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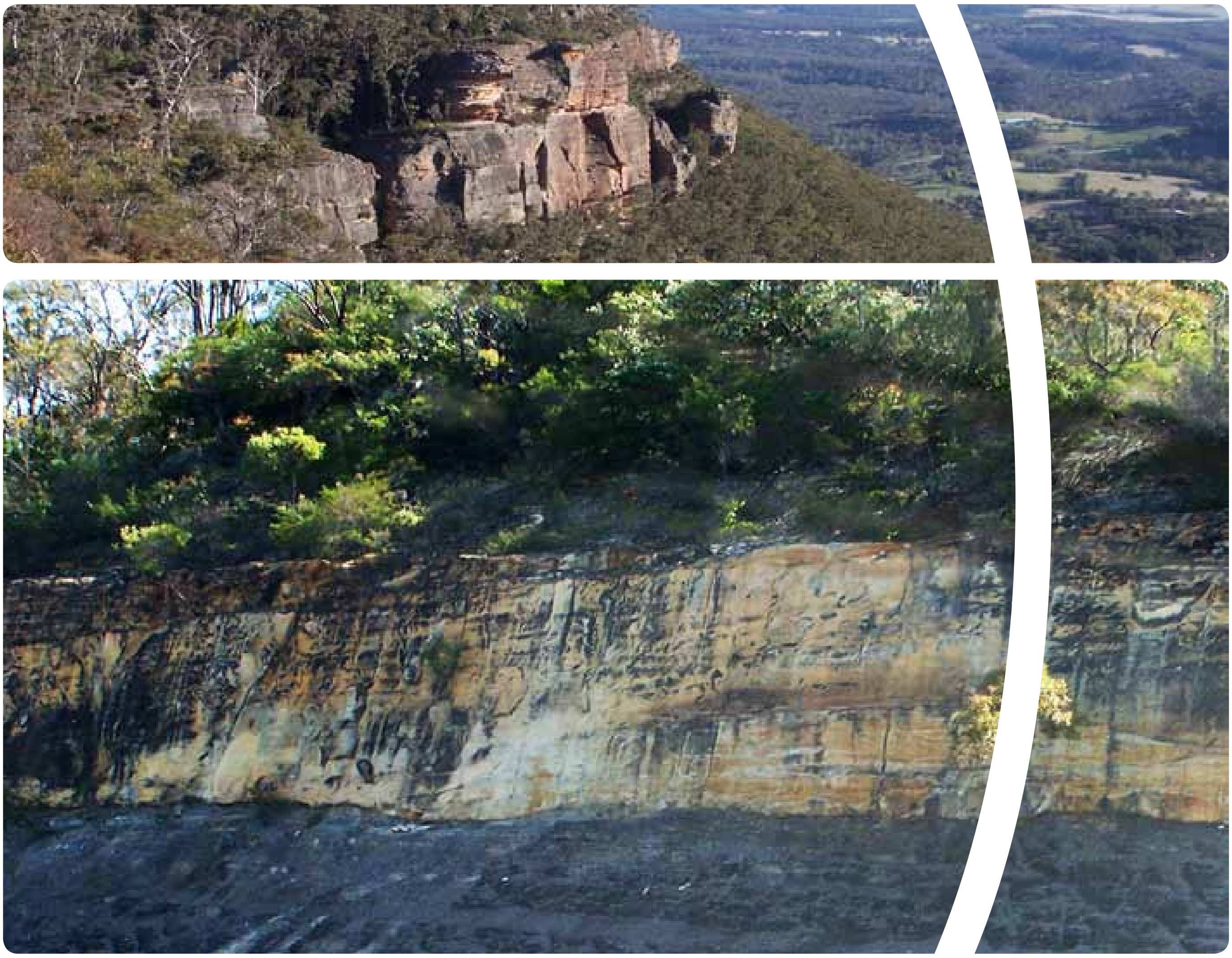
Impact of groundwater pumping on stacked water sources



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Impact of groundwater pumping on stacked water sources

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Executive summary

The objective of this report was to apply a conceptual MODFLOW groundwater model methodology to represent a stacked water source system.

The model aimed to evaluate:

- the impacts of groundwater pumping scenarios on a deep semi-confined groundwater source on the water table in the upper unconfined aquifer, and
- the impacts on natural outflows for a bounded system.

This modelling is referred to herein as the Stacked Water Source Model.

For both objectives the impact of storage change in the deep aquifer on the long term water balance and assessment of the time lagged impacts on the water table was determined. For the bounded system only the impact on outflows to either stream base flow or evapotranspiration was assessed.

The modelling results evaluated the impacts of extracting a volume from the deep water source for scenarios of varying aquitard leakance and varying distances from an outflow boundary.

Evaluations were made for:

1. Maximum impact on water table aquifer heads and leakage (i.e. no recharge applied)
2. Time for the water table aquifer and deep water source to recover to pre-development conditions with an average recharge regime applied after pumping stopped
3. Maximum impact on outflows in the upper water source (i.e. no recharge applied)
4. Impact on outflows in the upper water source with an average recharge regime applied
5. Influence of pumping duration on water table and outflow impacts.

For the model conceptualisation used, the Stacked Water Source modelling indicated that groundwater extraction from the deep water source had:

- decreased impact on the water table aquifer the smaller the vertical leakance property of the aquitards,
- increased impact on outflows in the upper water source the closer the extraction to the outflow boundary, and
- increased impact on the water table aquifer leakage and outflows for extended pumping durations.

The model and impact evaluation results could be used to inform the local expert panel on possible impact scenarios that may occur in the generic stacked water source model represented in this report.

1. Introduction

Management options that acknowledge the potential impact of pumping from deep aquifers on water availability in stacked water sources may be incorporated into water planning. The management responses would likely reflect the degree of impact on the water table and system outflows and the time lag between extraction and impact.

A groundwater source is considered to be the overall water source which may include up to several aquifer layers within the same water source. These hydrogeological boundaries are determined for groundwater sources. The determination for specific groundwater sources is outside the scope of this report.

The purpose of this document was to assess pumping impacts of a generic stacked water source 3-dimensional MODFLOW model on the water table aquifer and system outflows based on an extraction of groundwater volume from the deep water source layer.

2. Stacked groundwater sources

2.1 Modelling methodology

The Stacked Water Source model was setup for an area of infinite extent such that boundary conditions would not influence the model area. The spatial grid parameters are given in Table 1.

The model was set up with six layers and conceptualised with an aquitard layer between each water source layer.

The modelled aquifer parameters represent those of typical geologic values. The top two model layers were given a hydraulic conductivity suitable for alluvium. Some anisotropy was maintained in the model to represent more realistic conditions. Values for vertical leakance were assigned to the interface between each layer to simulate the presence of aquitards.

All scenarios were compared to a pre-development scenario with no groundwater extraction. Thus the impacts are the change between a no pumping scenario and that of the various groundwater extraction scenarios.

The scenarios investigated impacts on outflow by placing a constant head boundary at the western boundary. The location of groundwater extraction was moved from the centre of the model toward the western boundary to investigate the change in outflow with distance from the boundary.

The head level changes in each layer were reported:

- The impact of groundwater extraction on the water table aquifer was taken to be the amount of vertical groundwater leakage from the water table aquifer as a percent of the total groundwater extracted from the deep layer.
- The impact of groundwater extraction on the aquifer system outflow was taken to be the change in outflows from a no pumping condition, as the distance of groundwater extraction from the outflow boundary was changed.

2.1.1 Spatial grid

The spatial grid in the model defines the model area as a uniform square grid of constant elevation. The initial water table was given a slight slope to maintain the flow direction from east to west. The hydraulic head in each cell was calculated for each time step, or stress period. A plan view of the model grid and bore locations is given in Figure 1.

Table 1: Model spatial grid components

Grid component	Value
Grid cell size	500 m x 500 m
Model area size	100 km x 100 km
Number of layers	6
Number of columns	200
Number of rows	200
Number of active cells per layer	240000
Number of bores	12

2.1.2 Aquifer parameters

Aquifer parameters, layer elevations and water table elevations are shown in Figure 2.

2.1.2.1 Hydraulic conductivity

The hydraulic conductivities assigned to each layer were meant to represent a typical anisotropic stacked water source scenario. The top two layers were given properties to represent alluvial properties.

All scenarios were modelled keeping the hydraulic conductivity of each layer the same respectively throughout. The values used are listed in Table 2.

2.1.2.1 Vertical leakance term (Vcont)

Leakance describes the vertical transmission properties between layers. Leakance (known as Vcont in the modelling environment) depends on the vertical hydraulic conductivity, k_z, specified for the layer or the aquitard as well as the thickness of the layers and the aquitard. In MODFLOW an aquitard layer is simulated with the term Vcont which is in units of 1/d. For our purposes, we specified the vertical leakance between each layer. Since the purpose of this work did not attempt to go to the level of detail of flow within each aquitard, specifying the Vcont term and simulating the aquitard layers in this model was adequate.

The vertical leakance is an integrated term that is measureable over the radius of influence during a pumping test. The transmissivity calculated from a pumping test and the aquifer and aquitard thicknesses from the borehole logs can be used to determine the vertical leakance value. A more detailed definition, mathematical equation and a worked pumping test example for Vcont is given in the Appendix.

This method should be suitable for deriving Vcont values associated with pumping test results in order to interpret the results of the modelling presented in this report.

Various vertical leakance parameters ranging from 1.0E-04 to 1.0E-07 (1/d) were assigned to the interface between each layer to represent the aquitard layers as shown in Table 2.

They are considered to be representative of the range of vertical leakance values found in geologic formations in NSW. Some typical values for some selected formations are given in Table 3.

