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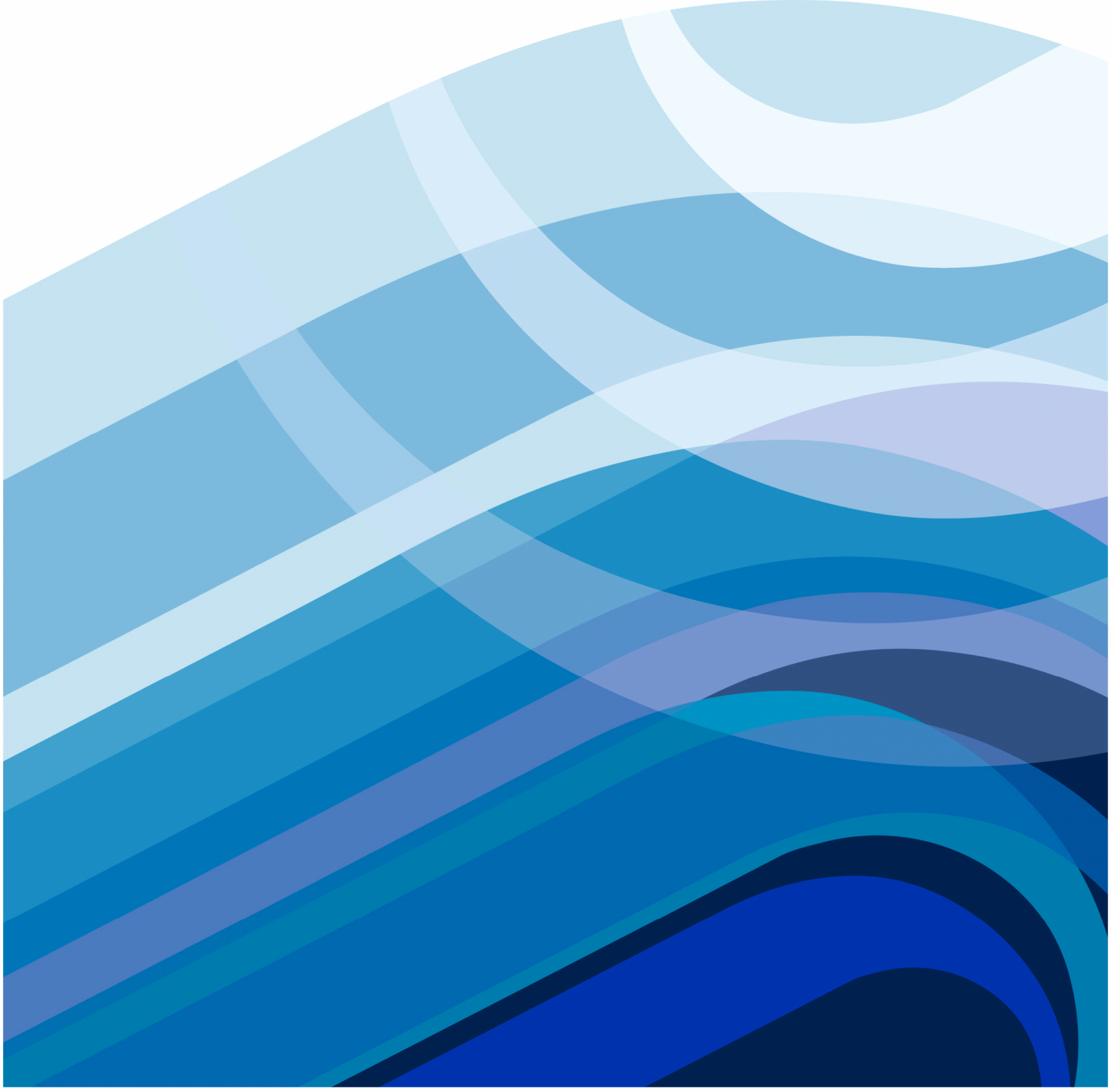
Modelling of Groundwater Levels on the Gnangara Mound



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Executive Summary

In recent years, groundwater levels on Gnangara Mound have declined in response to drying climate, increased abstraction for public and private water supply, maturation of pine plantations and changed fire regime of native woodlands. The continued drop of water levels on the Mound is threatening the ecological function in areas of lakes/wetlands and there are concerns about the sustainability of the Gnangara groundwater resources.

To provide a better understanding of how the groundwater system on the Gnangara Mound responds to the change in the climate regimes, land use and abstractions, a steady-state strip model was developed and simulations were undertaken for a wide range of scenarios. Modelling results show that:

- Water levels on the Gnangara mound vary significantly under different recharge (rainfall) regimes. The crest of the mound could drop up to 15 m under natural conditions (no stresses such as pumping and pine plantation) if the climate changes from a wet sequence (recharge =350 mm/a) to an extremely dry sequence (recharge =100 mm/a).

- The superficial aquifer responds slowly to the reduction in recharge. It takes about 50 years for the majority of the impacts to show up and takes even longer time to reach a new equilibrium. The estimated time scale for the superficial aquifer on Gnangara Mound is in order of 40-80 years.

- Under the climate regimes of the last few years (recharge = 150 mm/a) with a mature pine plantation (recharge =40 mm) and current abstraction rate (19 ML/d in the area covered by the strip model), the water level on Gnangara Mound will continue to fall. The steady state strip model predicts a further fall of about 10 m from current level at the crest of the Mound. Even under the climate regimes of last 30 years (recharge =200 mm/a), without removal of the pines and reduction in abstraction, water levels may continue fall a further 2 to 5 m.

- Under the drier climate of the last few years, the total cessation of abstraction from the superficial aquifer and a significant reduction in the confined abstraction alone will not be able to stop the falling water levels around the mound. Total removal of the pines is required to stabilise the water level.

- Conceptually, a MAR scheme with infiltration taking place upstream of abstraction can be used in the area with sufficient depth to the water table. However, the downstream impact of abstraction needs to be managed to ensure no adverse impacts occur, particularly along the linear wetlands. This can be done by either abstracting less than 100% of the injected volumes and/or via a local recharge scheme upstream of the wetlands. Further modelling work is required to assess which method is more cost effective.

Introduction

In recent years, groundwater levels on Gnangara Mound have declined in response to drying climate, increased abstraction for public and private water supply, maturation of pine plantations and changed fire regime of native woodlands. The continued drop of water levels on the Mound is threatening the ecological function in areas of lakes/wetlands and there are concerns about the sustainability of the Gnangara groundwater resources.

A regional groundwater model (PRAMS) has been developed to assist assessing the sustainable resource of Gnangara Mound (Barr et al. 2003, CyMod 2004, Davidson and Yu 2004, Silberstein et al. 2004, Xu et al. 2004). The PRAMS model is proving a robust tool to evaluate the impacts of various factors that contributed to the water level declines. Simulation results have also been used by the Corporation as the basis to support the application for annual abstraction allocation from regulators. Due to the complex nature of the model, simulations were typically carried out for periods up to maximum15-20 years.

Groundwater levels on Gnangara mound have continually evolved in dynamic manner to the stress (recharge/discharge) imposed on the aquifer systems. The propagation of the aquifer stresses through the system is related to the time scale of the aquifer, which is controlled by aquifer boundaries and physical properties. The time scale of an aquifer is given by:

$$t = \frac{L^2 S}{CT} \tag{1}$$

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 1-4 [PUWB used 3, in well function w(u), C=4, in others, e.g., Manga (1999), C=2]. For the Gnangara mound, S=0.2, T =1500 m2/d, L = 15~ 20 km (the distance from the boundary of Tamala limestone to the crest of the mounds). If C =2, the time scale of the superficial aquifer will be in order of 40-80 years, indicating the time required for the regional unconfined aquifer to come to a new equilibrium after a disturbance is of this order.

PRAMS modelling suggests that under the drier climate of the past 8 years, groundwater levels on Gnangara Mound will continue to decline.

Some questions include:

- What is the likely magnitude and rate of groundwater decline under a range of climate (rainfall) scenarios?
- What are the indicative impacts of the pine plantation, private pumping from the superficial aquifer and Corporation pumping from the superficial and confined aquifers?
- What might be the impact of managed aquifer recharge on groundwater levels?

This study attempts to give some indicative answers to these questions using a simple steady-state model. Impacts on the Mound of various recharge regimes (including managed aquifer recharge (MAR)), changes in land use and abstractions are examined. A transient simulation was also undertaken to verify the time scale of the superficial aquifer.

Model Development

A telescopic model was established based on the PRAMS 3.0 model for a 5 km strip across the Gnangara mound as shown in Figure 1. The strip model is bounded by the coast in the west and Ellen Brook in the east. The grid size and aquifer geometry and properties for the strip model remain the same as for PRAMS 3.0. The strip model consists of 5 layers corresponding to the layer definition in PRAMS 3.0. Layers 6-12 of PRAMS 3.0 were made inactive in order to simplify the strip model. Layer 5 of the strip model is considered as a fixed head boundary with the confined head set to the simulated heads in January 2003 or otherwise stated. Boundaries for the northern and southern end were considered as non-flow boundaries in all layers. In layer one, the environmental heads along the coast were set to zero. The Drain package of MODFLOW is used to simulate the Ellen Brook. Abstraction is simulated using the Well package. For private abstraction, the abstraction rates for 2003 were used (telescopic pumping rate for January 2003 adjusted by seasonal factor (0.5 to get the annual averaged daily rate). The annual averaged daily pumping rate for private bores is about 15 ML/d (~ 5GL/a) with distribution focussed around Coogee Swamp, (Figure 2). Public water supply bores P80-P120 and YB4 were also included in the strip model. Annual abstraction for bores P80-P120 is about 1 GL/a, which is slightly higher than the averaged annual abstraction from these bores in the past few years, and for YB4 about 0.5 GL/a.

Unlike PRAMS 3.0 where the groundwater recharge is determined by the Vertical Flux Model (VFM), the recharge for the strip model is specified as input and is considered as part of experimental design in the scenario simulation. As an indication as to what the recharge rate may be expected under different land use and climate regimes on the Gnangara mound, Figure 3 shows that the recharge estimates produced by PRAMS 3.0 averaged over the area used by Department of Environment (DoE) for calculation of storage depletion on the Gnangara Mound. Under the climate regime of the past few years, the recharge under native woodlands will be in order of 150 mm/a. Under the climate regime for 1985-1996, the recharge under native woodlands will be in order of 190 mm/a. For pines, averaged recharge is about 40 mm/a for the period 1985-2004 with recharge significantly reduced in recent years due to maturity of the pines.

To enhance model stability, a maximum evapotranspiration (EVT) of 2 mm/d with extinction depth of 2 m was used. Note that the depth to the water table in most of the model domain is greater that 10 m and therefore most of the area affected by this EVT is in the eastern part of the model where the low conductivity of Guildford formation is present.

Groundwater mainly flows from the top of the mound to the west discharging into the ocean. A small portion of groundwater flows toward the east discharging into Ellen Brook.

Steady state simulations were undertaken for a wide range of scenarios. Modelling results are presented in this report for a cross section just north of monitoring bore PM6 (Figure 1).

Model Calibration and Verification

As discussed earlier, the objective of the study is to produce some indicative results for steady-state water levels around the Gnangara mound under different recharge regimes. To ensure that the aquifer parameters used in the strip model are consistent with those used in the PRAMS 3.0, no recalibration was undertaken for the strip model. Instead a simple verification was carried out to gain confidence in the model. Figure 4 shows that the comparison of actual water levels measured in 1980 across the section and the simulation results under a condition similar to the actual environment (uniform recharge of 200 mm/a, no pines, no abstraction and confined heads roughly 10 m higher than current levels). The result demonstrates that the simulated heads are in good agreement with the observed, indicating that the parameters used in the strip model are consistent with the conceptual hydrogeology of the Gnangara mound.

Mound Levels vs Recharge

Simulations were undertaken for a number of recharge regimes ranging from 100 mm/a to 350 mm/a. For these model scenarios it is assumed that there were no pines and no pumping from the superficial aquifer, and the confined heads are around 1980 levels (obtained by adding 10 m to the simulated 2003 levels). The objective of this modelling exercise is to assess how the Mound responds to changes in recharge under no other stress conditions (no pine, no superficial pumping and relatively smaller confined pumping).

The simulated heads under various recharge regimes are shown in Figure 5. Results for locations at the top of the mound, PM6 and the linear wetlands are plotted in Figure 6. Simulation results as shown in Figure 5 and Figure 6 clearly demonstrate that the water levels around the Mound vary dramatically in response to a change in rainfall and hence recharge. At the top of the mound, the water level changes from 75 m AHD to 60 m AHD when recharge is reduced from 350 mm/a to 100 mm/a. Similarly, the model predicts a drop of 14 m from 60 m AHD to 46 mAHD at PM6 when recharge decreases from 350 mm/a to 100 mm/a. However, the change at the linear wetlands is relatively small, a drop of only about 4 m for the same change in recharge. This is due to the fact that the groundwater levels at the linear wetlands are, to a great extent, controlled by the very high transmissivity of Tamala limestone west of the linear wetlands. Figure 6 also shows that the effects of recharge on the water table of the Mound are greater when recharge is at the low end compared with the impact under high recharge regimes.

Effect of Pines, Superficial Pumping and Head Drop in Confined Aquifer

A set of modelling scenarios were developed to examine the impacts of anthropogenic activity such as pumping and pine plantations. The baseline used for the comparison is chosen to be close to the pre 1980 conditions: recharge =200 mm/a, no pine plantations, no pumping from superficial aquifer and confined heads are about 10 m higher than current levels. Simulation was then undertaken by changing one parameter at a time, for example, when examining the effect of pines, the recharge in the area with pines is reduced to 40 mm/a. The steady state water levels for the scenarios with pine plantations, abstraction from superficial aquifer, and increased confined pumping are shown in Figure 7. For comparison, the water level for the current recharge regime (150 mm/a) is also included in the figure. The relative impacts compared with the baseline are shown in Figure 8.

