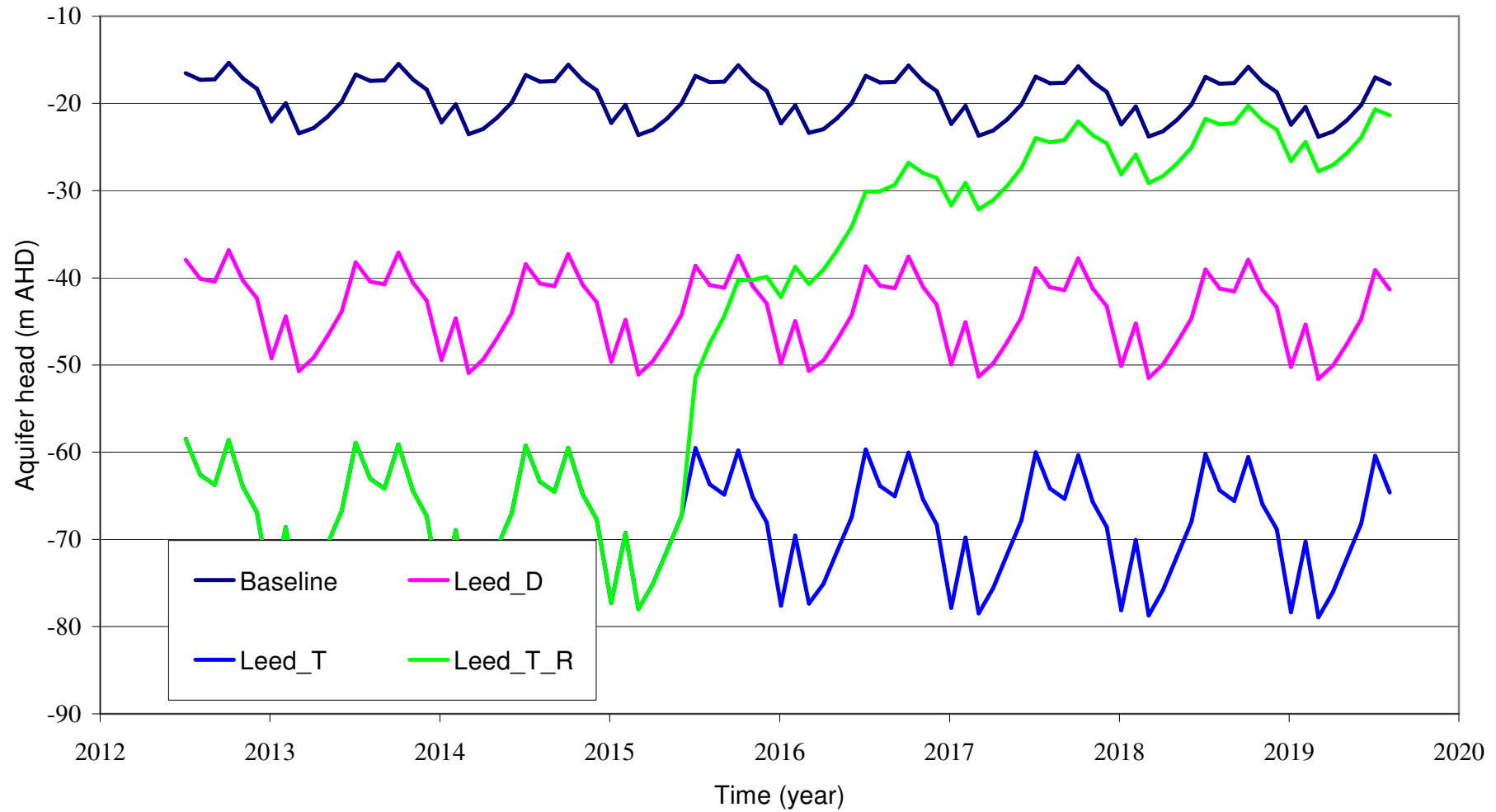


Figure 32 Leederville head response at AM36 to change in Leederville abstraction

Leederville aquifer head response at bore AM17 to increased Leederville abstraction