Table 2: Aquifer parameters by layer scenarios

Layer	Horizontal Hydraulic Conductivity (k_x, k_y) (m/d)	Vertical Hydraulic Conductivity (k_z) (m/d)	Storativity, S	Specific yield, Sy	Vertical Leakance (VCONT) (1/d)
1	5	0.5	0.0001	0.2	1.0E-04, 5.0E-05, 1.0E-05, 5.0E-06, 1.0E-06, 5.0E-07, 1.0E-07
2	10	1	0.0001	0.2	As above
3	2.5	0.25	0.0001	0.1	As above
4	1	0.1	0.0001	0.1	As above
5	1	0.1	0.0001	0.1	As above
6	1	0.1	0.0001	0.1	As above

Table 3: Typical geologic properties and estimated vertical leakance values

Unit	Hydrogeological Description	Horizontal Hydraulic Conductivity K_x (m/d)	Vertical Hydraulic Conductivity K_z (m/d)	Thickness (m)	Vertical Leakance (1/d)
Wianamatta Group	Unconfined, perched	0.01	0.05	29	
Hawkesbury Sandstone	Unconfined Aquifer	0.1	0.05	186	
Bald Hill Claystone	Aquitard	1.00E-05	2.00E-06	25	8.00E-08
Bulgo Sandstone	Leaky Confined Aquifer	5.50E-04	1.10E-04	174	
Stanwell Park Claystone	Aquitard	3.00E-05	6.00E-06	17	3.53E-07
Scarborough Sandstone	Leaky Confined Aquifer	0.01	5.00E-03	32	
Wombarra Claystone	Aquitard	3.00E-05	6.00E-06	21	2.86E-07
Coal Cliff Sandstone	Leaky Confined Aquifer	0.001	5.00E-04	10	
Bulli Coal Seam	Aquifer	5.00E-02	2.50E-02	2.5	
Loddon Sandstone	Confined Aquifer	1.00E-04	2.00E-05	100	

Comparisons were made for various leakance values with the bore in the centre of the model area, or 50 kilometres from the model boundary.

Water movements on a layer by layer basis was analysed to quantify the change in vertical leakance due to groundwater extraction for the various scenarios.

2.1.3 Groundwater extraction

Groundwater was extracted from the deepest model layer to effectively dewater an area of $3x10^6$ m^2 for 12 months.

The volume of groundwater extracted is limited by the vertical leakance value so that the smaller aquitard vertical leakances the less the volume required to be pumped. The groundwater volume extraction modelled based on the vertical leakance values is outlined in Table 4.

Discharge from a bore was simulated by extracting volumetric rates over each stress period. A volume of groundwater was extracted over a 365 day time period over one stress period. This allowed the extraction of a known volume of groundwater. The pumping duration was then extended for pumping durations up to 25 years to investigate pumping duration impacts on the water table and outflows.

The model was then run with no groundwater extraction for 100 years with yearly stress periods to allow aquifer reaction to recovery. This period was run separately with and without recharge.

Twelve bores were active at the same time with equal pumping rates. This simulated a total volume of extraction and allowed the model to extract larger volumes without the limitations of modelling a single bore. Several distances were also investigated at 50, 40, 30, 20, 10 and 5 kilometres from the outflow boundary.

Table 4: Modelled scenarios for storage volumes removed based on vertical leakance factor

Vertical leakance (Vcont) (1/d)	Total pumping rate Q (m^3/day)	Total volume of storage extracted (GL)
1.0E-04	48,000	17.520
5.0E-05	37,200	13.578
1.0E-05	21,000	7.665
5.0E-06	16,800	6.132
1.0E-06	12,000	4.380
5.0E-07	11,520	4.205
1.0E-07	9,600	3.504

2.1.4 Recharge and evapotranspiration

No recharge was applied to the pumping duration period of the model. However, an annual recharge rate was applied to the model recovery period of 100 years after pumping ceased so that the water table did not simply dewater by the volume pumped.

An annual recharge rate and evapotranspiration were not applied to the model to simulate the maximum impacts on outflows and the water table. The transient model was set up to observe the impact on the model layers after a volume of storage was extracted and allowed to recover. This method allowed for the direct observation of model reaction without the interference of recharge volumes.

Recharge was applied to the model for investigation of the impacts on outflows and the time for the water table aquifer and deep water source to return to natural conditions. Recharge was applied at 5 per cent of an average annual rainfall of 720 mm/year or at a rate of 0.0001 m/day over the entire model grid.

Figure 1: Plan view of the model grid area and pumping bore locations

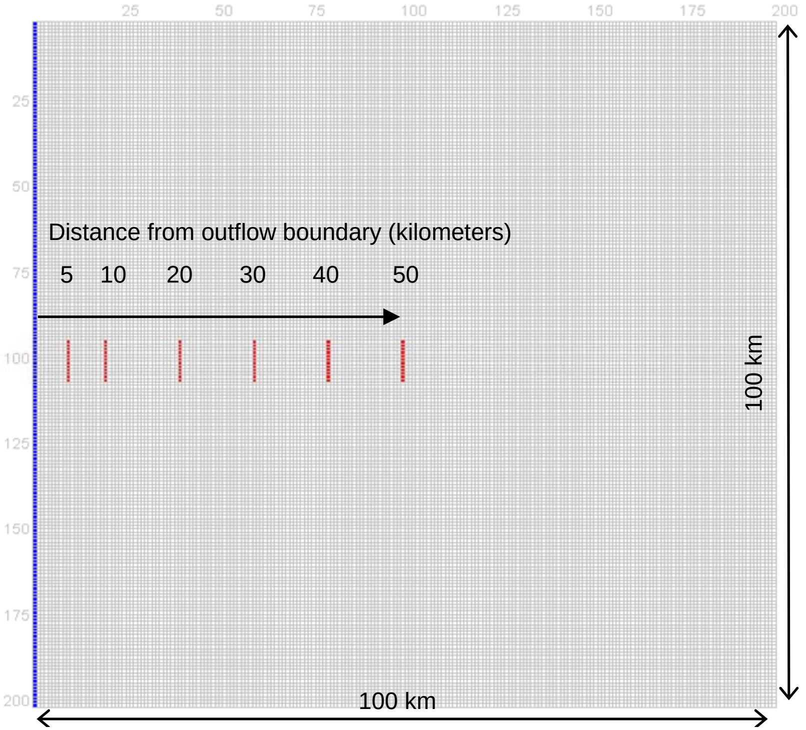
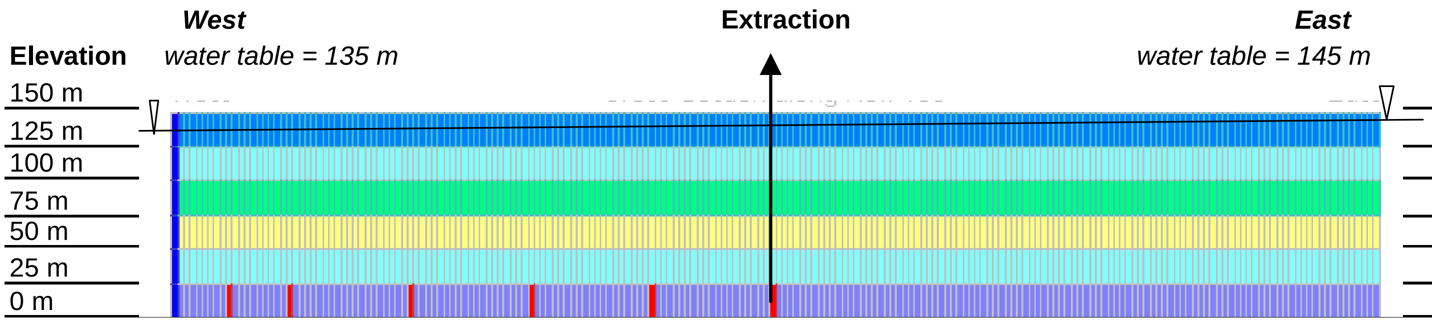


Figure 2: Cross-sectional view of the model layers showing layer elevations, water table elevations and layer properties



Properties

k_x	k_y	k_z	S	Sy
5	5	0.5	0.0001	0.2
10	10	1	0.0001	0.2
2.5	2.5	0.25	0.0001	0.1
1	1	0.1	0.0001	0.1
1	1	0.1	0.0001	0.1
1	1	0.1	0.0001	0.1

3. Model results

A set of scenarios to represent the various parameters and conditions that may be seen in stacked water source systems were modelled.

3.1 Water table aquifer impacts after one year of groundwater extraction

Scenarios for varying degrees of vertical leakance were modelled to determine the effects of groundwater extraction from the deep water source on the water table aquifer and the differences for systems that are “leaky” versus “non-leaky”. These scenarios illustrated the sensitivity of the stacked water source system due to various estimated aquitard properties.

3.1.1 Vertical leakance scenarios

Varying vertical leakances were investigated using Vcont (1/d) values of 1.0E-04, 5.0E-05, 1.0E-5, 5.0E-06, 1.0E-06, 5.0E-07 and 1.0E-07. Comparisons were made with the bore in the centre of the model area, or 50 kilometres from the model boundary.

Comparison between the impact on the water table aquifer vertical leakage between a bounded aquifer and an aquifer of infinite extent showed no significant change in the results. This indicates that the point of extraction for varying leakance scenarios was not influenced by the model boundaries.

The term Vcont is explained in the previous section and is explained in further detail in the Appendix A.

The modelled scenarios are given in Table 2 and Table 4.

3.1.2 Maximum volume pumped from deep water source

The maximum volume pumped decreased as the vertical leakance term decreased, as shown in Figure 3. This reflects the stacked water source system’s ability to transmit water based on the aquitard properties assigned in the model. The relationship between vertical leakance and maximum volume pumped is illustrated in Figure 4.