Simulation results demonstrate that reduction in recharge across the Mound has large impacts over a large area whilst the other effects are more localised. Pines have the largest impacts in magnitude but the maximum impacts are centred around the pine plantation area. Effects of pumping from the superficial aquifer are centred around the east of linear wetlands reflecting the heavy horticulture use in the area. The impact of the drop in the confined head is also consistent with the conceptual hydrogeology (Davidson and Yu 2004). Between the coast and linear wetland, the existence of the Kardinya Shale aquiclude prevents direct propagation from the confined Leederville aquifer to the superficial aquifer and hence less impact is expected. To the east of the linear wetlands, the Kardinya Shale is absent but the less permeable Pinjar member of the Leederville aquifer is present with a reasonable thickness which attenuates the propagation of impacts. Large impacts at the centre and to the east reflect strong hydraulic connection between the superficial aquifer and Leederville aquifer in these areas due to the absence of the Kardinya Shale and the Pinjar member and that the more transmissive Wanneroo member of the Leederville aquifer subcrops to the superficial aquifer in this area.

The impacts of reduced recharge, the pines and abstraction from the superficial and confined aquifers on the linear wetlands, PM6 and the top of mound are summarised in Table 1. It should be noted that these results were obtained from steady-state simulations and may not necessarily reflect the actual impacts because the system has yet (and may never) reach the predicted steady state).

Scenarios	Linear wetlands (m)	PM6 (m)	Top of Mound (m)
Recharge reduction from 200 mm/a to 150 mm/a	1.0	3.3	3.8
Pine plantation	1.2	2.7	0.7
Superficial pumping	1.4	1.2	0.4
Confined head drop	0.3	1.2	2.5

Table 1 Impacts of reduced recharge, pines and abstraction on water levels

Mound Levels under Current Regimes

A simulation was undertaken to assess the steady state water level under current regimes on the Gnangara mound [current recharge = 150 mm/a, with pines (recharge = 40 mm/a), current pumping from the superficial aquifers (19 ML/a in the area of strip model) and current confined heads (2003)]. The results are shown in Figure 9. If the current conditions around the Mound prevail, the water level will continue to fall, which is consistent with the previous model results using PRAMS 3.0. The steady state model predicts a further fall of about 10 m from the current observed water table at the crest of the mound before a new equilibrium is reached. At site PM6, the steady state water table under the current regimes would be about 42 m AHD compared with the current level of about 52 m AHD.

Even under the climate regime of the last 30 years (estimated recharge =200 mm/a), without removal of the pines and reduction in abstraction or other measures such as increased burning of native vegetation, water levels may continue to fall by a further 2 to 5 m.

Scenarios to remove the pines, cease all abstraction from the superficial aquifer and reduce confined abstraction to 1980 levels were investigated. Modelling results are presented in Figure 10. As expected, the model predicts a recovery of water levels for all three scenarios, but the extent of the recovery is limited. Total cessation of abstraction from the superficial aquifer and a significant reduction in the confined abstraction alone will not be able to stop falling water levels. Even under the extreme case (removal of pines, total cessation of abstraction from the superficial aquifer and reduction of confined pumping to 1980 levels), the water levels will not be able to recover to 1980's levels. However, the model predicts that the decline in water level can be arrested under this condition and water levels will stabilise around current levels.

Managed Aquifer Recharge (MAR)

Simulations were undertaken to evaluate the potential use of managed aquifer recharge (MAR) around the Mound for the benefit of public water supply or horticulture use. The baseline used for comparison purpose is the case with recharge = 200 mm/a, no pines and a current abstraction rate from the superficial aquifer (19 ML/a) and current confined heads (2003). Infiltration using a trench is considered and the width of the trench was assumed to be 1 m. In order to model the mounding head at the centre of the trench, the strip model grids were refined to have a 1 metre column for the infiltration trench. Recharge rate to the column is then adjusted according to the infiltration rate.

One option examined in this study is to infiltrate water (possibly sourced from reverse-osmosis treated waste water) to the east of the Pinjar borefield and withdraw it again from the existing Pinjar borefield. Figure 11 shows the water table response under different infiltration rates and abstraction scenarios. The impact on the water table compared with the baseline is given in Figure 12. For a recharge rate of 5 m/d (~2GL/a per km), the mounding head under the trench will be about 10 m if the water is not taken out and will reduce to about 7 m if water is taken out at the Pinjar borefield. For an infiltration rate of 2 m/d (0.7 GL/a per km), the corresponding mounding heads will reduce to 6 m and 3 m, respectively. The depth to the watertable in the area is in the range of 10-15 m. An infiltration rate greater than 5 m/d is likely to cause some flooding in the area.

Figure 12 also shows the potential for adverse impacts downstream of the abstraction borefield. In this case, the model predicts that use of the Pinjar borefield to abstract 100% of the volume of the injected water will cause a net 0.3 to 1.0 m drawdown at the Linear wetlands. This impact could be managed perhaps via a local recharge scheme.

The second option examined is to infiltrate wastewater to the west of the Pinjar borefield for horticulture use after the removal of pines (Figure 13). An infiltration rate of 5 m/d is assumed and abstraction for horticulture use downstream of the infiltration trench is varied to evaluate the impacts on the Linear wetlands. Figure 14 shows the water table responses and Figure 15 illustrates the corresponding impacts compared with the baseline. The model predicts that the mounding head is about 12 m at the centre of the infiltration trench and the water table would rise by 4 m along the Linear wetland if no abstraction takes place. If 100% of the infiltrated water is taken out for horticulture, there will be an adverse impact of 0.3 m drawdown on the Linear wetlands. If only 70% of infiltrated water is taken out, there will be about a 0.5 m environmental benefit to the wetlands.

The effects of removing the abstraction around the Linear wetlands or shifting the horticulture inland were also examined. Abstraction in a strip 2.5 km wide (~ 2 GL/a) was shifted east as shown in Figure 16. Figure 17 shows the impacts on the water tables. Simulation results indicate that cessation of abstraction for horticulture use around the wetlands will have an environmental benefit of 0.7 m. However, shifting horticulture inland alone has only a very small environmental benefit (~0.15 m). Also, the drawdown impacts from abstraction inland are much greater than those caused by abstraction near the wetlands. This is due to the difference in the hydraulic conductivity in the two areas with the hydraulic conductivity of Tamala Limestone around wetlands much higher than the inland Bassendean Sand.

The effects of MAR and removal of private abstraction around the wetlands were also examined. Figure 19 shows the trade off between the environmental benefits and abstraction for horticulture use as a percentage of infiltrated water under two modelling scenarios. Results indicate that to achieve a 1 m rise in water level around the Linear wetlands, only half of the recharge (~10 GL/a) can be recovered for horticulture use with the current abstraction around the Linear wetlands unchanged. The benefit for horticulture is about 7 GL/a (5 GL/a for the new horticulture and 2 GL/a for the horticulture around the wetlands). In the case of the removal of horticulture around the wetland, the corresponding recovery rate will be around 75%, namely 7.5 GL/a available for horticulture use. The water benefit of shifting the horticulture inland is only about 0.5 GL/a. It should be noted that this result may be affected by the spatial distribution of current abstraction along the wetlands used in the model. Further modelling work is required to determine whether the additional water benefit can be achieved in a broader scheme.

The third option examined in this work is the same as the second option but with 70% recovery for horticulture and increased abstraction at the Pinjar borefield. The water table responses and impacts compared with the baseline are shown in Figure 20 and Figure 21. These demonstrate that the potential for increased abstraction at the Pinjar borefield is limited due to downstream impacts on the linear wetlands.

It is assumed that the soils above the current water level in the area for MAR consist of Spearwood sand rather than Tamala limestone. As such, results are not applicable in the area where limestone is present.

Drawdown Impacts of Abstracting 70% Net Recharge from Different Landscape positions on Gnangara Mound

Simulations were undertaken to evaluate the impacts of abstracting 70% of net recharge from different locations of the Mound. Figure 22 shows the Mound with flow toward to the west divided into four zones with similar areas. A distributed abstraction equal to about 70% of the net recharge is applied to each zone and groundwater modelling was undertaken to assess the drawdown impacts. The baseline used for comparison purpose is the case with recharge = 200 mm/a, no pines and non abstraction rate from the superficial aquifer and current confined heads (2003).

Figure 23 shows the modelled impacts of the distributed abstraction of 70% net recharge from different landscapes on the watertable on the Gnangara Mound. This demonstrates that the drawdown impacts for different cases are significantly different. The impact of abstracting from the top of the Mound (zone 4) is the largest and the impact of abstracting from the discharge area (zone 1) is almost negligible.

These results indicate that to minimise the drawdown impact on Gnangara Mound watertable, the best place to abstract the groundwater will be along the coast where the groundwater discharges into the ocean provided that the risk of seawater intrusion is properly managed. To maximise the impacts of MAR on the watertable of the Mound, the most appropriate location would be near the central area or top of the Mound. However, development of a borefield for groundwater abstraction or injection needs to consider broader objectives (e.g. water quality) and other physical constraints (e.g., access to land, environmental impacts etc), which may exclude these ‘optimal’ locations.

Transient Simulation

A transient model was developed to evaluate the time required for the superficial aquifer to come to a new equilibrium after a significant reduction in recharge. In this model run, it is assumed that the mound is originally at a steady-state condition (R=200 mm/a) and is now shifted to a new recharge regime (R=150 mm/a). To simplify the data input, it is assumed that there are no pines and no abstraction from the superficial aquifer and that confined heads are around 2003 levels. A steady state simulation was first undertaken to obtain the initial heads for the transient modelling.

Figure 24 shows the transient heads for PM6 and at the top of the Mound. Modelling results clearly demonstrate one of the major features of the unconfined aquifer system: that the water levels respond to the reduction in recharge slowly and the time required to reach a new equilibrium is quite long. Figure 25 shows the percentage of full impacts versus time. Results show that it takes about 40, 60, 80, and 150 years to have 80%, 90%, 95% and 99% of the total impacts respectively. This result is consistent with the theoretical estimate of the time scale using equation (1) for the superficial aquifer on the Gnangara mound, which is in the order of 40-80 years.

Conclusions

Simulation results using a simple strip model show that:

- Water levels on the Gnangara mound vary significantly under different recharge (rainfall) regimes. The crest of the mound could drop up to 15 m under natural conditions (no stresses such as pumping and pine plantation) if the climate changes from a wet sequence (recharge =350 mm/a) to an extremely dry sequence (recharge =100 mm/a).

- The superficial aquifer responds slowly to the reduction in recharge. It takes about 50 years for the majority of the impacts to show up and takes even longer time to reach a new equilibrium. The estimated time scale for the superficial aquifer on Gnangara Mound is in order of 40-80 years.

- Under the climate regimes of the last few years (recharge = 150 mm/a) with a mature pine plantation (recharge =40 mm) and current abstraction rate (19 ML/d), the water level on Gnangara Mound will continue to fall. The steady state strip model predicts a further fall of about 10 m from current level at the crest of the Mound. Even under the climate regimes of last 30 years (recharge =200 mm/a), without removal of the pines and reduction in abstraction, water levels may continue fall a further 2 to 5 m.

- Under a continuation of the drier climate of the last few years, the total cessation of abstraction from the superficial aquifer and a significant reduction in the confined abstraction alone will not be able to stop the falling water levels around the mound. Total removal of the pines is required to stabilise the water level.

- Conceptually, a MAR scheme with infiltration taking place upstream of abstraction can be used in the area with sufficient depth to the water table. However, the downstream impact of abstraction needs to be managed to ensure no adverse impacts occur, particularly along the Linear wetlands. This can be done by either abstracting less than 100% of the injected volumes and/or via a local recharge scheme upstream of the wetlands. Further modelling work is required to assess which method is more cost effective.