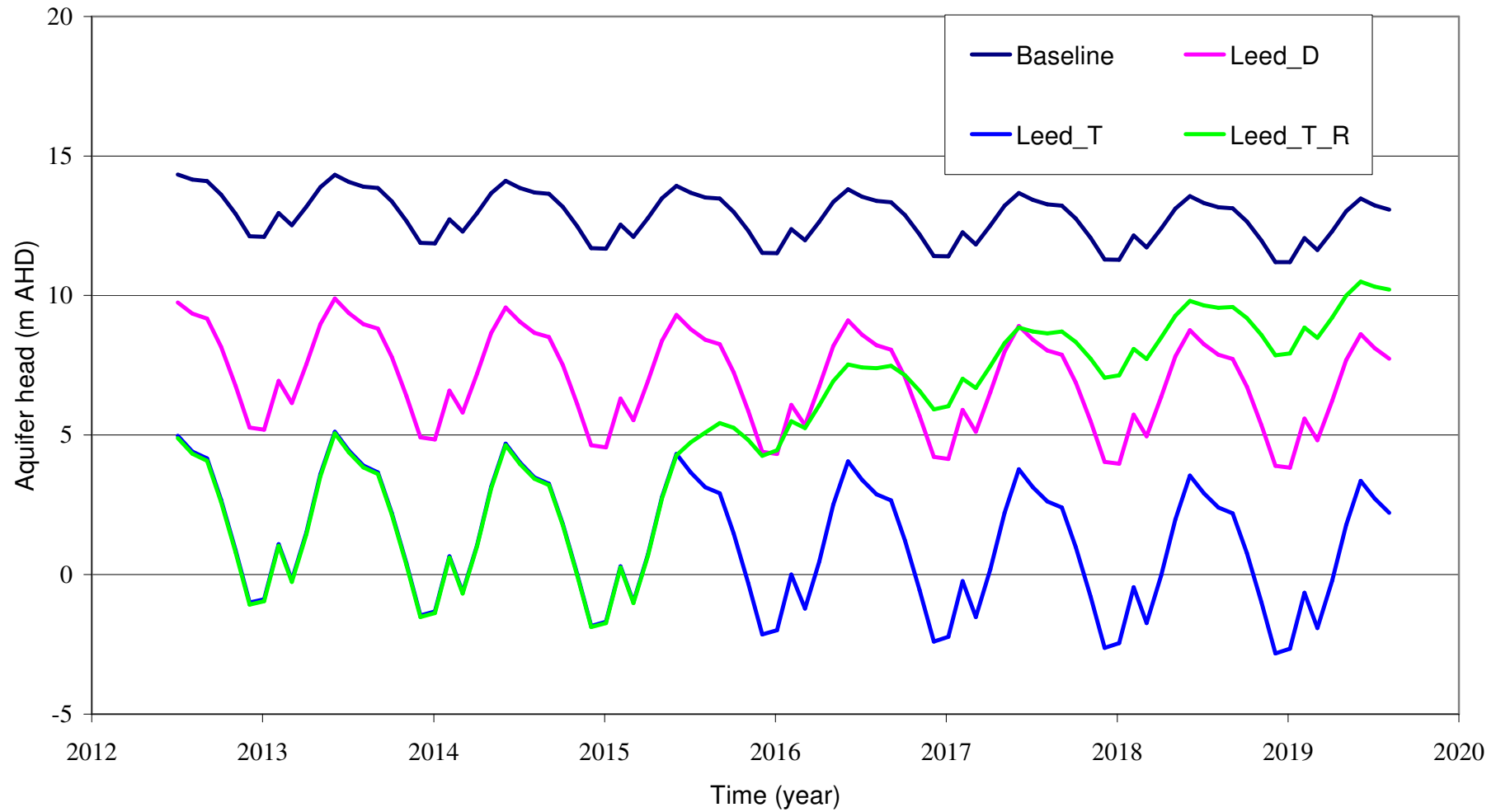


Figure 33 Leederville head response at AM17 to change in Leederville abstraction

Leederville head response to increased