Figure 3: Maximum volume pumped for various vertical leakance values (no recharge)

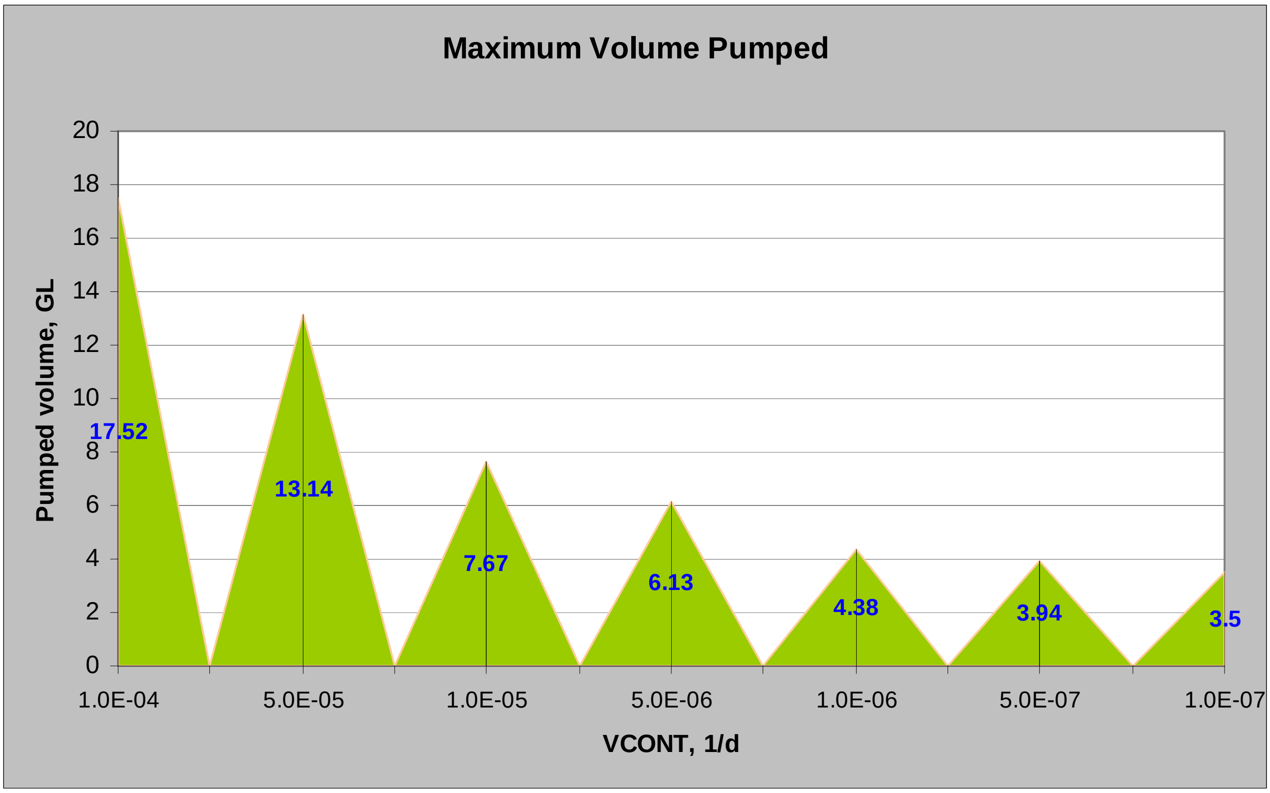
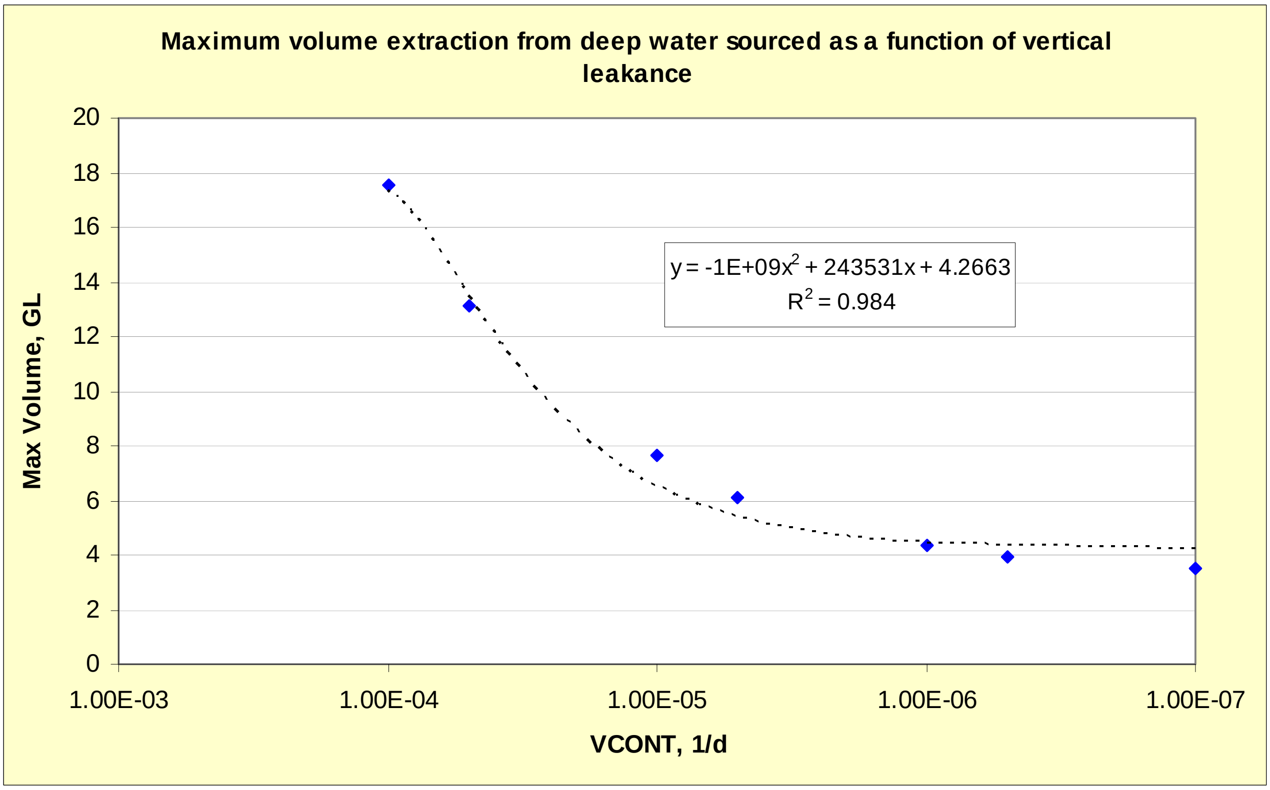
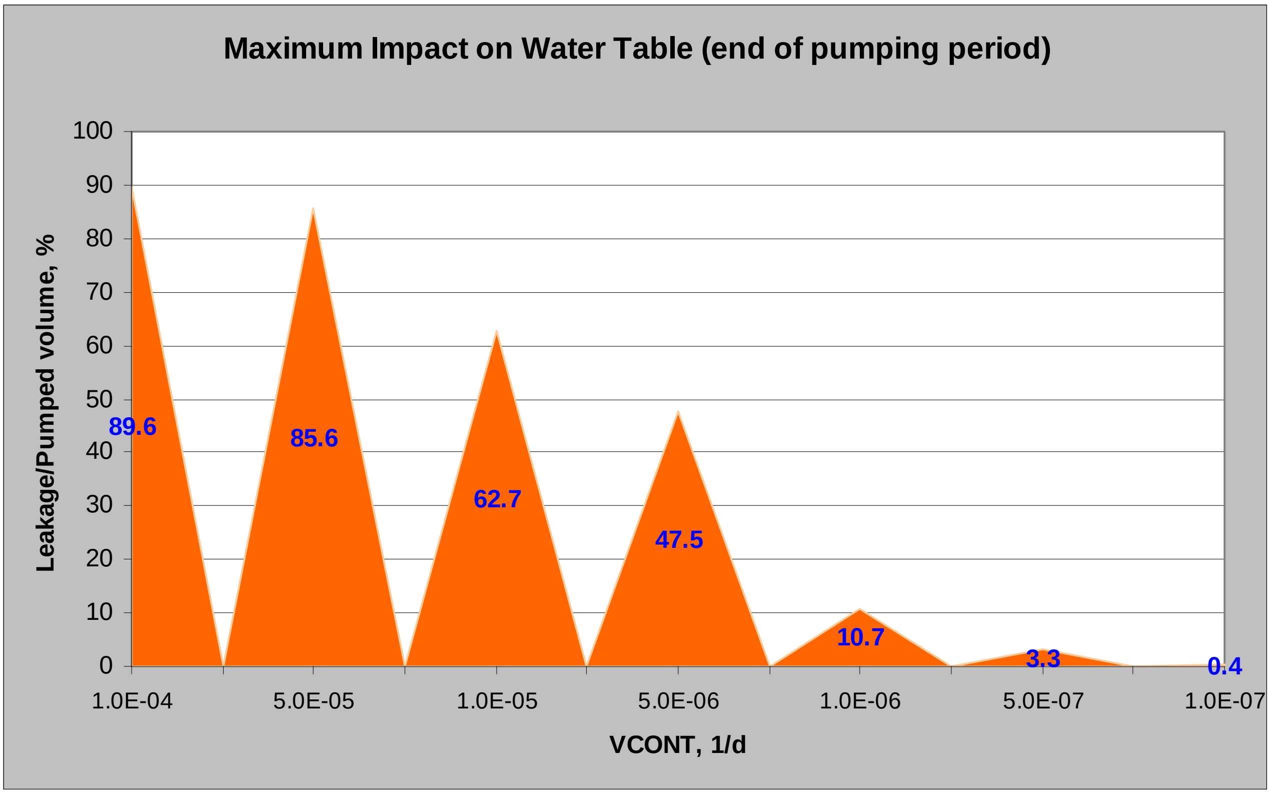


Figure 4: Maximum volume extraction from deep water source as a function of vertical leakance (no recharge)



The maximum impact on the water table under a no recharge scenario is shown in Figure 5. The impact on the water table aquifer decreased as the vertical leakance value became smaller. The impact is the proportion as a percentage of leakage from the water table aquifer to the volume of groundwater pumped.