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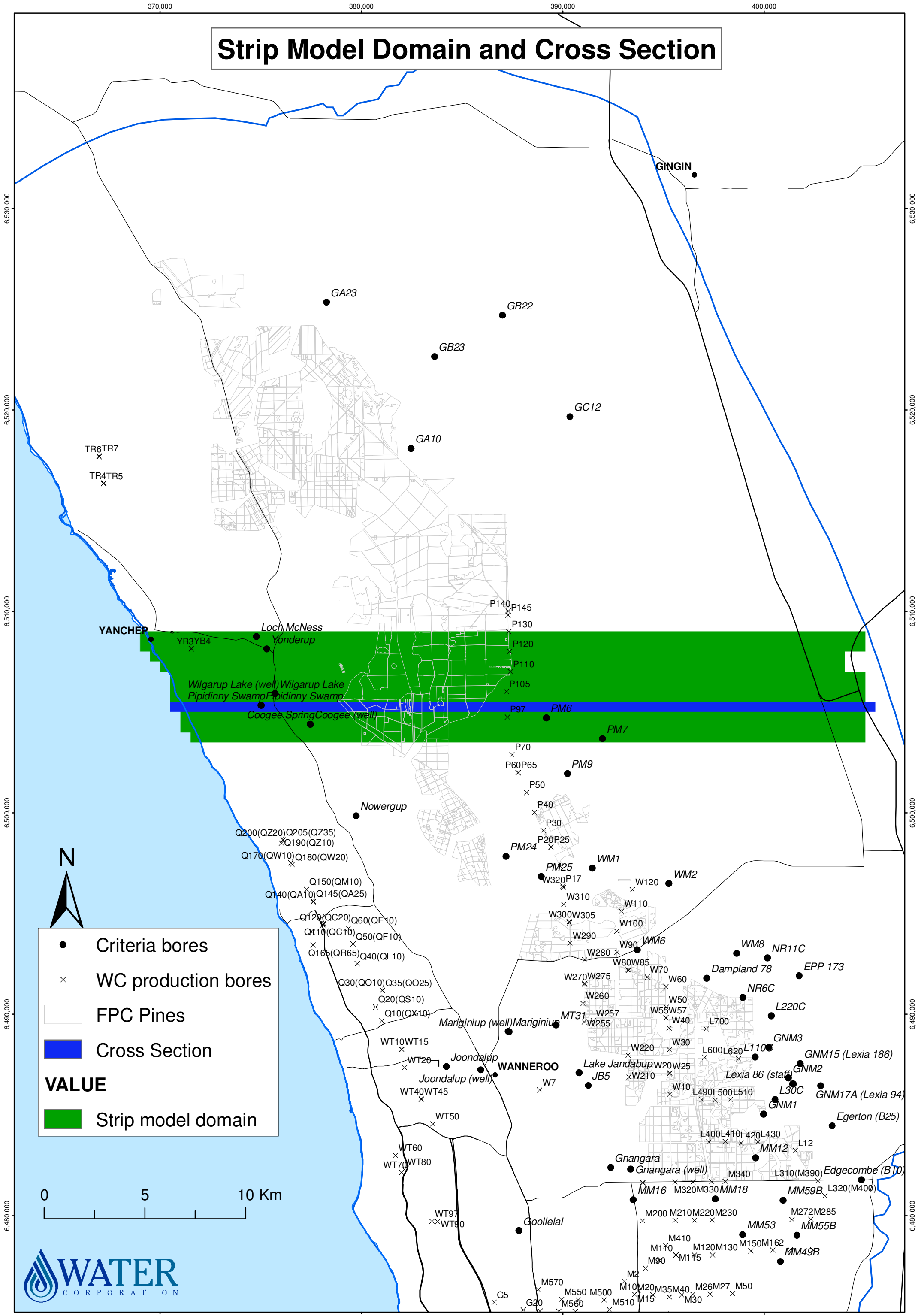