abstraction in the Leederville aquifer

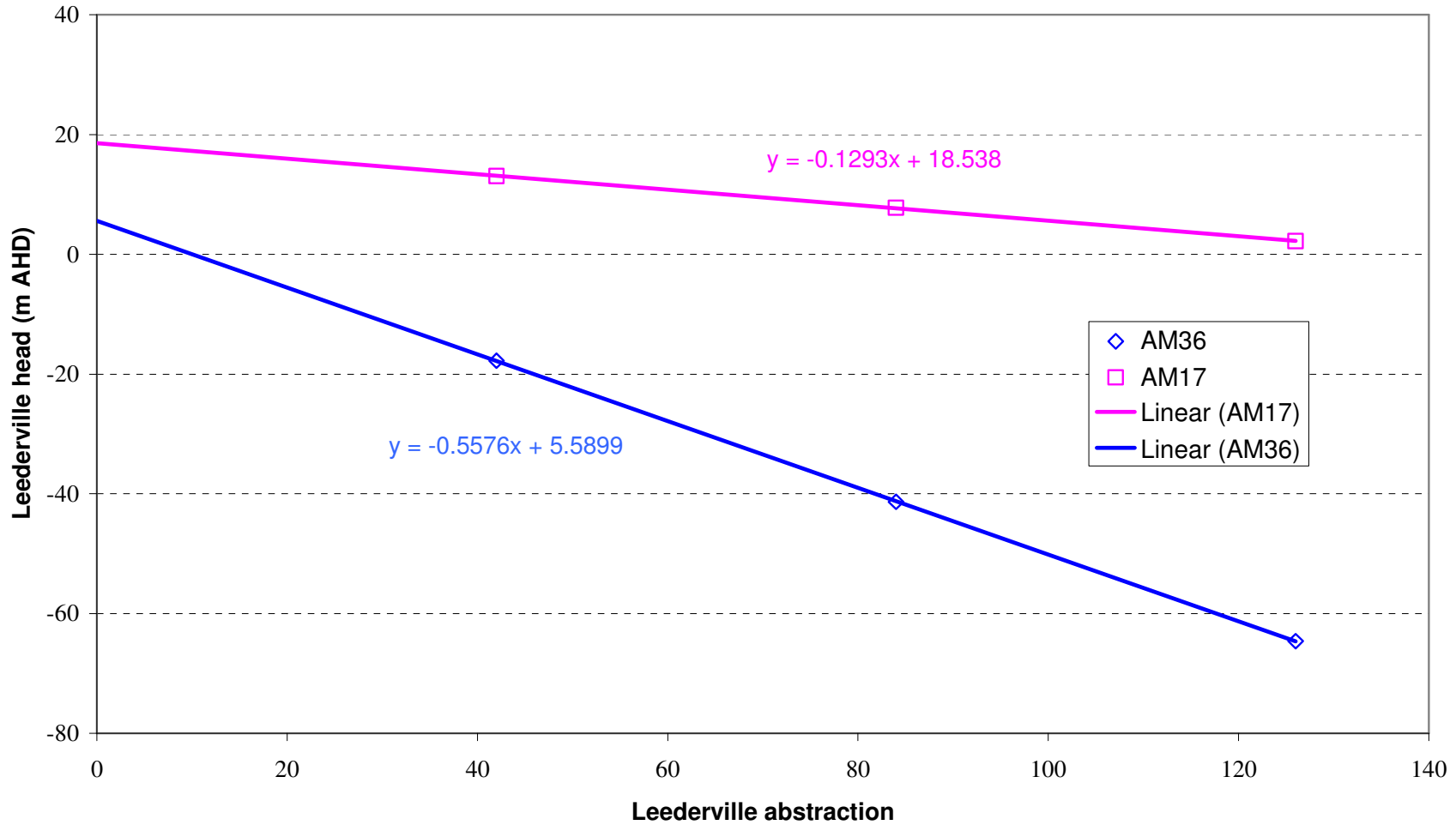


Figure 34 Leederville head response to increased abstraction in the Leederville aquifer