Figure 5: Maximum impact on water table aquifer as a function of vertical leakance (no recharge)



As the vertical leakage decreased, the leakage proportions by layer changed. At larger vertical leakage values (highly leaky) the leakage from Layer 1 was largest as opposed to a small vertical leakage (non-leaky) where leakage from Layer 1 was small.

This indicated that,

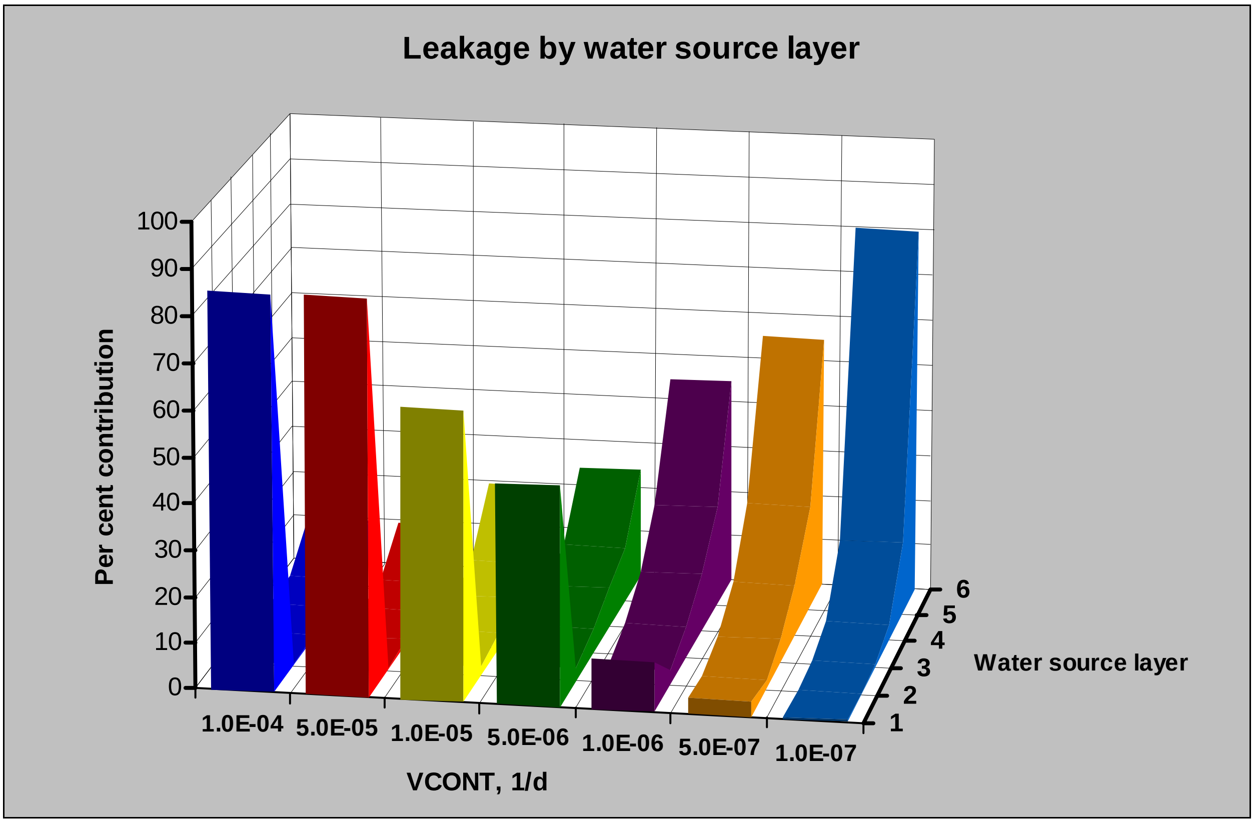
- for a leaky system, the groundwater pumped is largely sourced from the upper layers, and
- for a non-leaky system, the groundwater pumped is largely sourced laterally from the deep water source.

The distribution of leakage by layer for the various vertical leakance scenarios is tabulated in Table 5 and illustrated in Figure 8.

Table 5: Table of maximum leakage by water source layer as a function of vertical leakance (no recharge)

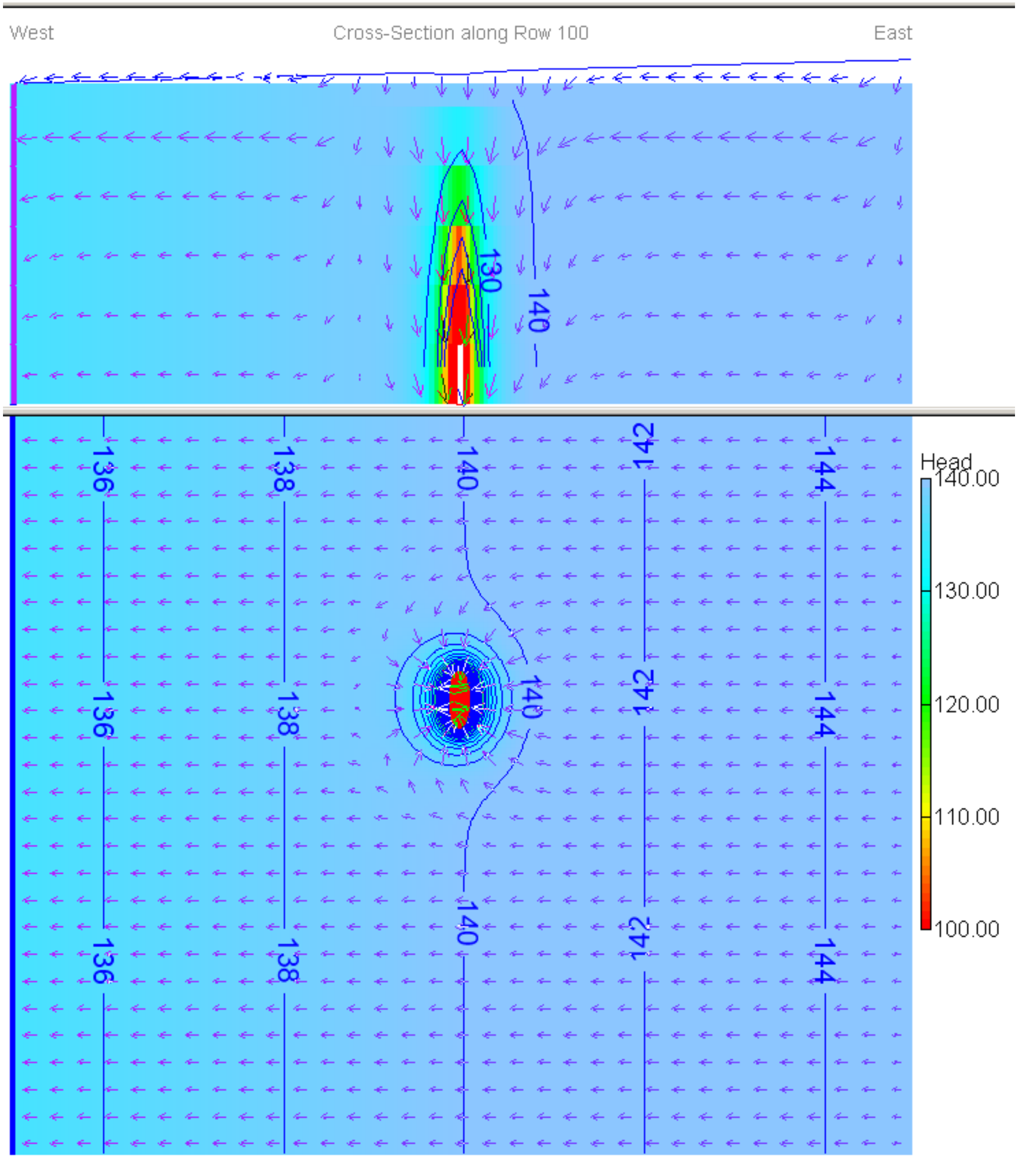
Vertical Leakance (Vcont) (1/d)	Total Volume Pumped(GL)	Per cent contribution by layer of total volume pumped Water Source Layer					
		1	2	3	4	5	6
1.00E-04	17.52	89.59	0.29	0.54	0.78	1.04	7.67
5.00E-05	13.14	85.56	0.51	0.98	1.46	1.95	9.42
1.00E-05	7.67	62.74	1.76	3.53	5.4	7.41	18.97
5.00E-06	6.13	47.52	2.64	5.4	8.46	11.98	23.75
1.00E-06	4.38	10.7	3.03	6.89	12.63	21.83	44.59
5.00E-07	3.94	3.31	2.02	5.15	11.1	23.14	54.89
1.00E-07	3.5	0.38	0.16	0.77	3.5	15.84	79.66

Figure 6: Graph of leakage by water source layer as a function of vertical leakance (no recharge)



A cross-sectional figure illustrating the heads due to pumping for the leaky case for a Vcont of 1.0E-04 1/d is shown in Figure 7. It clearly shows a depression in the water table in Layer 1.