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Figure 1 Strip model domain

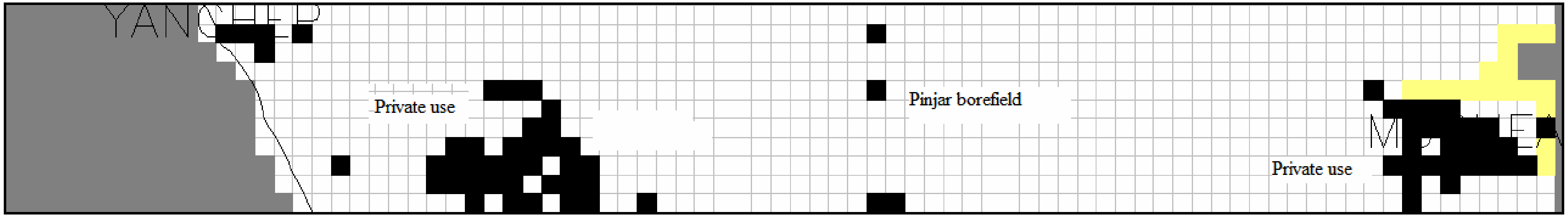

Figure 2 Spatial distribution of pumping

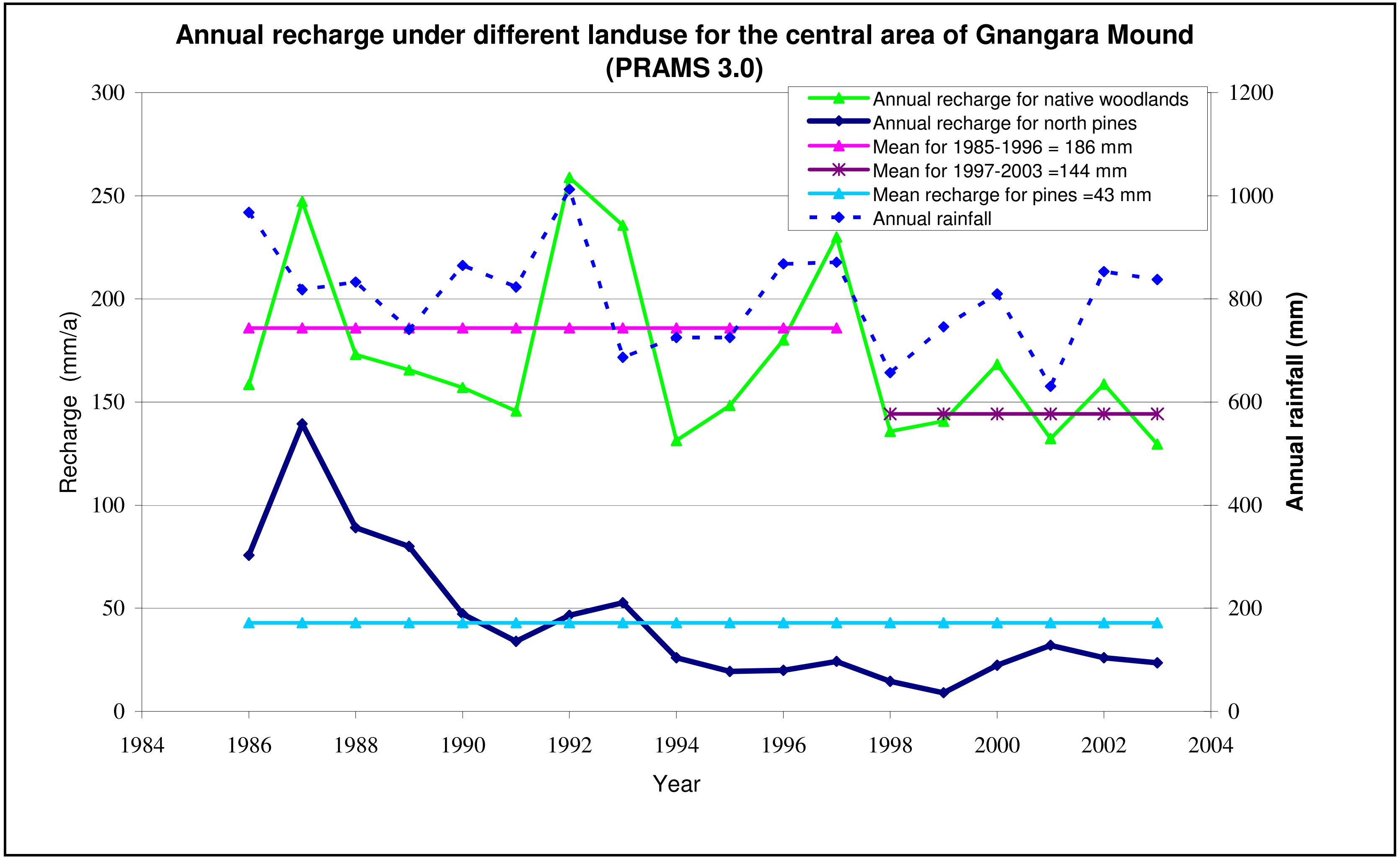

Figure 3 Recharge estimated by PRAMS for the Mound

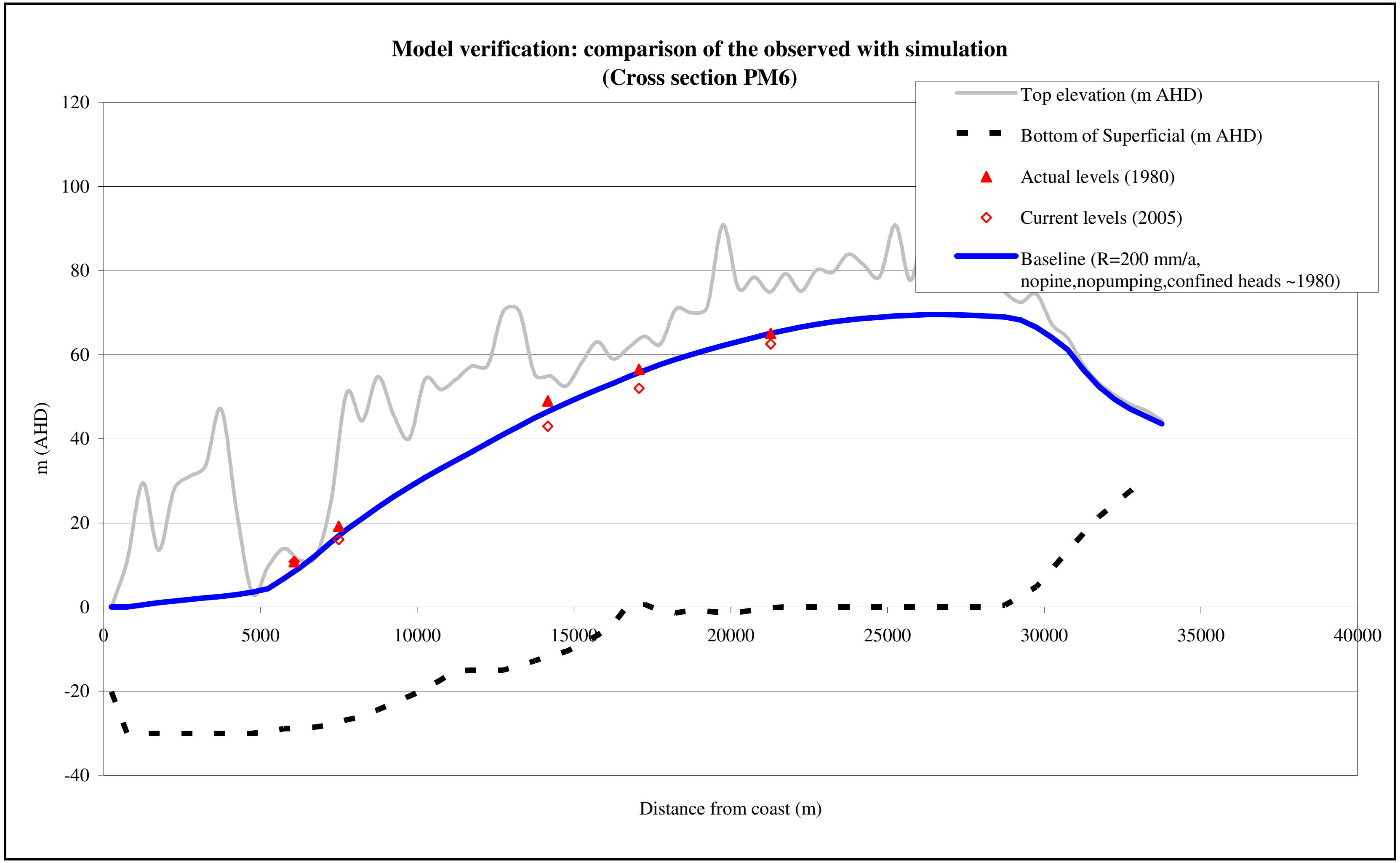

Figure 4 Model verification

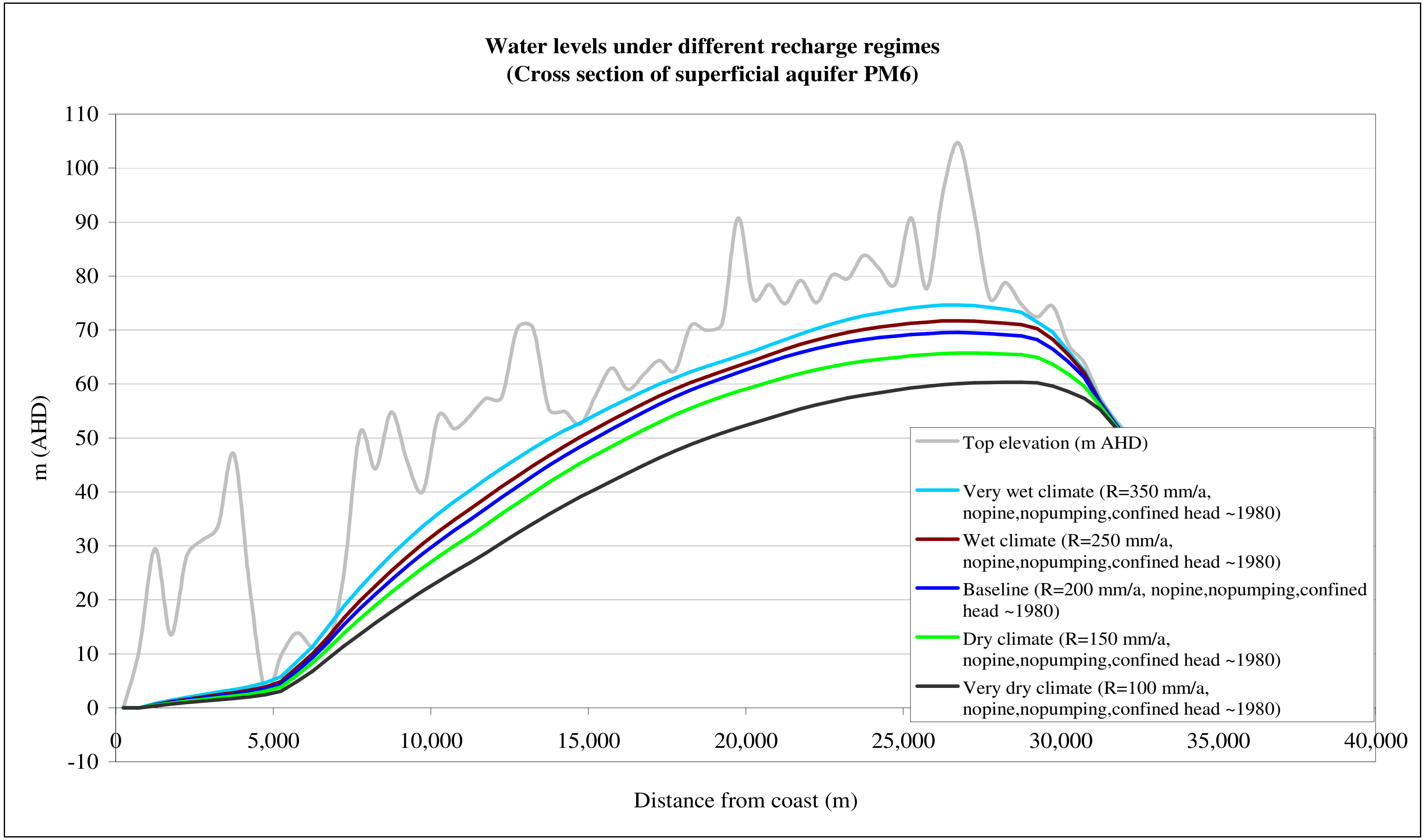

Figure 5 Mound levels versus recharge

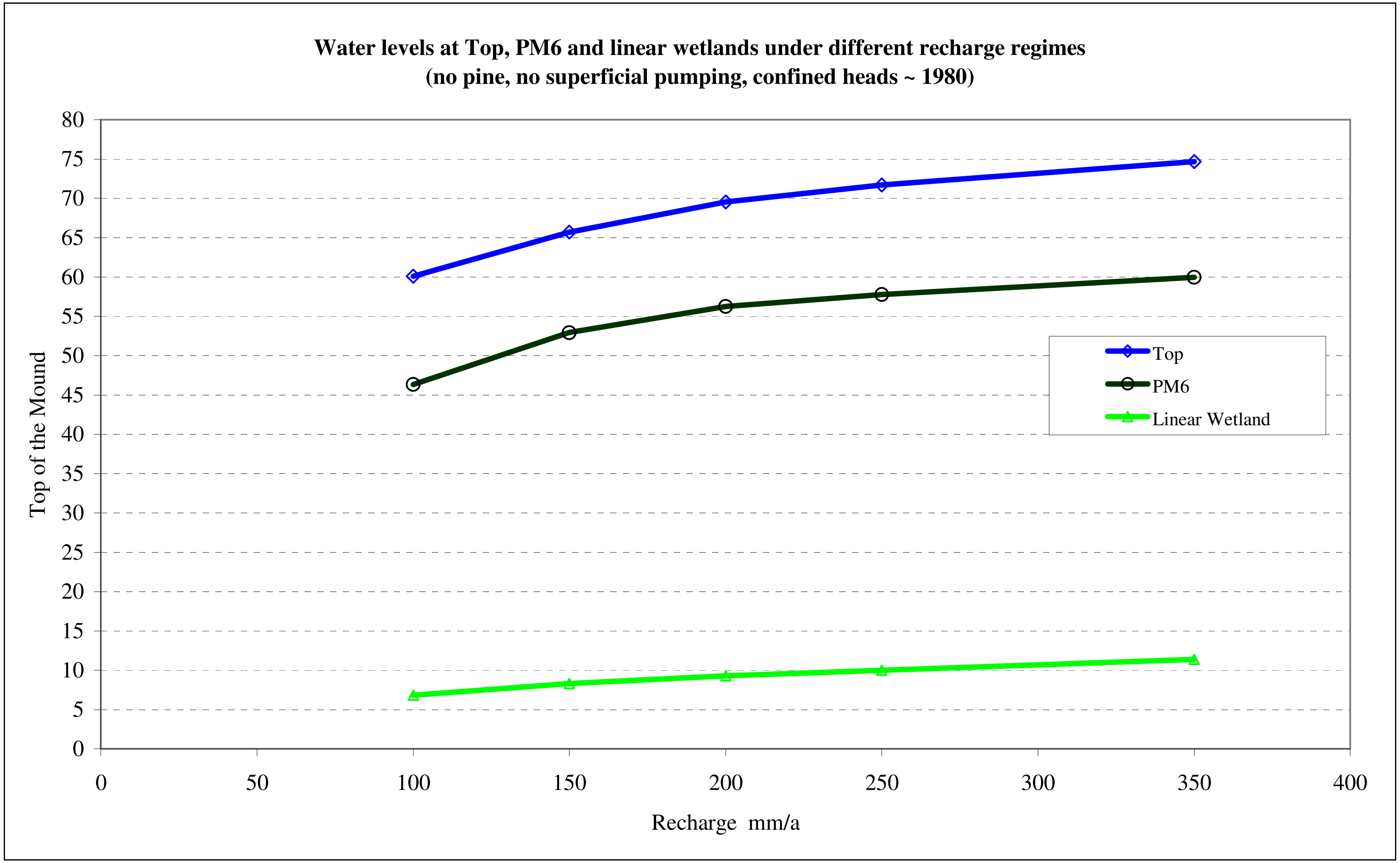

Figure 6 Water levels vs Recharge at several points

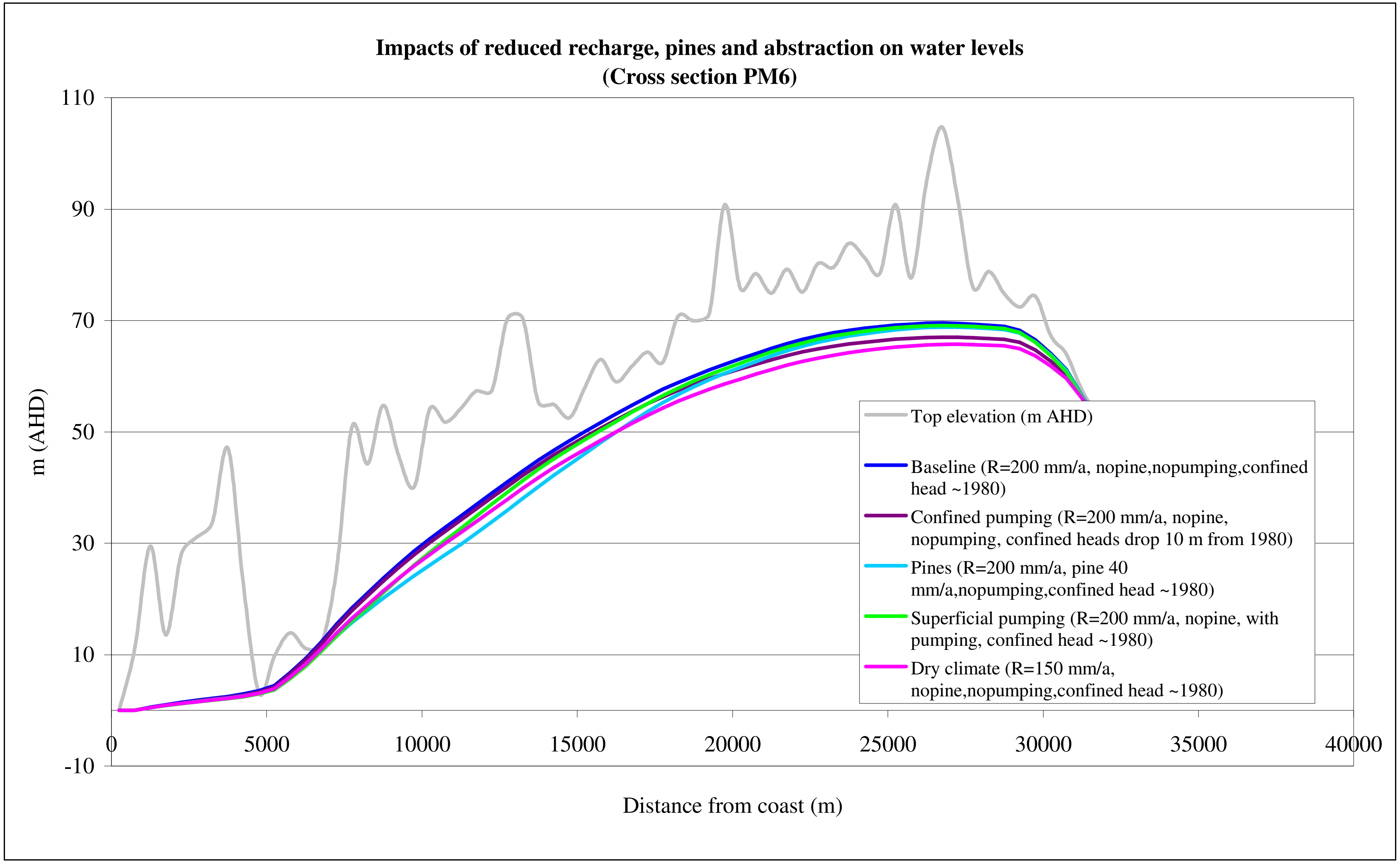