Superficial aquifer head response to increased Leederville abstraction

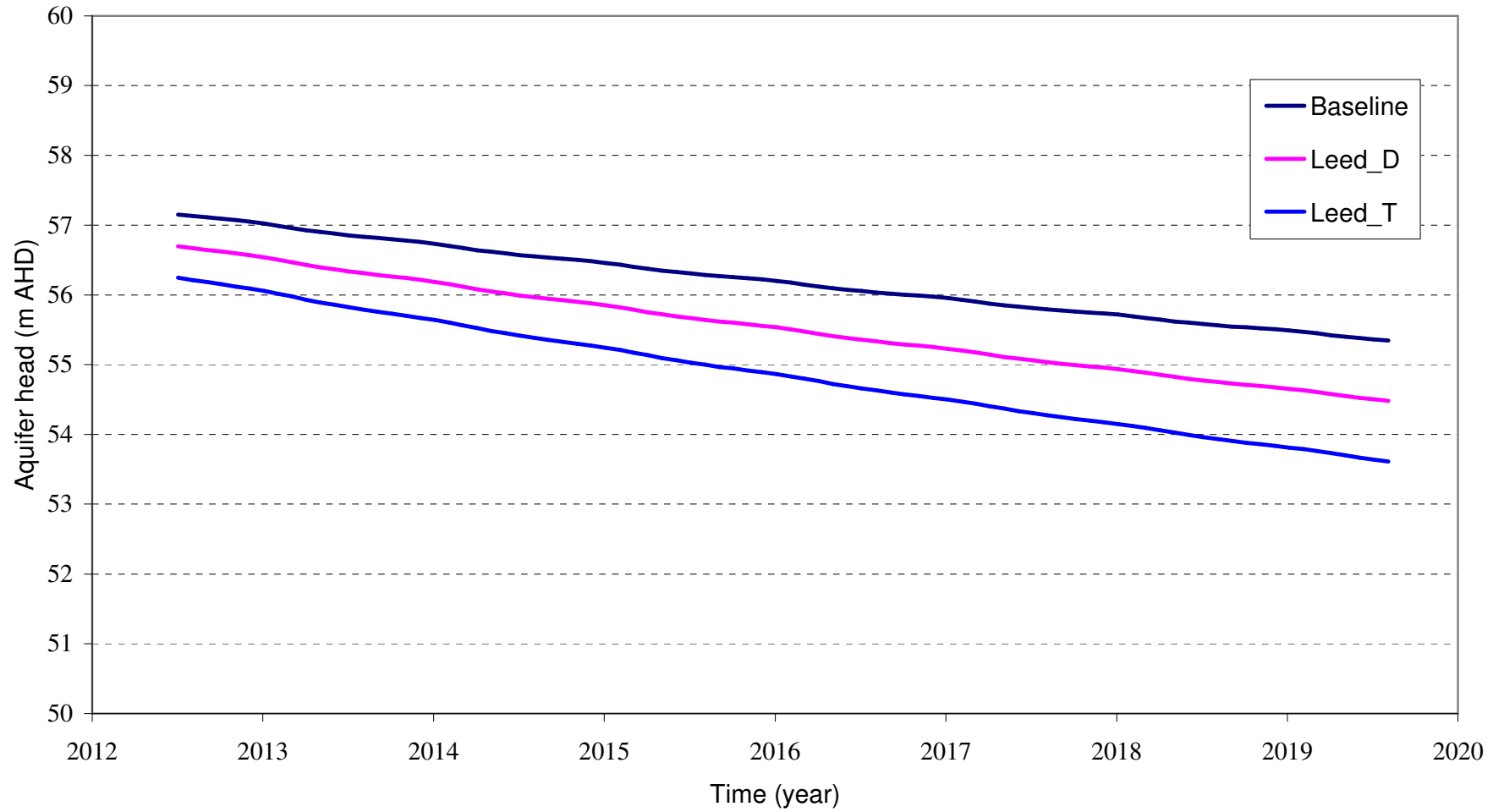


Figure 35 Superficial aquifer response to increased Leederville abstraction

**Impacts on the Superficial aquifer on the Gnangara Mound by 15 year continued pumping
in the Leederville aquifer**