Figure 7: Cross-sectional and plan view of deep layer 6 for Vcont = 1.0E-04 1/d showing water level contours and directional vectors

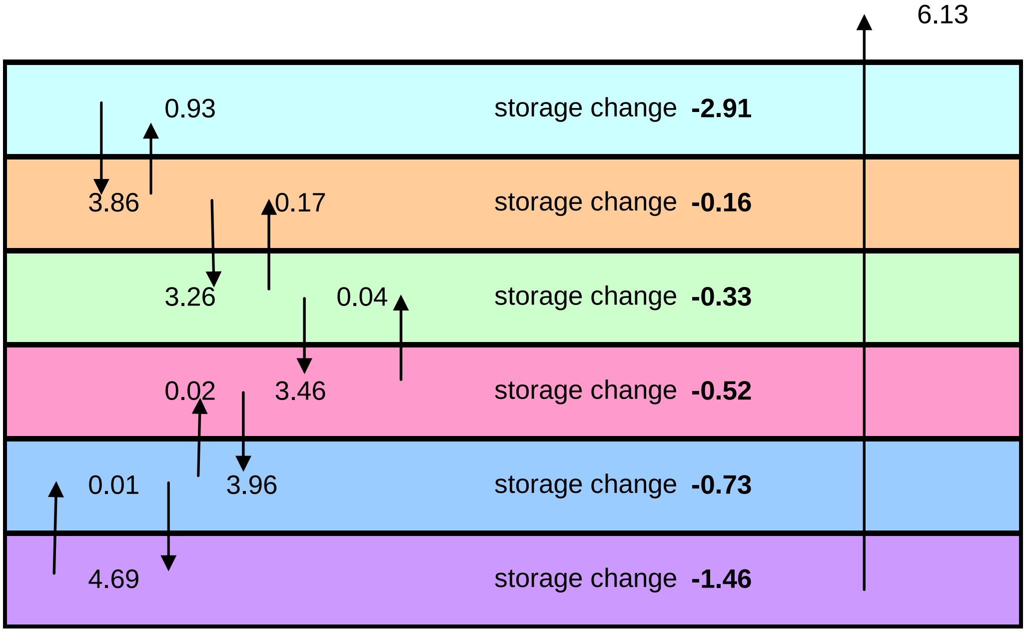


3.1.2 Maximum change in storage by layer

The vertical leakage between each layer and the storage changes in each layer for the maximum volume pumped is illustrated in Figure 8 for a vertical leakance value of 5.0E-06. Table 5 gives the distribution of leakage by layer for the various vertical leakance scenarios.

The leakage and change in storage distribution figures for all vertical leakance scenarios are given in the Appendix.

Figure 8: Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer at end of one year of pumping



3.1.3 Time to reach pre-development conditions

The water source layer heads at the end of the one year pumping scenarios were used to observe the recovery of the system to pre-development conditions. Recharge was applied at the average rate of 0.0001 m/day and all pumping was ceased.

- The time for the water table aquifer to fully recovery as a function of varying vertical leakance values is given in Figure 9, which shows that for the two leakiest values recovery occurred in the water table aquifer in 5 and 3 years respectively. It also shows that for vertical leakance values of 1.0E-05 1/d and less the recovery period was less than 1 year.
- The time for the deep water source to fully recovery as a function of varying vertical leakance values is given in Figure 10, which shows that for the leakiest values recovery occurred in the deep water source layer in three years and in the non-leakiest case in 23 years.

Figure 9: Time to reach pre-development conditions in the water table aquifer (with recharge)

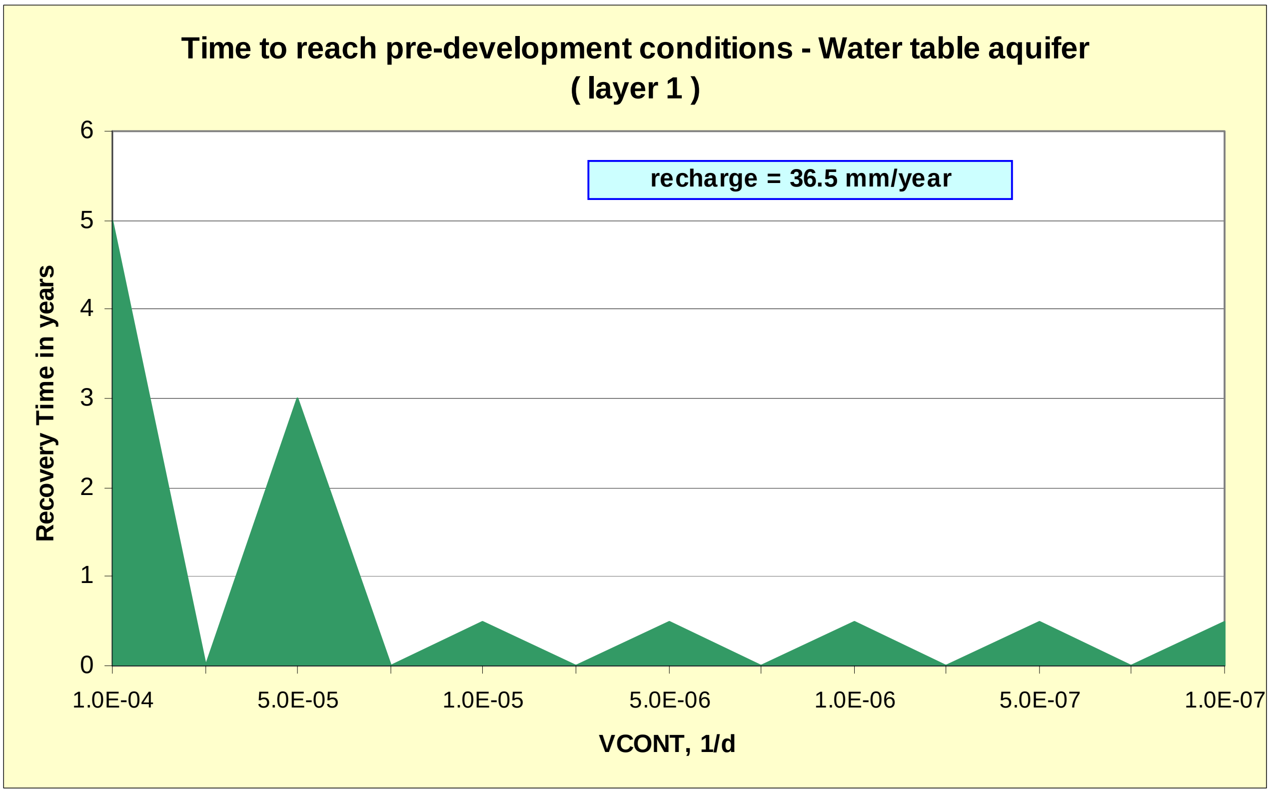
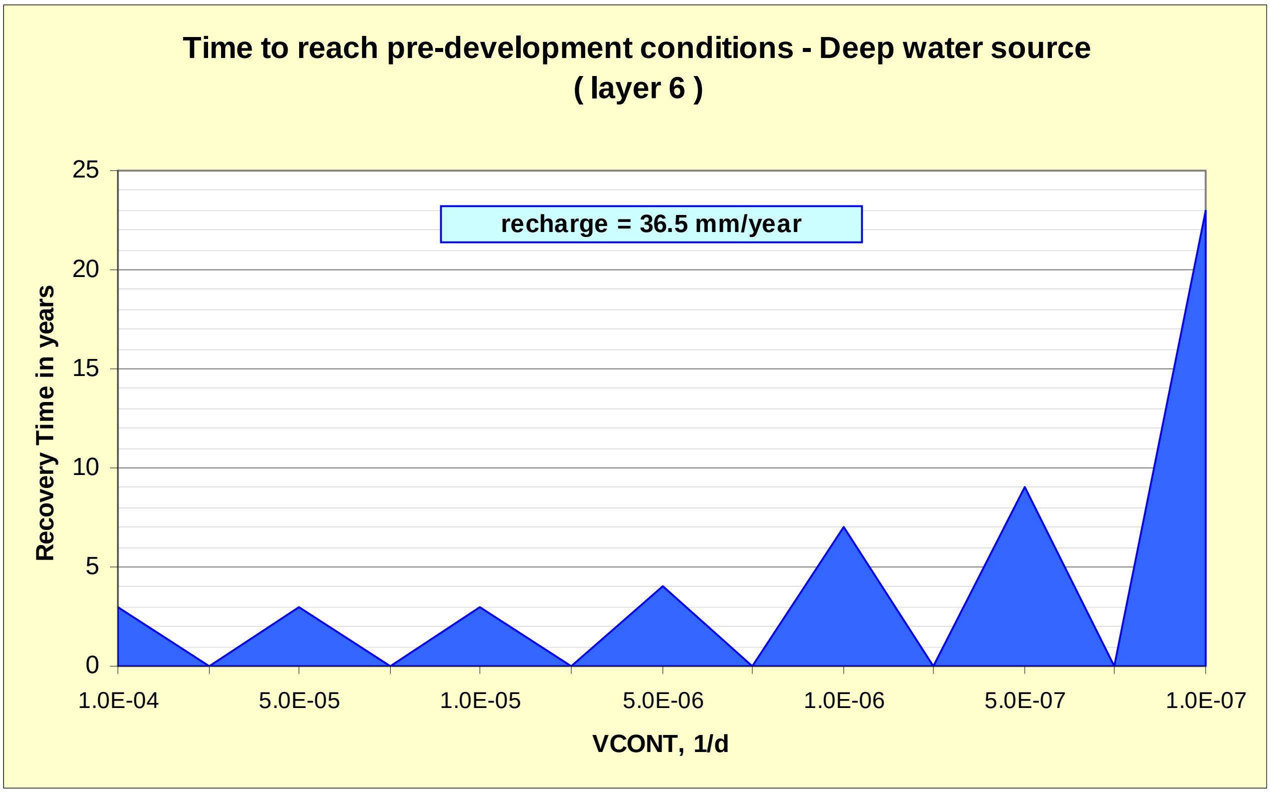


Figure 10: Time to reach pre-development conditions in the deep water source (with recharge)



3.2 Water table aquifer impacts from deep pumping

Scenarios were run to observe the impact of groundwater extraction on the water table and other water source layers over increased pumping durations up to 25 years. Scenarios were run consistent with the one year pumping duration scenarios without recharge during the pumping period, and an average recharge applied for the model recovery duration.