Figure 7 Water table response to recharge, pines and abstraction

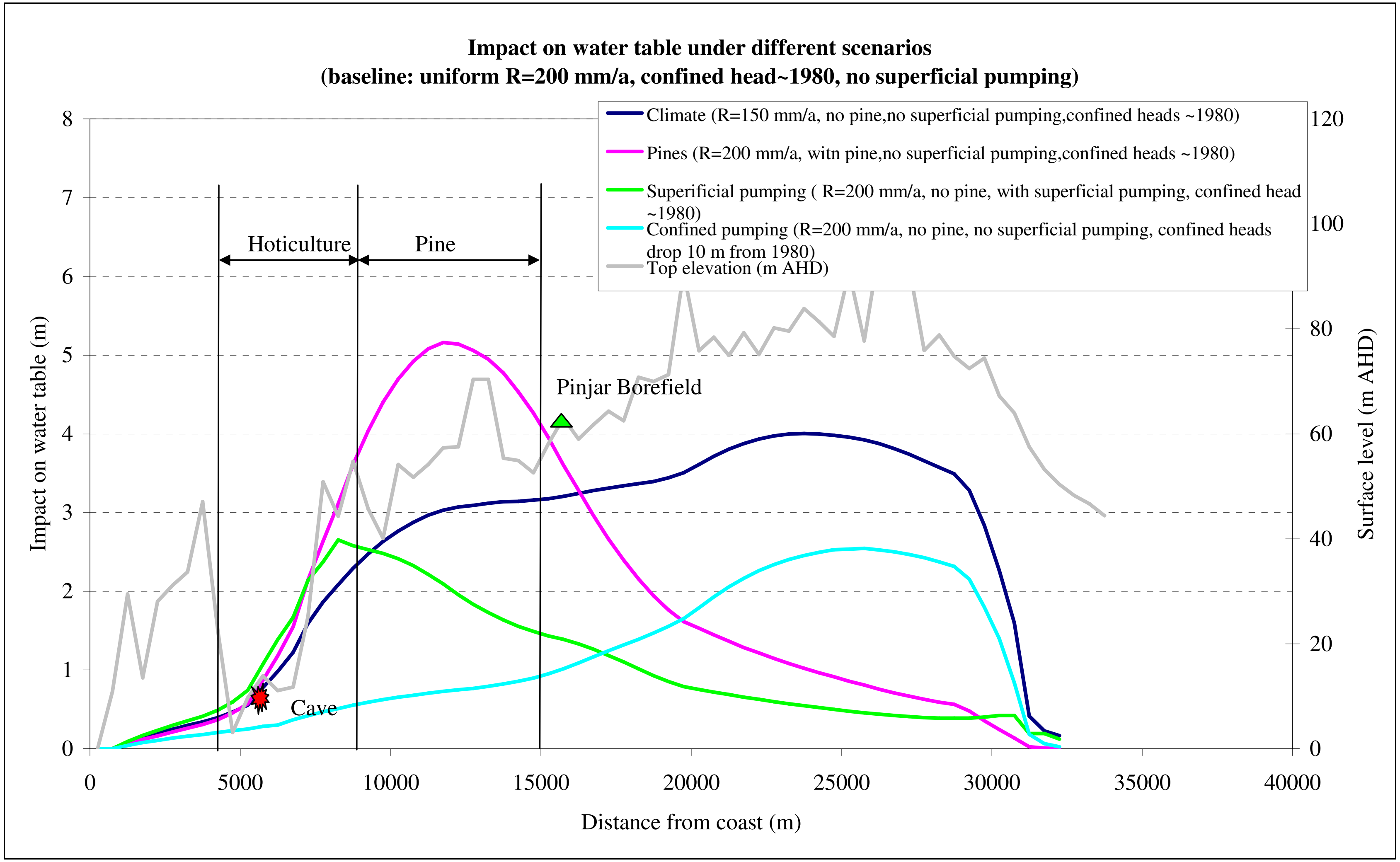

Figure 8 Impacts on water table under reduced recharge, pines and abstraction

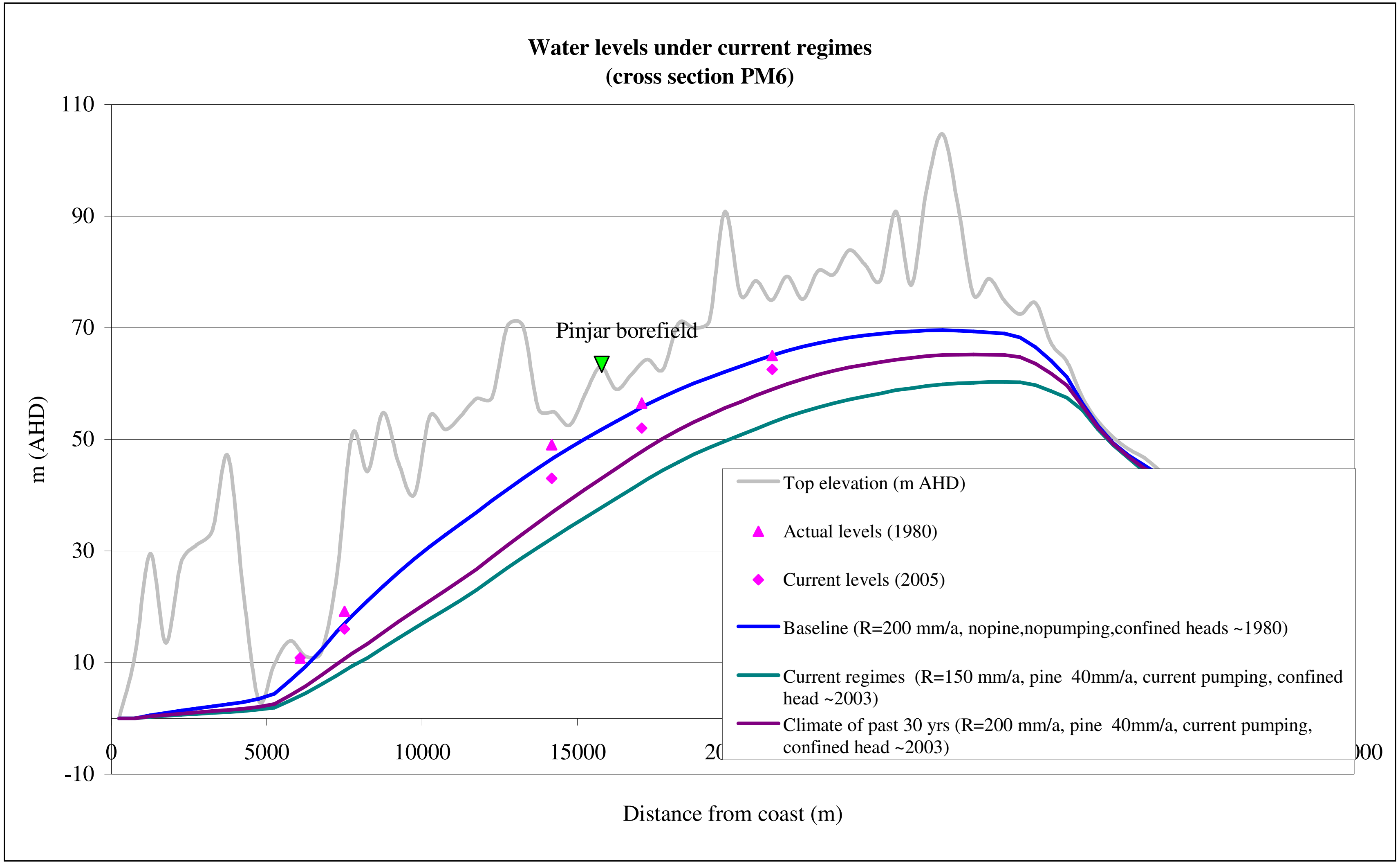

Figure 9 Steady state water level for current regimes

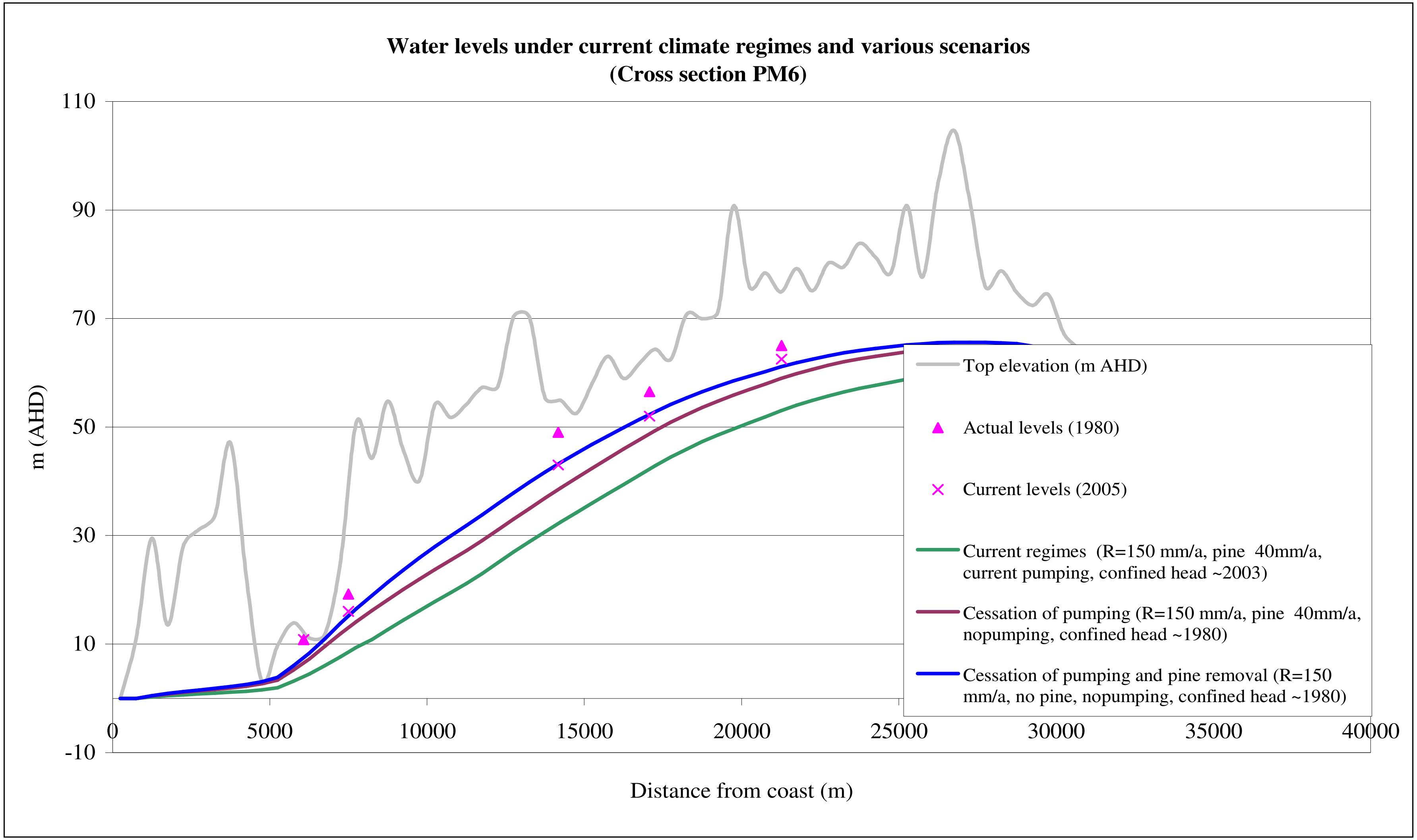

Figure 10 Predicted water level under various scenarios for current climate regime

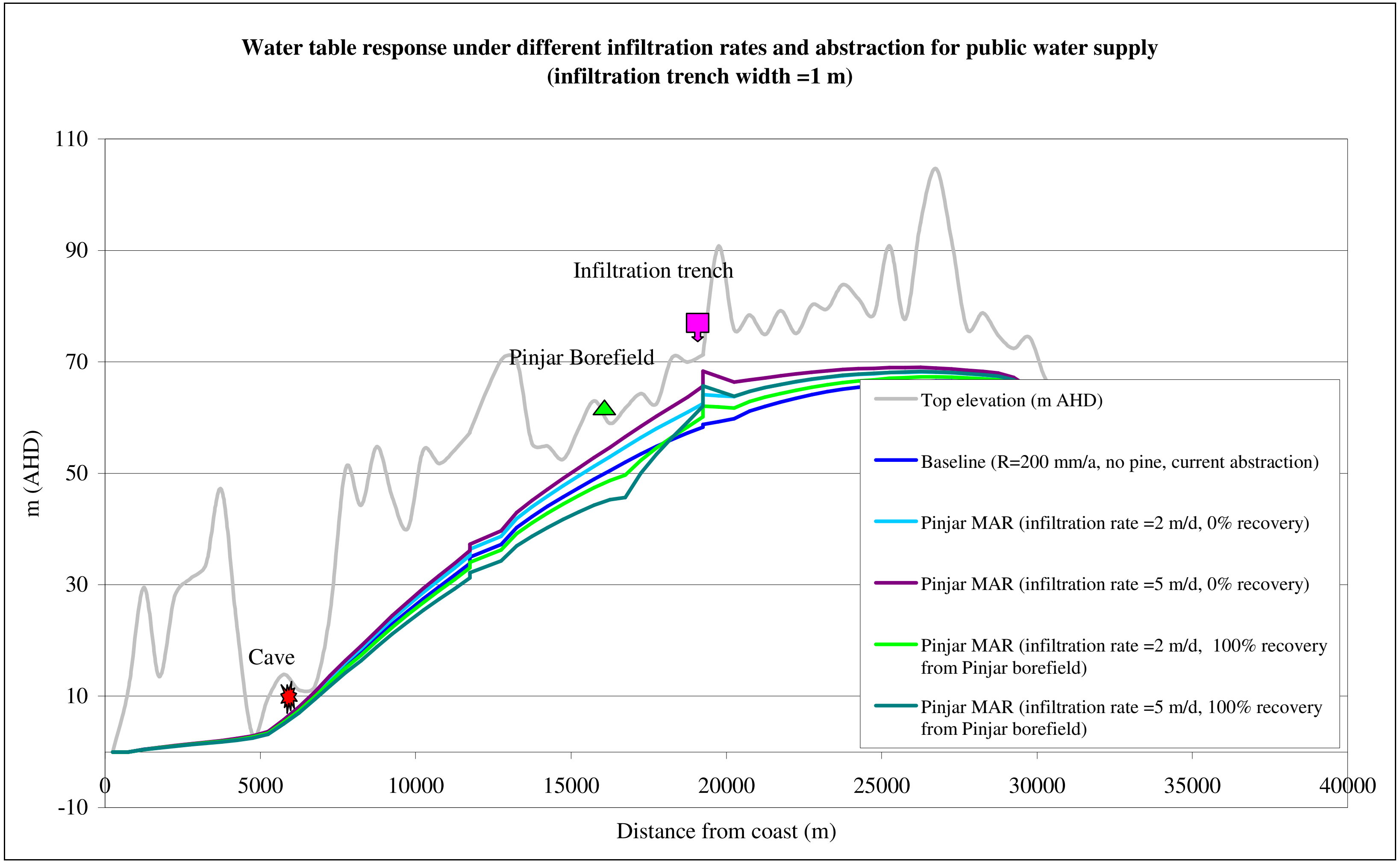

Figure 11 Water levels response to infiltration and increased abstraction for public water supply from Pinjar borefield