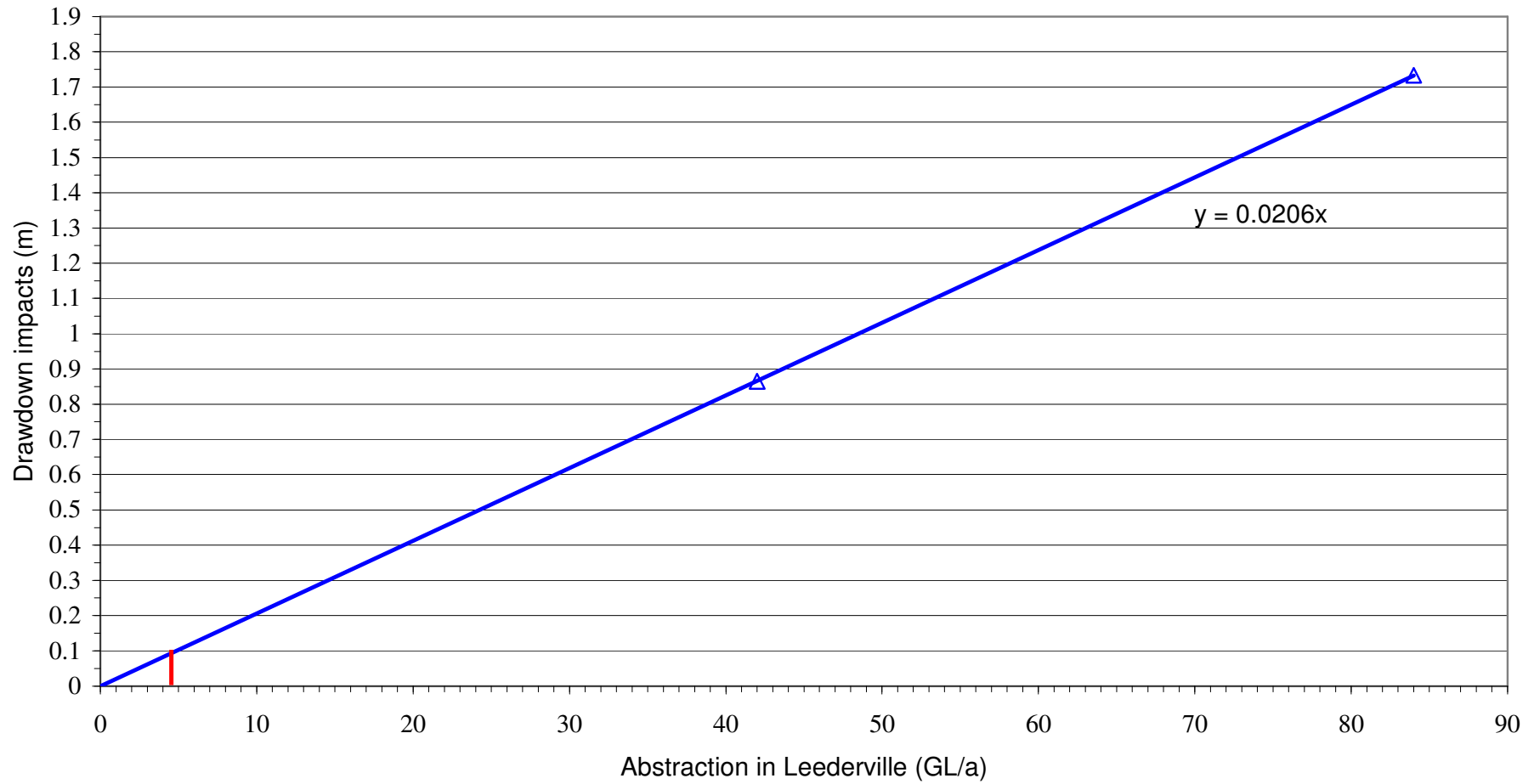


Figure 36 Impacts on the Superficial aquifer by Leederville abstraction

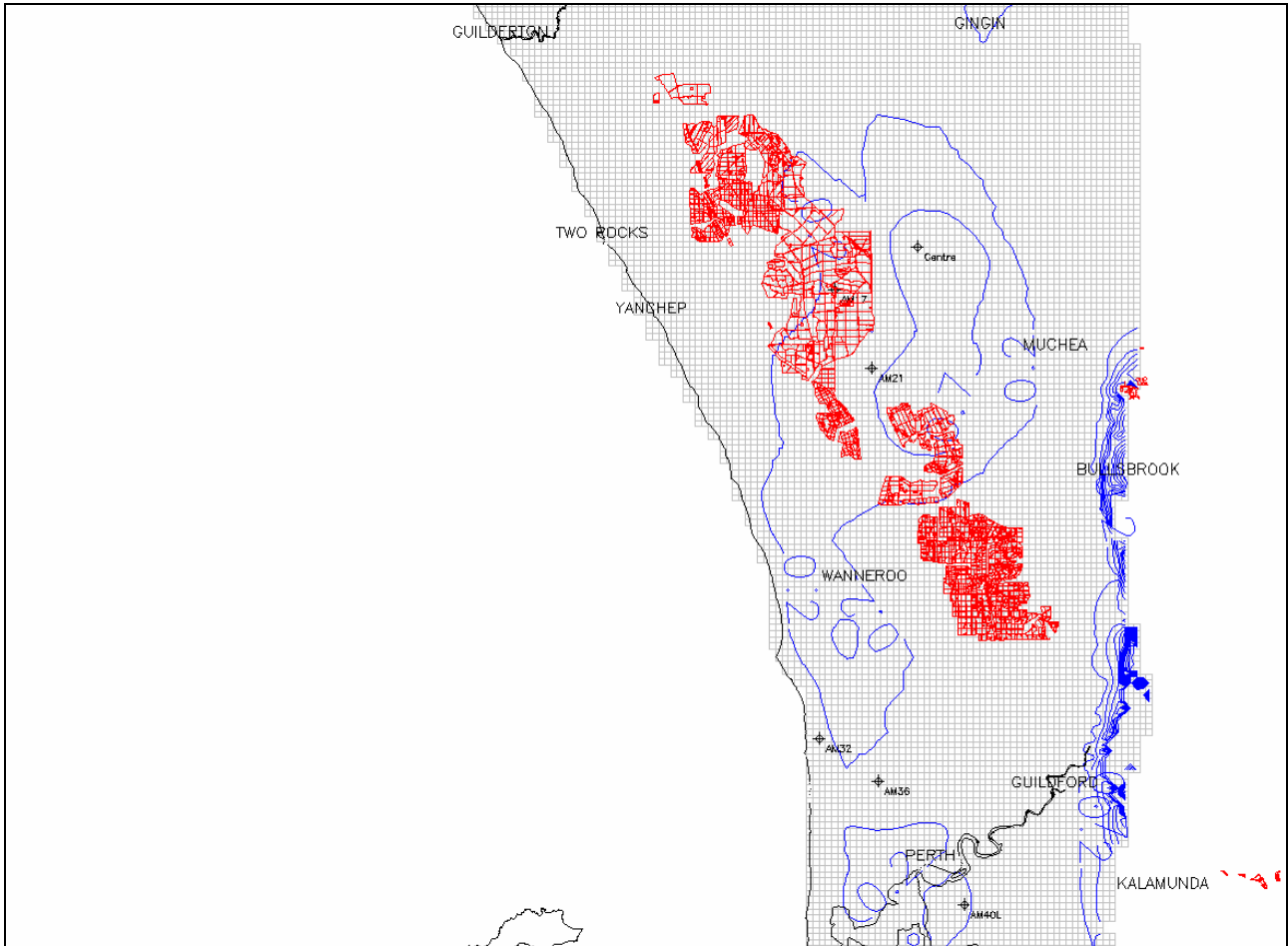


Figure 37 Water table drawdown impacts of abstracting 42 GL from Leederville for 15 years

water balance (difference for two scenarios)

(Unit in GL)