3.2.1 Vertical leakance scenarios

The middle range value for Vcont of 5.0E-06 1/d was selected to investigate and compare the influence of pumping duration on the maximum impact to the water table aquifer.

3.2.2 Maximum volume pumped from deep water source

The maximum volume pumped as a total volume for the time period is given in Table 6. The pumping rate decreased slightly as the pumping duration was increased.

3.2.3 Maximum change in storage by layer

The vertical leakage between each layer and the storage changes in each layer for the maximum volume pumped for a pumping duration of 25 years is illustrated in Figure 12 for a vertical leakance value Vcont of 5.0E-06 1/d.

The leakage and change in storage distribution figures for all the pumping duration scenarios for the median vertical leakance value are given in the Appendix.

The results showed that the

- impacts on the water table aquifer varied with pumping duration from the deep water source, and
- impacts on the water table aquifer increased as pumping duration increased.

These results are tabulated in Table 6 and shown graphically by layer in Figure 11.

Table 6: Table of maximum leakage by water source layer as a function of pumping duration for Vcont = 5.0E-06 1/d (no recharge)

Pumping duration (years)	Total pumping rate Q (m^3/day)	Total volume pumped(GL)	Per cent contribution by layer of total volume pumped Water Source Layer 1	2	3	4	5	6
1	16,800	6.13	47.52	2.64	5.4	8.46	11.98	23.75
2	16,800	12.26	62.92	1.76	3.53	5.41	7.43	18.86
3	16,200	17.74	71.82	1.35	2.69	4.07	5.53	14.50
4	15,600	22.78	77.89	1.11	2.19	3.30	4.46	10.96
5	15,000	27.38	82.64	0.95	1.86	2.80	3.77	7.97
10	14,640	53.44	90.22	0.29	0.55	0.82	1.10	2.47
15	14,440	78.84	93.39	0.39	0.73	1.08	1.42	3.00
20	14,280	104.24	94.99	0.31	0.57	0.83	1.10	2.21
25	14,220	129.76	95.93	0.28	0.47	0.68	0.89	1.77

Figure 11: Graph of leakage by water source layer as a function of pumping duration for a Vcont = 5.0E-06 1/d (no recharge)

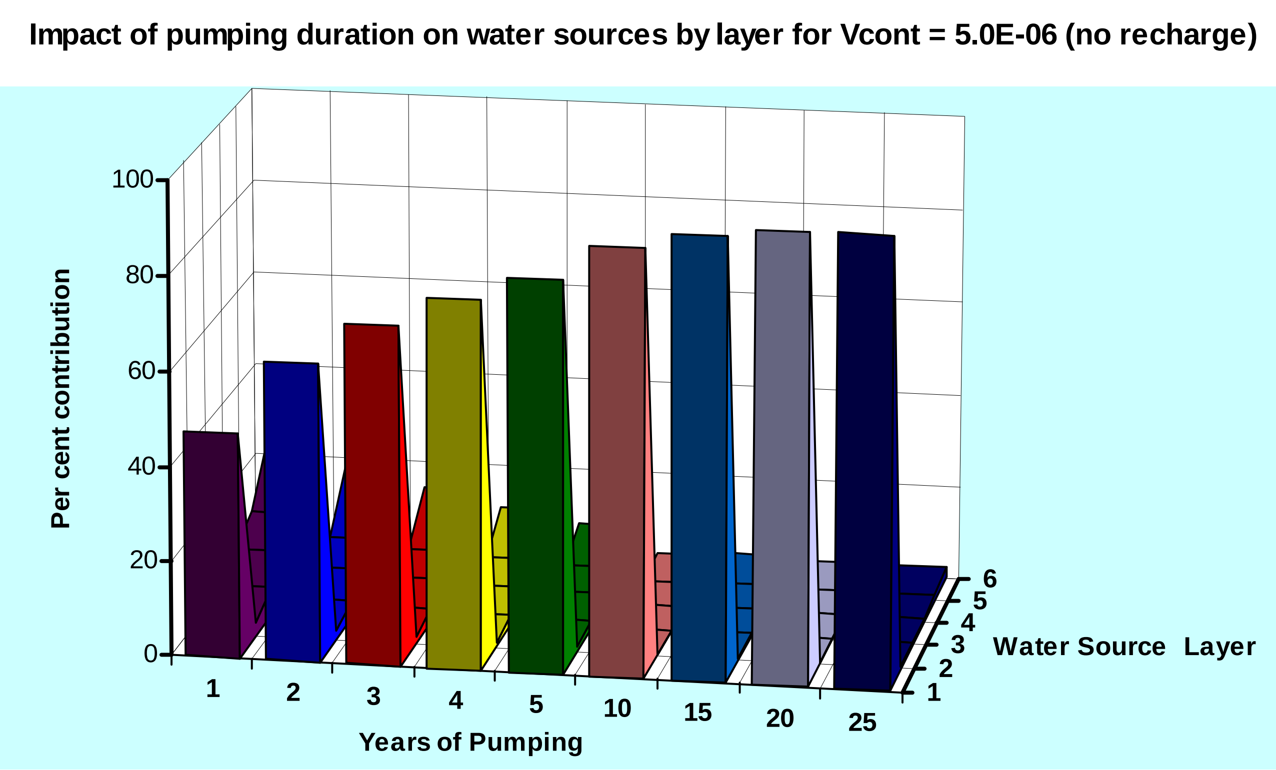
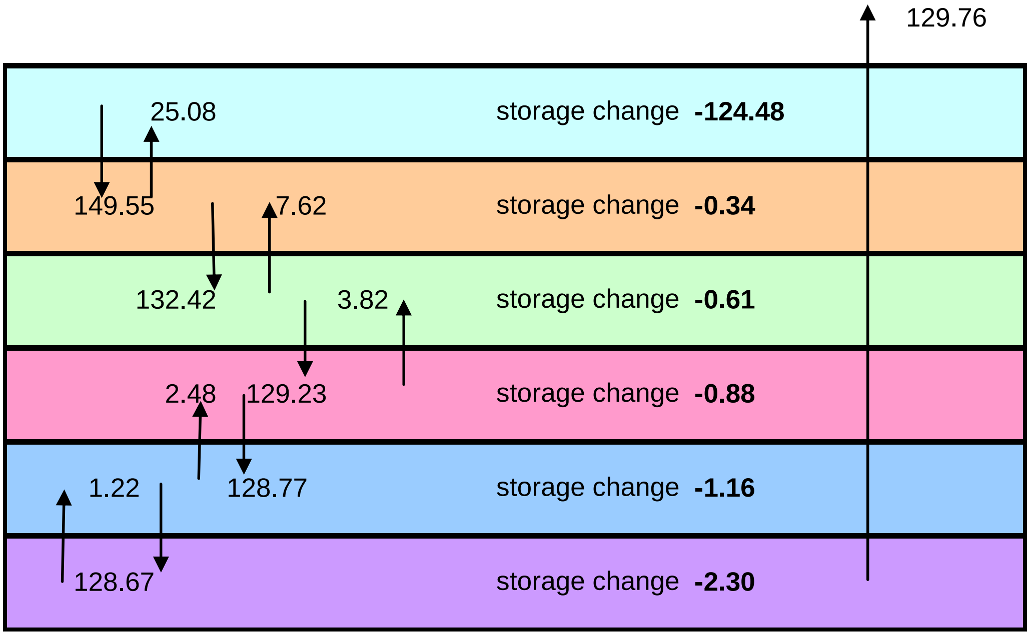


Figure 12: Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer at end of 25 years of pumping

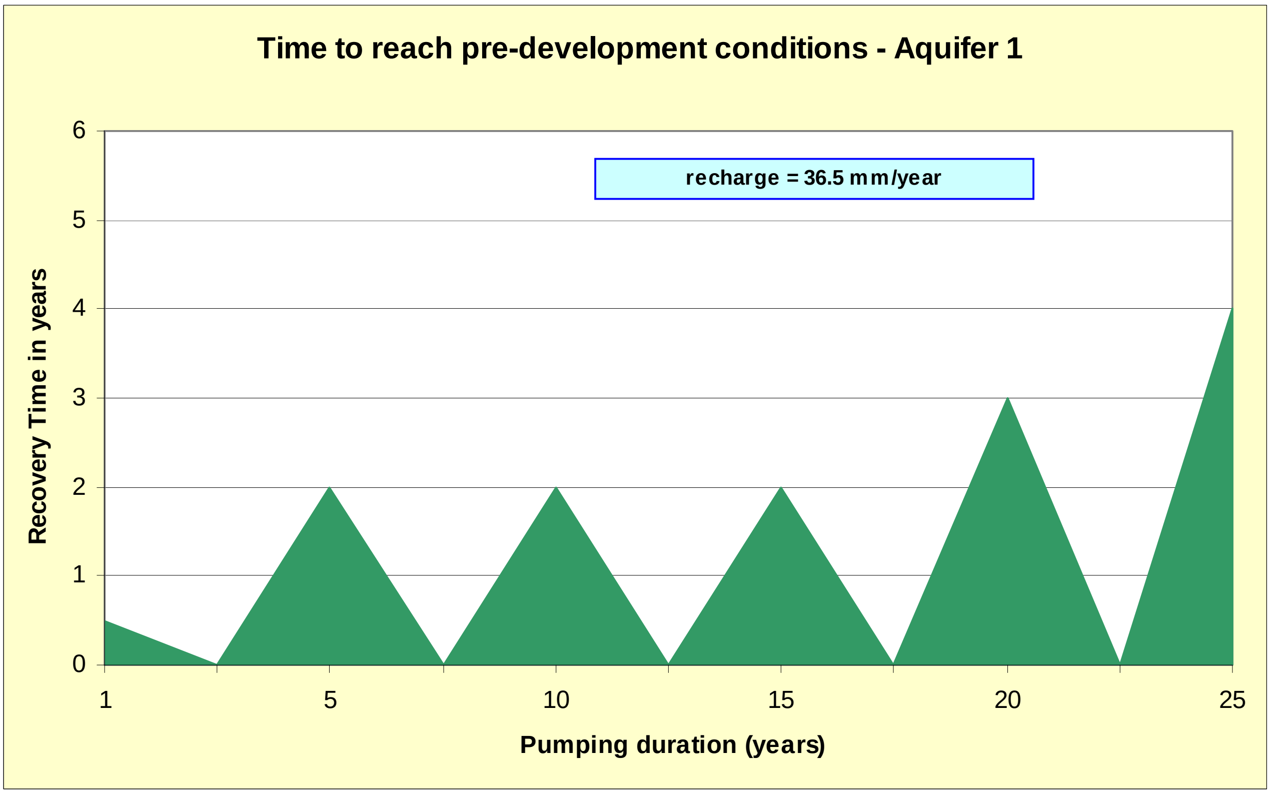


3.2.4 Time to reach pre-development conditions

The water source layer heads at the end of the various pumping duration scenarios were used to observe the recovery of the system to pre-development conditions. Recharge was applied at the average rate of 36.5 mm/year and all pumping was ceased.