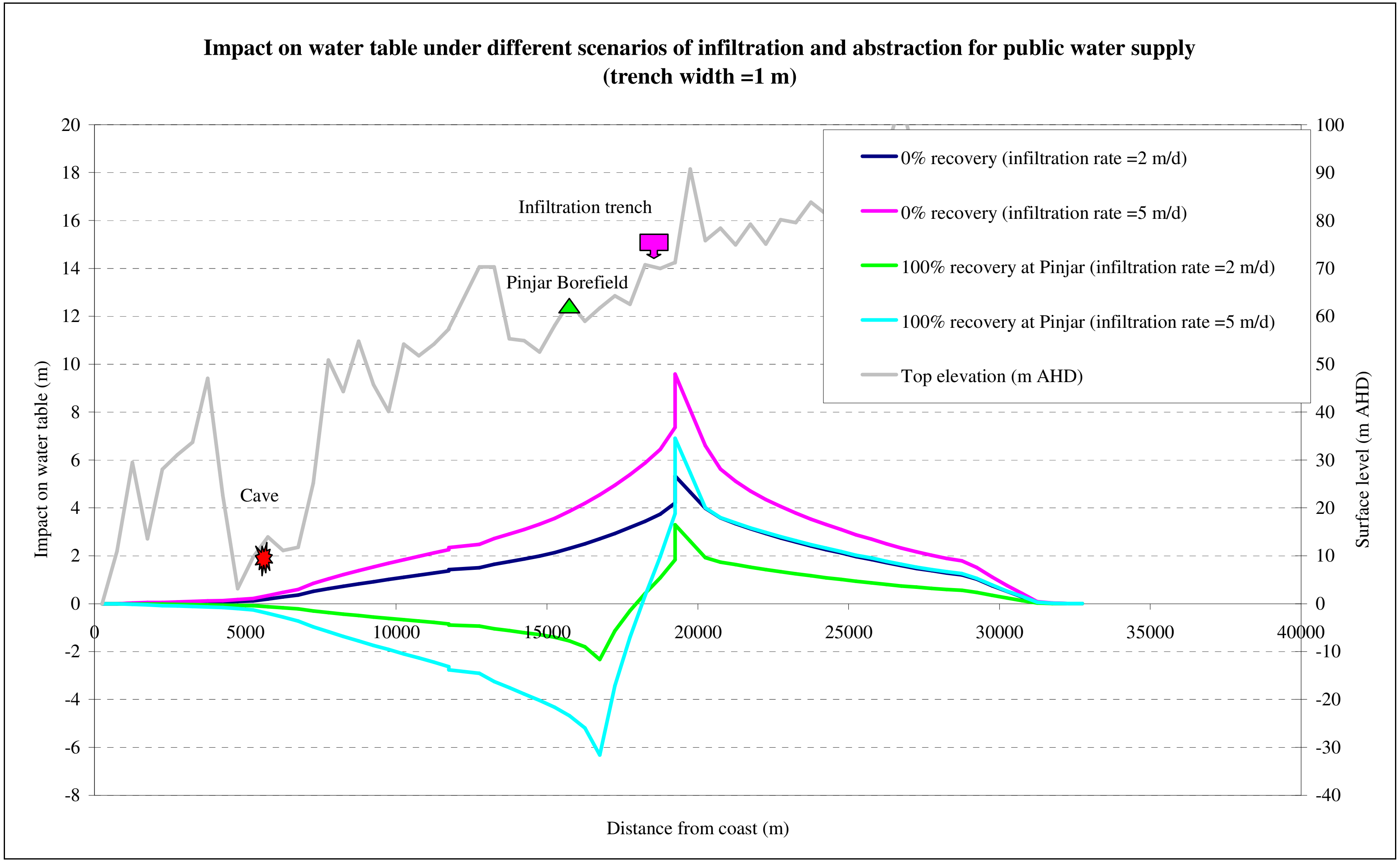

Figure 12 Impacts of MAR at Pinjar

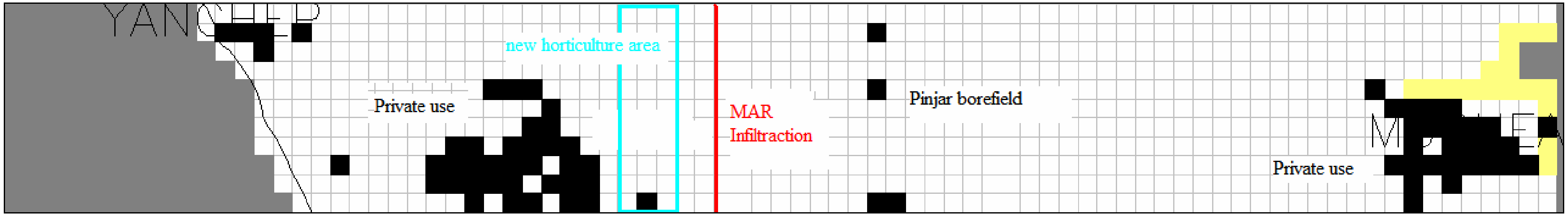

Figure 13 Infiltration scheme for horticulture use

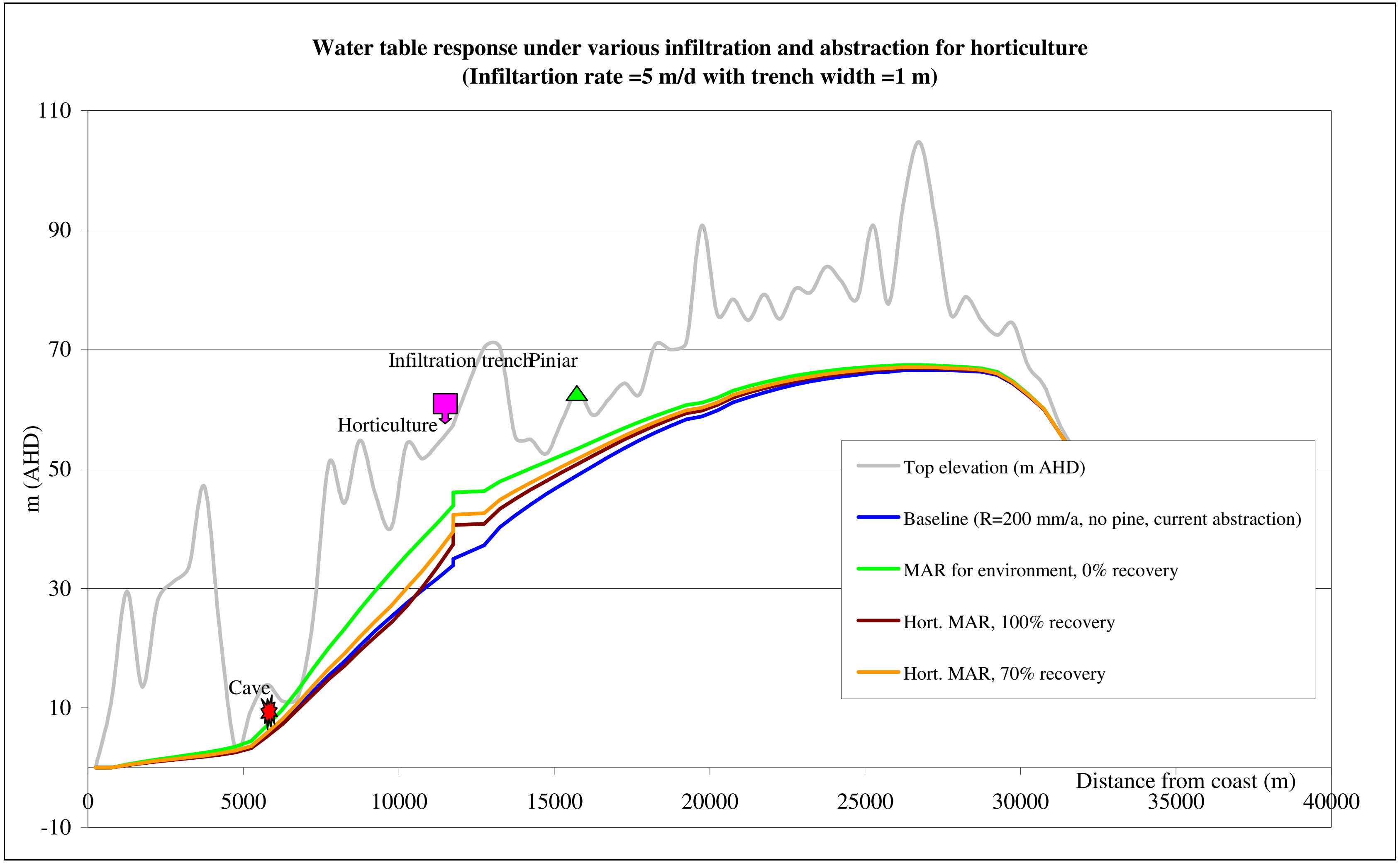

Figure 14 Water table response to infiltration and abstraction for horticulture

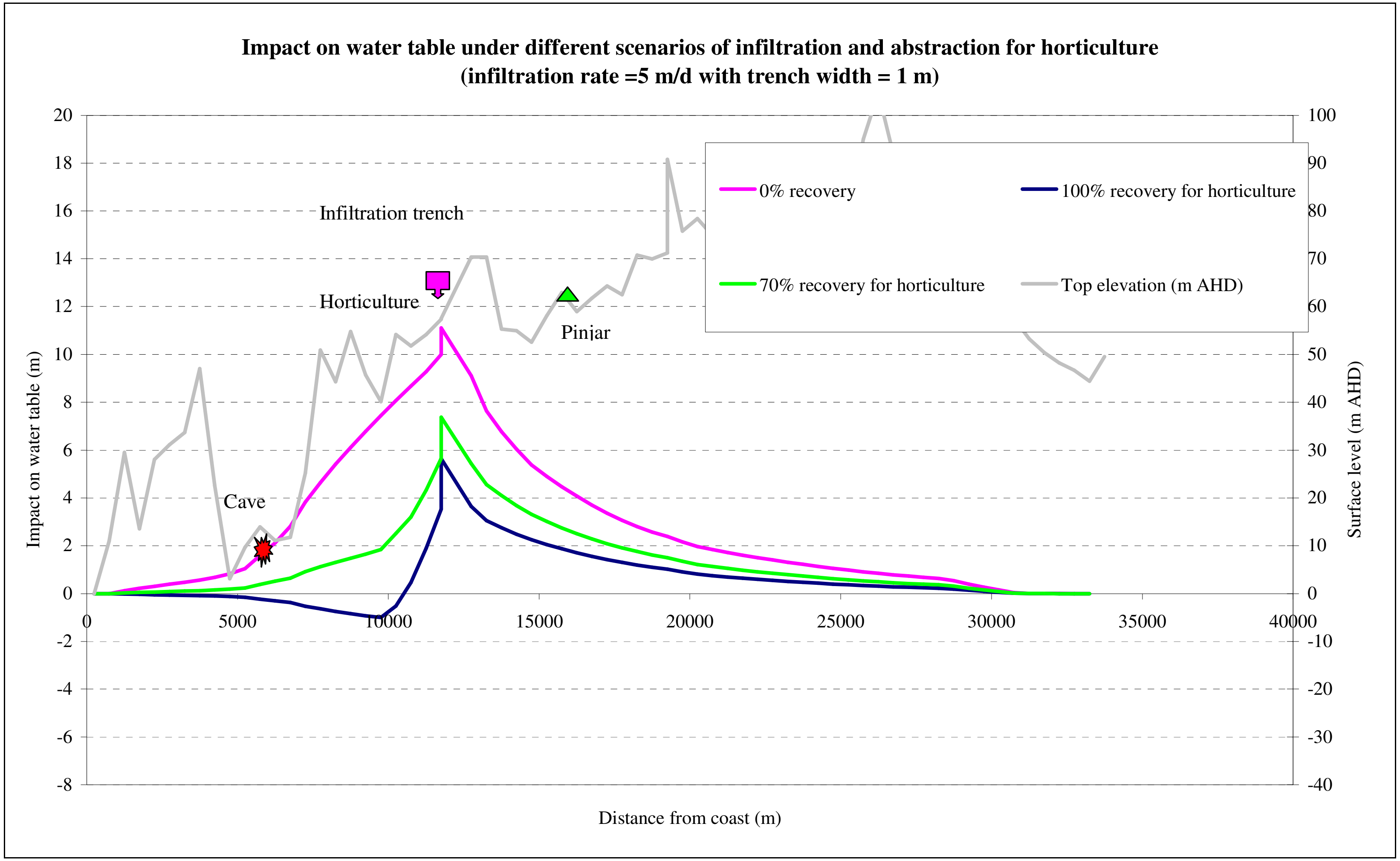

Figure 15 Impacts on water table of infiltration and abstraction for horticulture