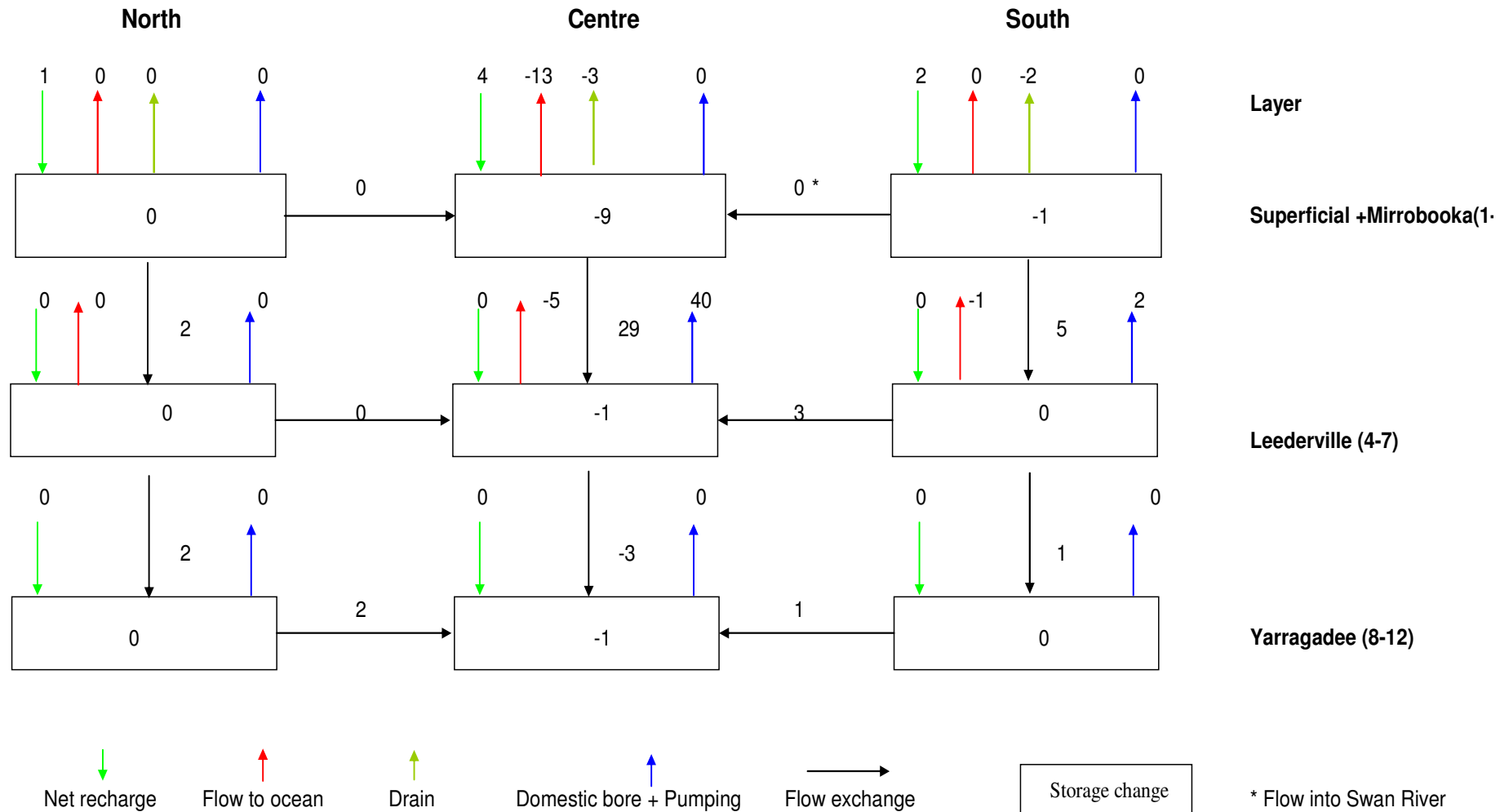


Figure 38 Trace of Leederville abstraction at rate 42 GL/a

Leederville storage recovery
 (after 10 yrs pumping @ 126 GL/a then reduce to 42 GL/a)