- The time for the water table aquifer to fully recover as a function of increased pumping durations is given in Figure 13 which shows that the time for the water table aquifer to reach pre-development conditions after 25 years of pumping at the rates given in Table 6 was double the recovery after 5 years of pumping.
- The time for the deep water source to fully recover as a function of increased pumping durations at a Vcont of 5.0E-06 1/d was four years for all pumping durations.

Figure 13: Time to reach pre-development conditions in the water table aquifer (with recharge) as a function of pumping duration



3.3 Outflow impacts after one year of groundwater extraction

Scenarios for varying distances of groundwater extraction were run to determine the effects on the system outflows. These scenarios illustrated the sensitivity of the stacked water source system due to the proximity of groundwater extraction to the outflow boundary.

3.3.1 Outflow impact scenarios

Distances from the outflow boundary were investigated at 50, 40, 30, 20, 10 and 5 kilometres. Refer to Table 4 for the list of modelled scenarios for a no recharge and average recharge scenarios.

3.3.2 Maximum impact on outflow

The maximum impact on outflows from the water table aquifer for a no recharge condition as a function of varying vertical leakance values (Table 7) can be compared with impacts when the average recharge was applied (Table 8).

Results for maximum outflow impacts for the various vertical leakances as a function of distance are displayed graphically in Figure 16. Results for maximum outflow impacts for the various distances as a function of vertical leakance are displayed graphically in Figure 17.

The maximum impact on outflows from the water table aquifer:

- decreased when recharge was applied to the model area,
- increased as the pumping distance from the outflow boundary was decreased,
- had little variation for Vcont values less than 1.0E-06 1/d,
- had little variation for distances from boundary greater than 20 kilometres, and
- outflows began to cease in Layer 1 under the average recharge scenario when pumping occurred within 2.5 kilometres of the outflow boundary for the leakiest Vcont value of 1.0E-04 1/d.

Table 7: Maximum impact on boundary outflow as per cent decrease in outflow for various pumping distances and vertical leakance values (no recharge)

No Recharge applied	Vertical leakance value range 1/d						
Distance from outflow boundary (km)	1.0E-04	5.0E-05	1.0E-05	5.0E-06	1.0E-06	5.0E-07	1.0E-07
5	-21.9%	-17.9%	-9.3%	-8.4%	-7.92%	-7.90%	-7.85%
10	-12.9%	-12.1%	-9.3%	-8.5%	-7.93%	-7.88%	-7.85%
20	-10.3%	-9.5%	-8.6%	-8.3%	-7.94%	-7.89%	-7.85%
30	-10.3%	-9.4%	-8.4%	-8.2%	-7.93%	-7.89%	-7.85%
40	-10.3%	-9.4%	-8.3%	-8.1%	-7.92%	-7.88%	-7.85%
50	-10.3%	-9.4%	-8.3%	-8.1%	-7.91%	-7.88%	-7.85%

Table 8: Maximum impact on boundary outflow as per cent decrease in outflow for various pumping distances and vertical leakance values (with recharge)

Recharge applied	Vertical leakance value range 1/d						
Distance from outflow boundary (km)	1.0E-04	5.0E-05	1.0E-05	5.0E-06	1.0E-06	5.0E-07	1.0E-07
5	-10.3%	-7.1%	-3.6%	-3.3%	-3.07%	-3.05%	-3.0%
10	-5.1%	-4.8%	-3.6%	-3.3%	-3.06%	-3.05%	-3.0%
20	-4.1%	-3.8%	-3.3%	-3.2%	-3.08%	-3.05%	-3.0%
30	-4.1%	-3.7%	-3.2%	-3.2%	-3.08%	-3.05%	-3.0%
40	-4.1%	-3.7%	-3.2%	-3.1%	-3.07%	-3.05%	-3.0%
50	-4.1%	-3.7%	-3.2%	-3.1%	-3.07%	-3.05%	-3.0%

Figure 14: Maximum impact on outflows from water table aquifer after 1 year pumping as a function of distance (with recharge)

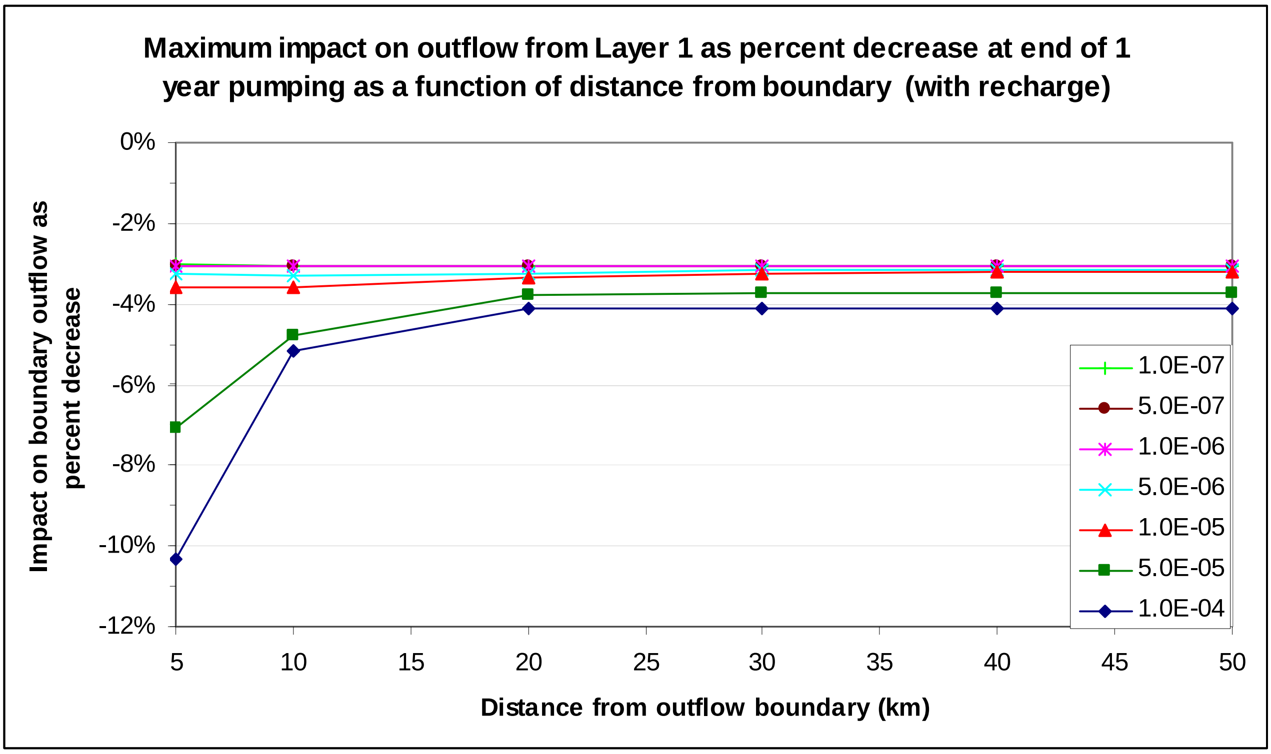
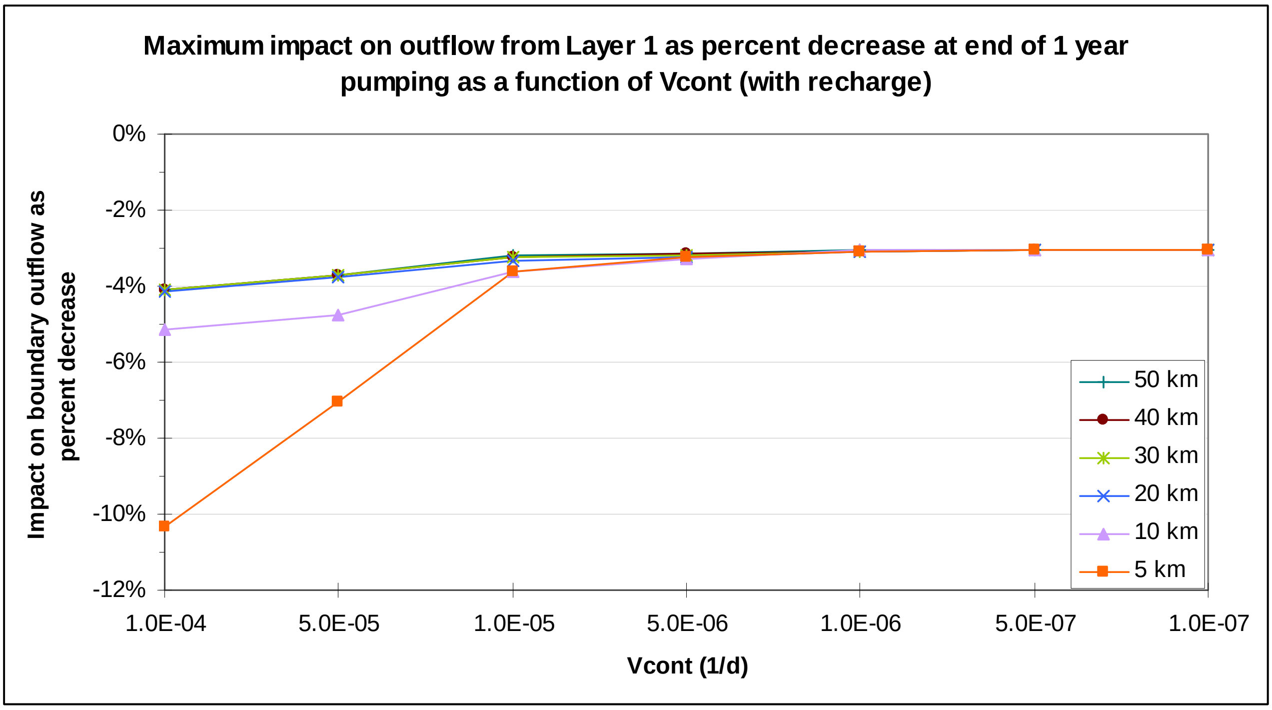