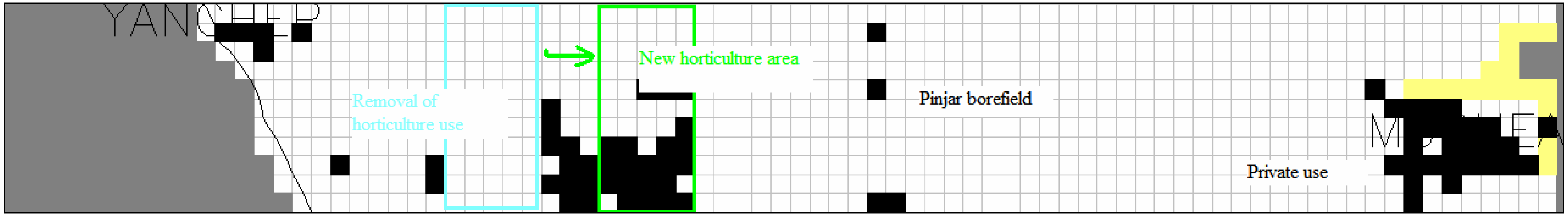

Figure 16 Moving horticulture away from the Wetlands

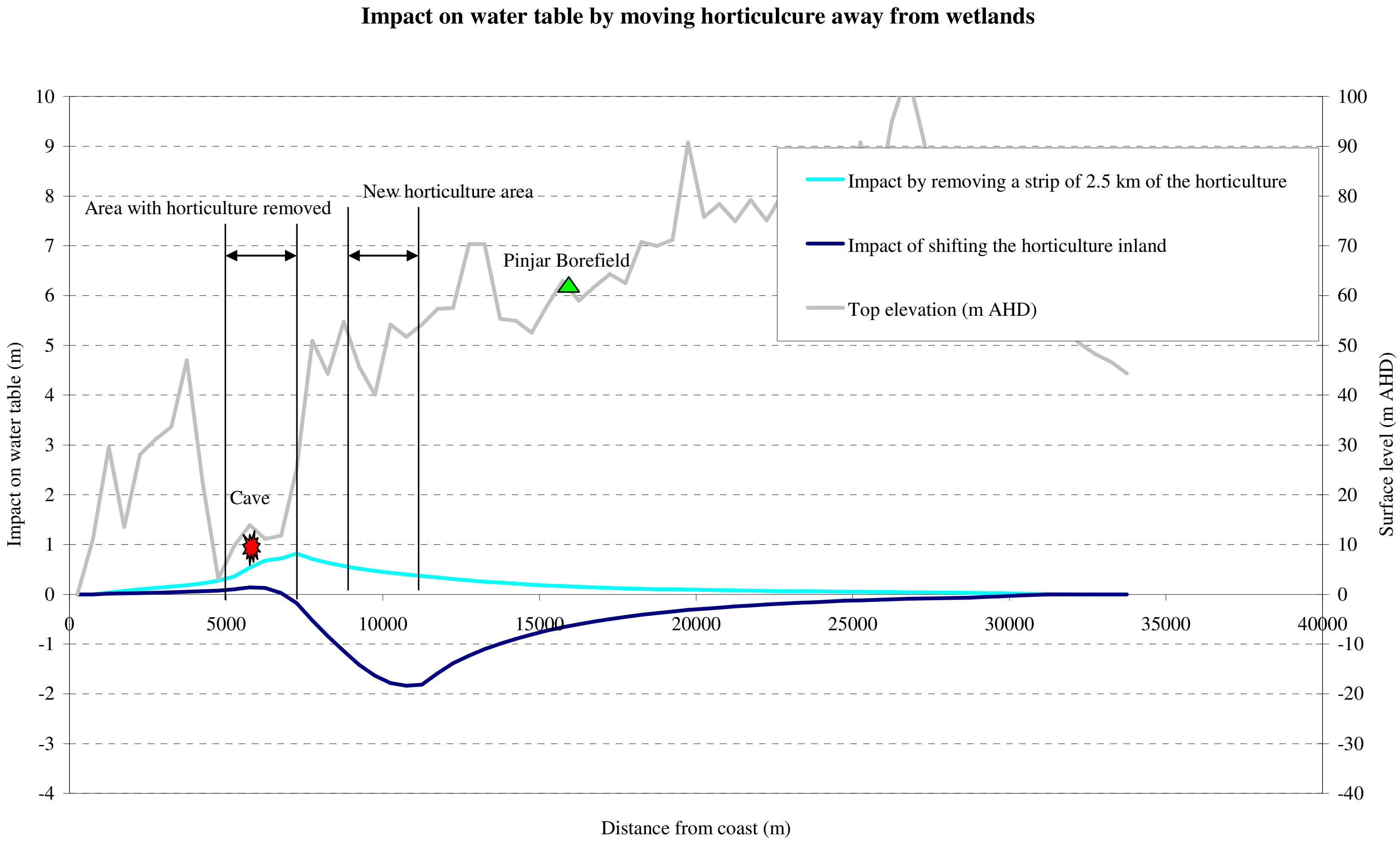

Figure 17 Impacts by moving horticulture inland

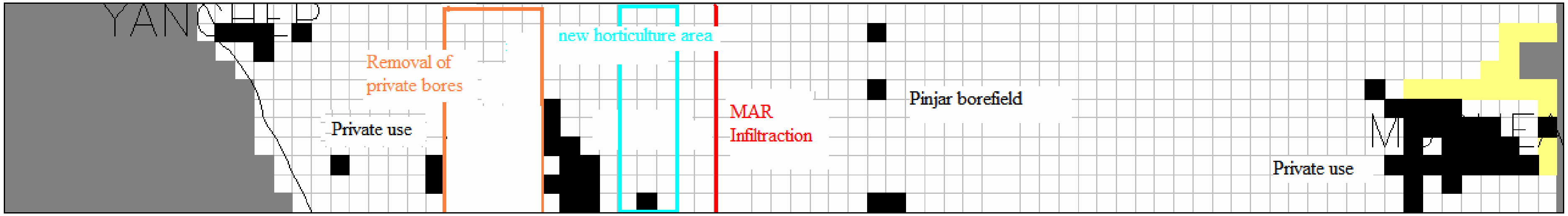

Figure 18 MAR and removal of horticulture along the linear wetlands

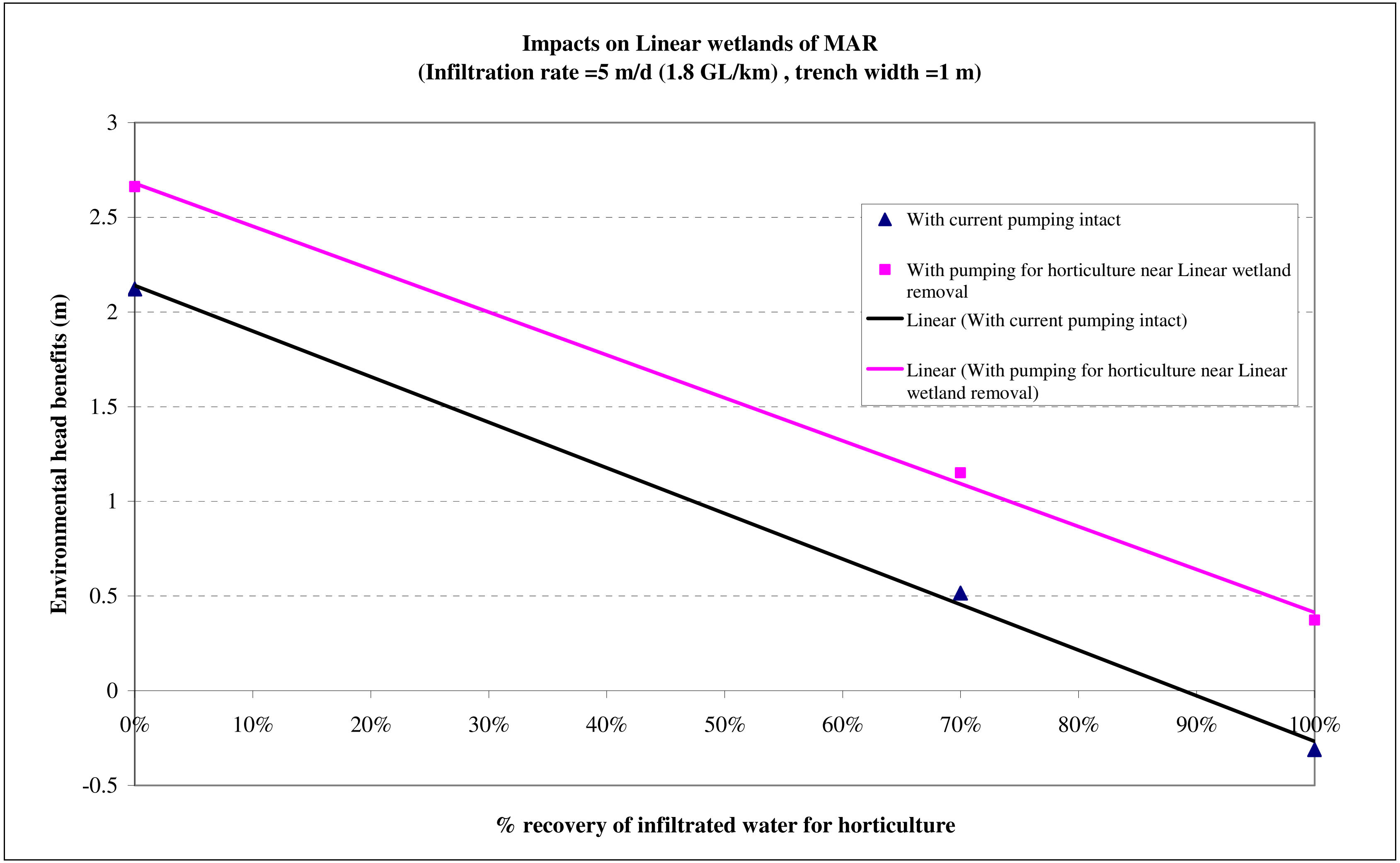

Figure 19 Environmental benefits under different abstraction rates for horticulture

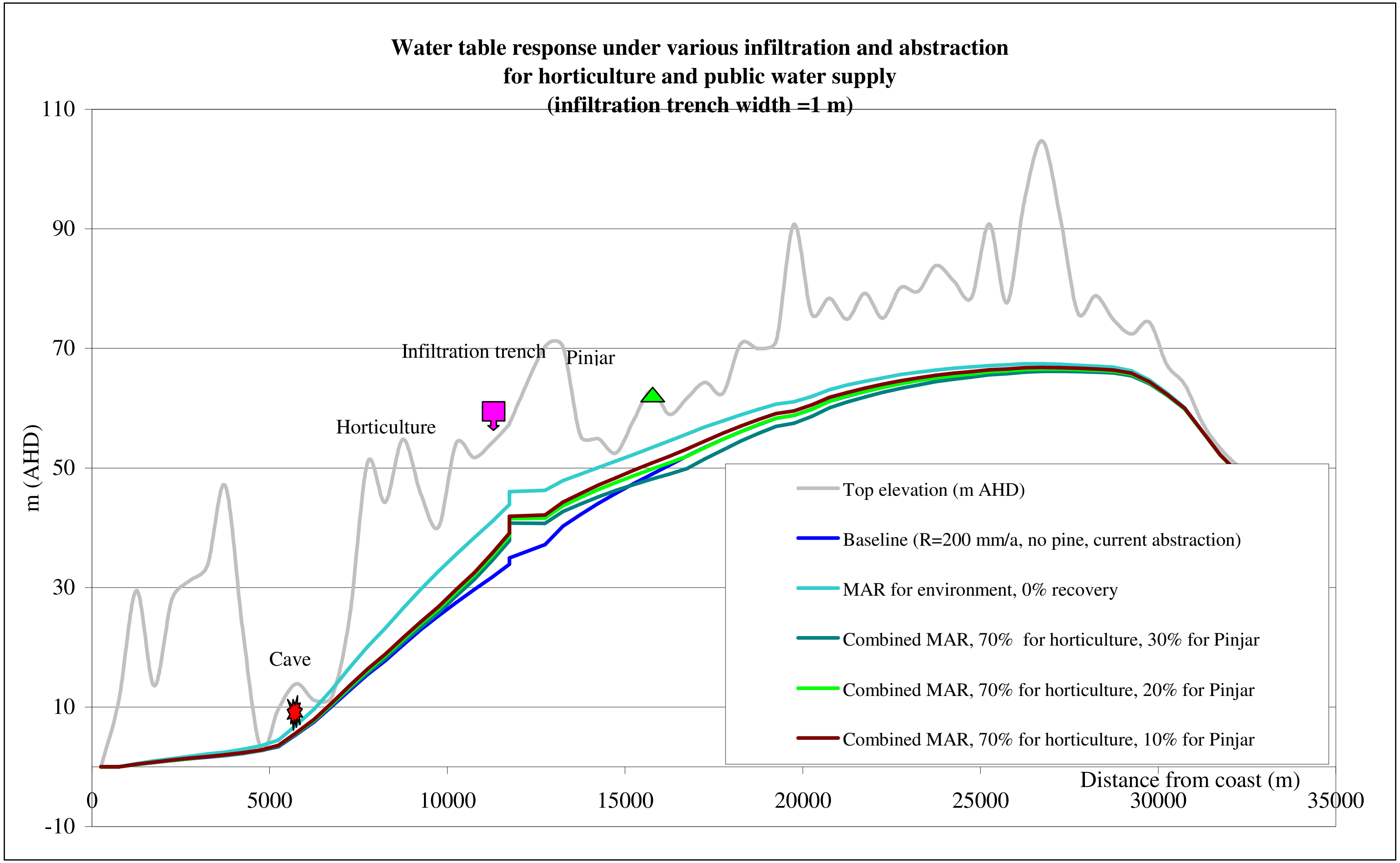

Figure 20 Water table response to infiltration and abstraction for horticulture and public water supply

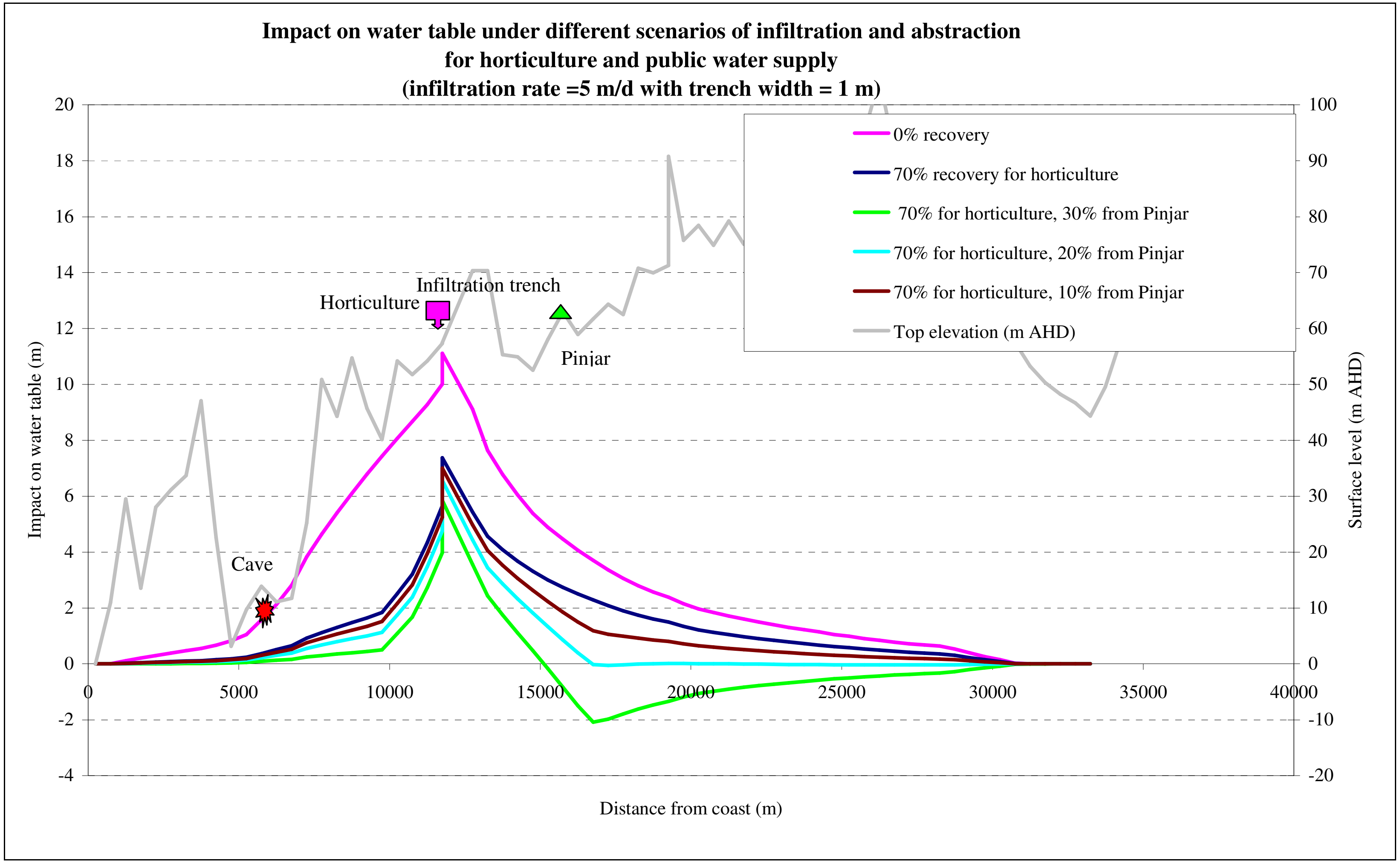

Figure 21 Impacts of abstraction for horticulture and from Pinjar with MAR scheme