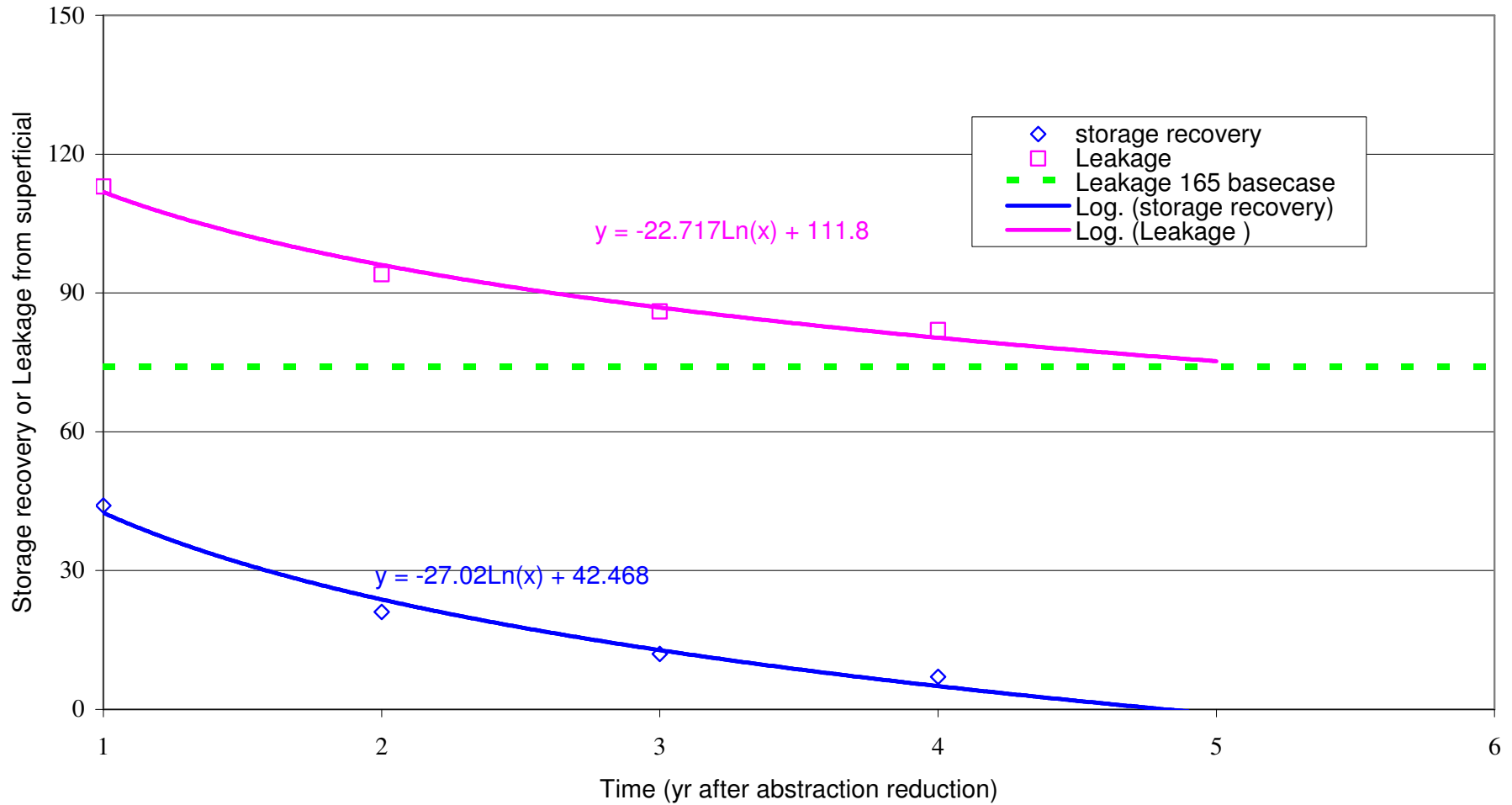


Figure 39 Leederville aquifer recovery

Leederville storage recovery
(after 10 yrs pumping of 126 GL/a then reduce to 42 GL/a in 165 basecase)