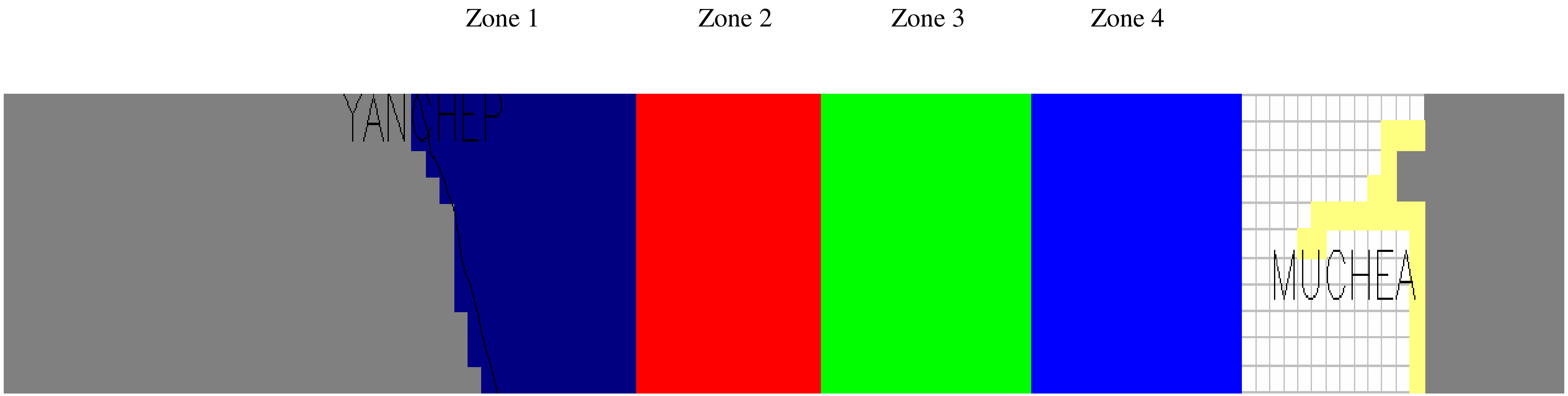

Figure 22 Abstraction zones at different landscape of the Mound

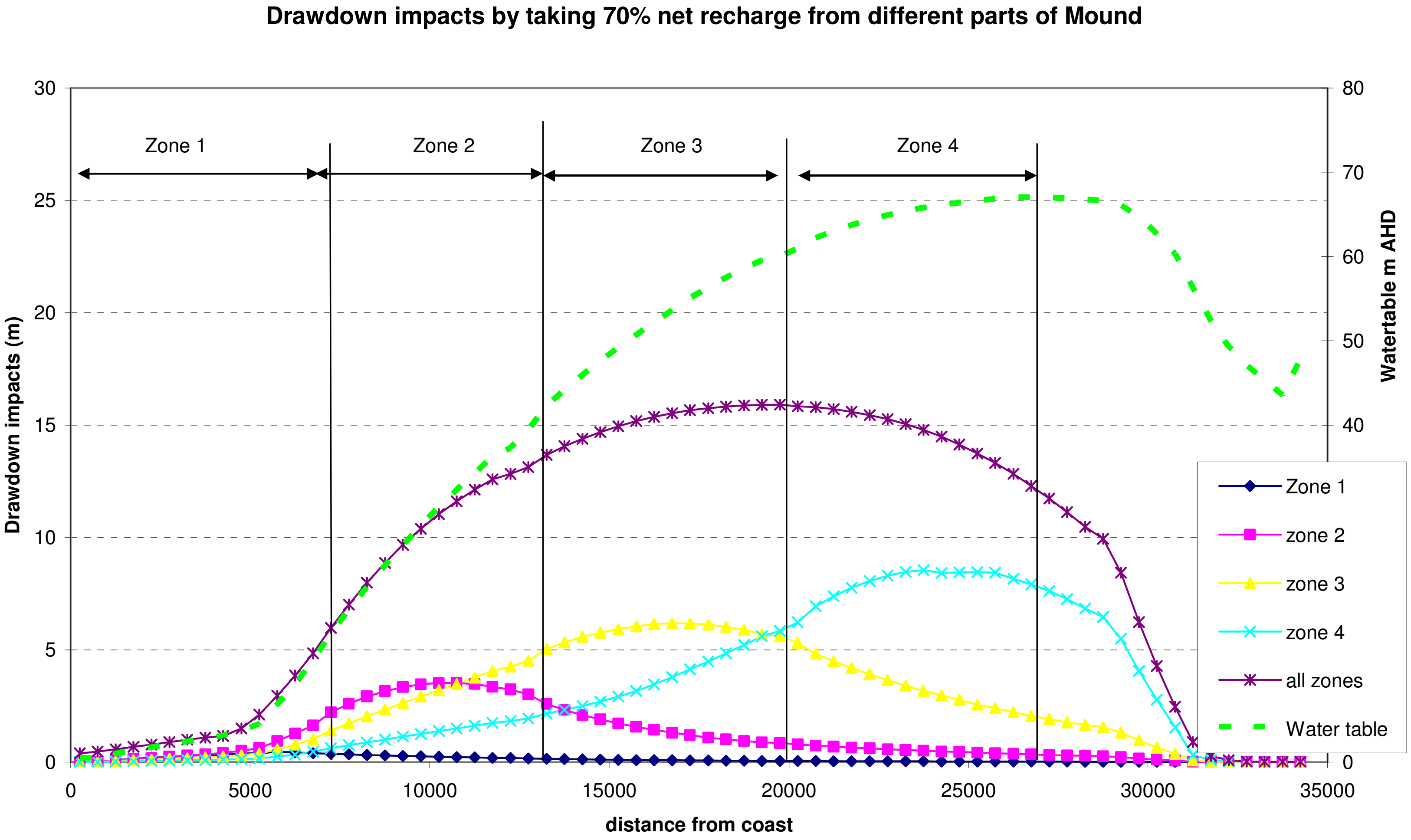

Figure 23 Drawdown impacts by taking 70% net recharge from different part of Mound

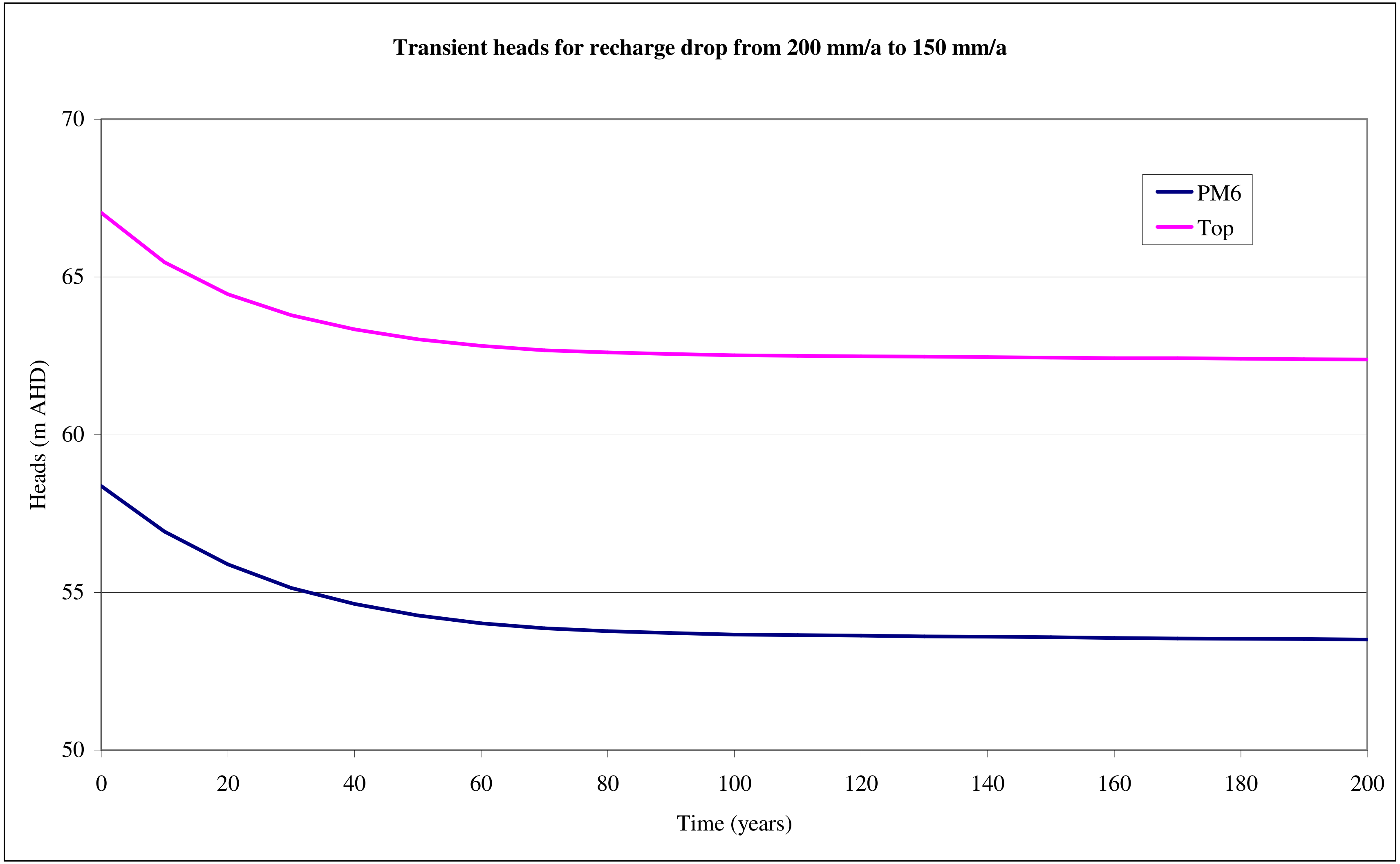

Figure 24 Transient heads

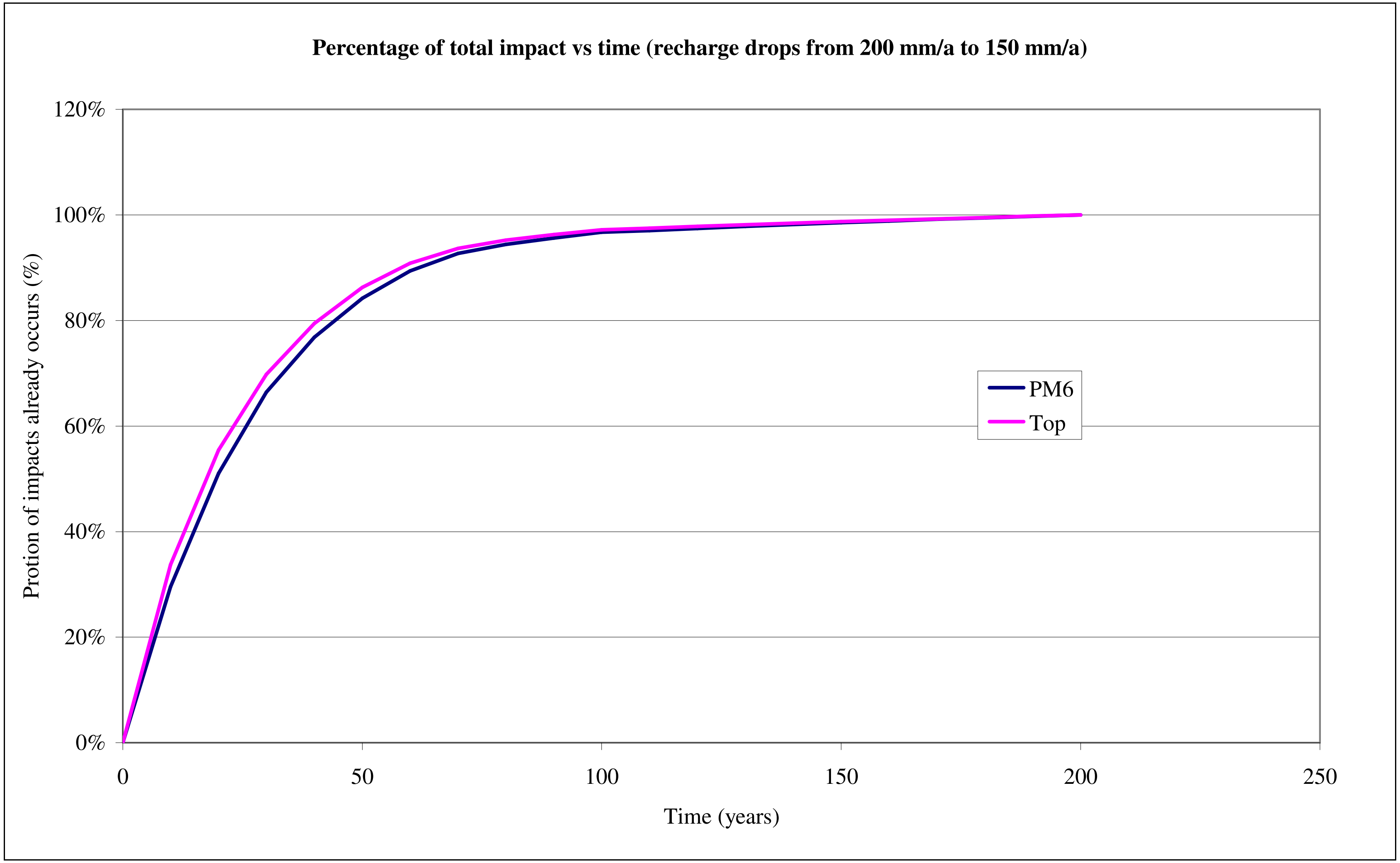

Figure 25 Impacts vs time