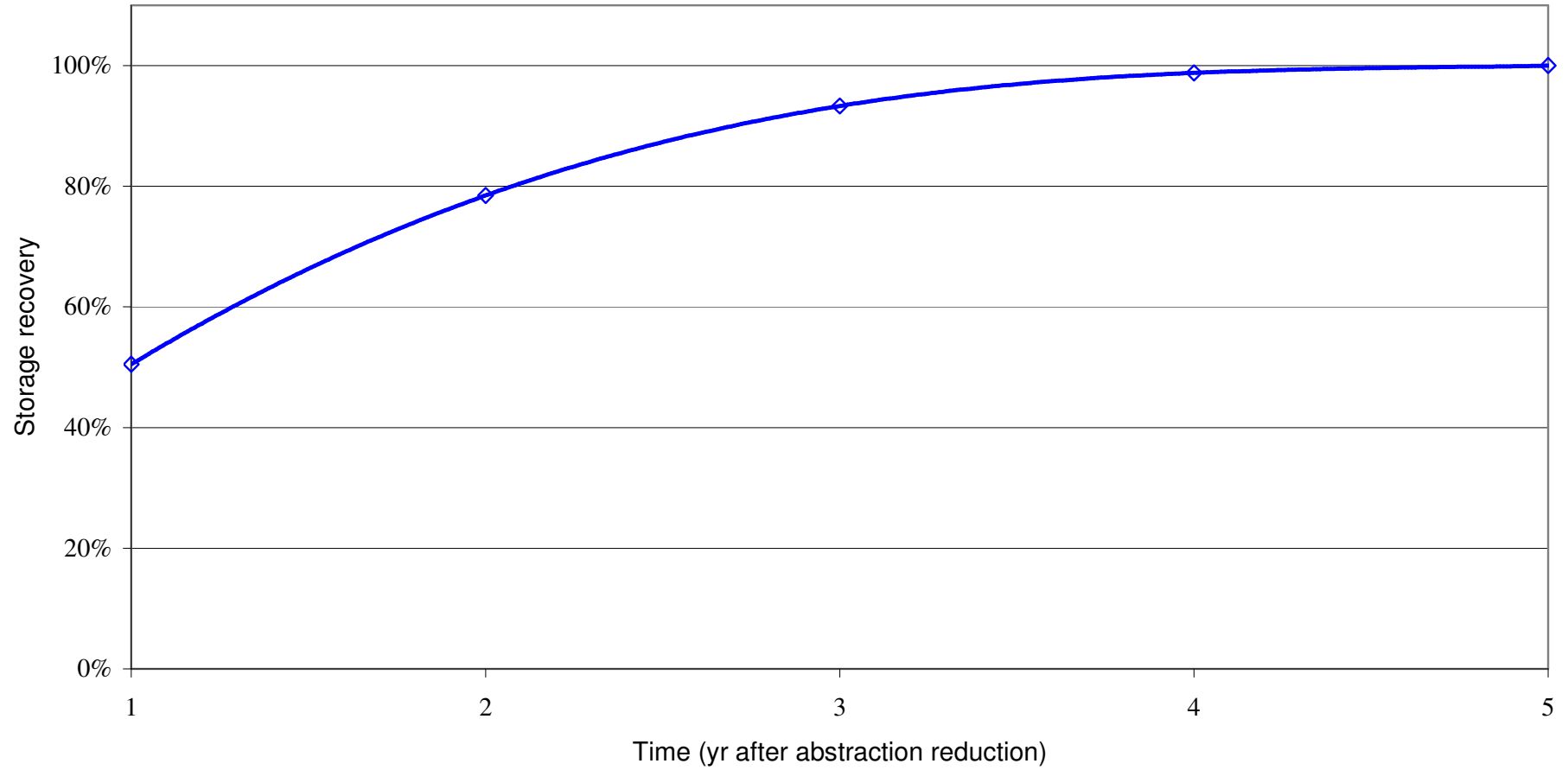


Figure 40 Percentage Leederville recovery vs time