Figure 15: Maximum impact on outflows for water table aquifer aquifer after 1 year pumping as a function of vertical leakance (with recharge)



3.4 Outflow impacts from pumping

Scenarios for varying distances of groundwater extraction were run for pumping durations of 5 and 25 years to determine the effects on the system outflows. These scenarios illustrated the sensitivity of the stacked water source system due to the proximity of groundwater extraction to the outflow boundary and the duration of pumping. Scenarios were run consistent with the one year pumping duration scenarios without recharge during the pumping period, and an average recharge applied for the model recovery duration.

3.4.1 Maximum impact on outflow

The maximum impact on outflows from the water table aquifer for an average recharge condition as a function of distance from the outflow boundary for the middle range vertical leakance value Vcont of 5.0E-06 1/d is given in Table 9 for pumping durations of one, five and twenty-five years. This is displayed graphically in Figure 16.

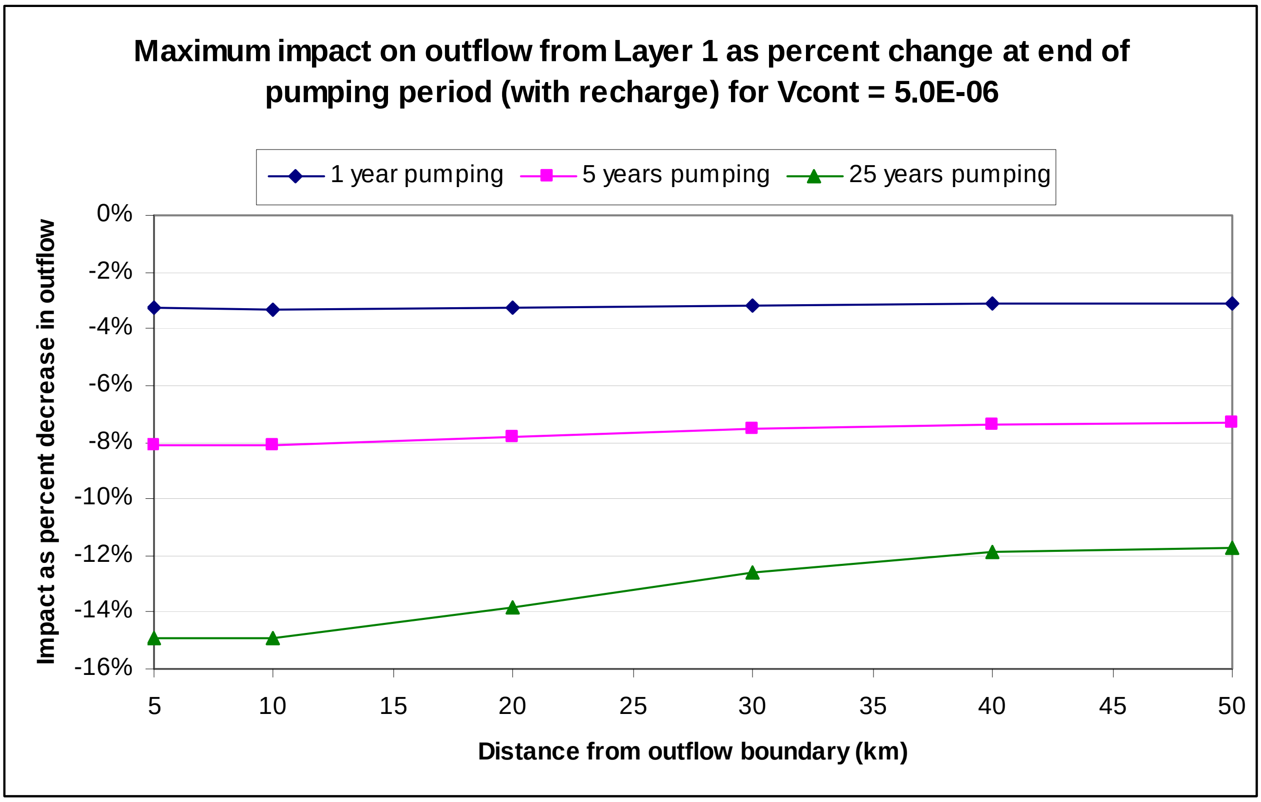
The maximum impact on outflows from the water table aquifer:

- increased as the pumping duration increased,
- increased as the pumping distance from the outflow boundary was decreased.

Table 9: Maximum impact on boundary outflow as per cent decrease in outflow for various pumping durations for Vcont = 5.0E-06 1/d (with recharge)

	Pumping duration		
Distance from outflow boundary (km)	1 year	5 years	25 years
5	-3.3%	-8.1%	-14.9%
10	-3.3%	-8.1%	-14.9%
20	-3.2%	-7.8%	-13.8%
30	-3.2%	-7.5%	-12.6%
40	-3.1%	-7.4%	-11.9%
50	-3.1%	-7.3%	-11.7%

Figure 16: Maximum impact on boundary outflow as per cent decrease in outflow for various pumping durations for Vcont = 5.0E-06 1/d (with recharge)



4. Conclusion

The modelling results evaluated the impacts of extracting a volume from the deep water source for scenarios of varying aquitard leakance and varying distances to an outflow boundary.

The model and impact evaluation results should be used to inform the local expert panel on possible impact scenarios that may occur in the generic stacked water source model represented in this report.

The results from the Stacked Water Source modelling mainly indicated that for groundwater extraction from the deep water source:

- For decreasing leakance values (from 1.0E-04 1/d to 1.0E-07 1/d) the impact on the hydraulic head was confined to the deeper aquifers. Where leakance was higher, the impacts were seen on the water table aquifer and the water table itself.
- For a leaky system, the groundwater pumped is largely sourced from the upper layers.
- For a non-leaky system, the groundwater pumped is largely sourced laterally from the deep water source.
- A volume of storage could be taken from the deep aquifer, under certain scenarios was seen to have little impact on the upper aquifer layers to no impact.

The maximum impact on outflows from the water table aquifer

- increased as the pumping distance from the outflow boundary was decreased,
- had little variation for Vcont values less than 1.0E-06 1/d,
- had little variation for distances from the outflow boundary greater than 20 kilometres.

As pumping duration increased

- the impact on the water table aquifer increased,
- the impact on water table outflows increased, and
- the proportion of groundwater pumped being sourced from the water table aquifer increased.

The time for recovery to reach pre-development conditions

- was longer as vertical leakance values decreased,
- was longer for the deep water source than the water table aquifer (due to recharge and vertical leakance)
- was longer for extended pumping durations
    - for a Vcont of 5.0E-06 1/d the recovery time varied from less than one year to four years in the water table aquifer when pumping was increased from one year to twenty-five years.

5. References

Fetter, C.W. (2001), *Applied Hydrogeology, Fourth Edition.* Prentice Hall, Inc.

McDonald, Michael G. and Harbaugh, Arlen W. *Electronic Manual for MODFLOW, A Modular 3D Finite-Difference Ground-Water Flow Model,* USGS.

Reilly, Thomas E. (2001), *System and Boundary Conceptualisation in Ground-Water Flow Simulation,* USGS.

Appendix A: Technical definition of Vcont and worked example

Definition of Vcont

Vertical leakance of a confining layer is represented by the term Vcont in MODFLOW. The Vcont term is ultimately the conductance of the interval between two cell nodes divided by the cell area. The nodes are located at the midpoints of the aquifers which are separated by a semi confining unit. Vcont incorporates hydraulic conductivity and thickness, rather than independent inputs for thickness and conductivity. A diagram for the calculation of vertical leakance is given in Figure 17.

The nodes are within two aquifers which are separated by a semi confining unit represented by the lower half of the upper aquifer, the semi confining unit, and the upper half of the lower aquifer. This Vcont term is represented in Equation A.1. The program multiplies Vcont by cell area to obtain vertical conductance (McDonald and Harbaugh).

$$Vcont_{i,j,k+1/2} = \frac{1}{\dfrac{\Delta z_{u/2}}{K_{zu}} + \dfrac{\Delta z_{C}}{K_{zc}} + \dfrac{\Delta z_{L/2}}{K_{zL}}}$$

Equation A.1

where

Δz_u = thickness of the upper aquifer

Δz_c = thickness of the confining bed

Δz_L = thickness of the lower aquifer

K_{zu} = vertical hydraulic conductivity of the upper aquifer

K_{zc} = vertical hydraulic conductivity of the semiconfining unit

K_{zL} = vertical hydraulic conductivity of the lower aquifer

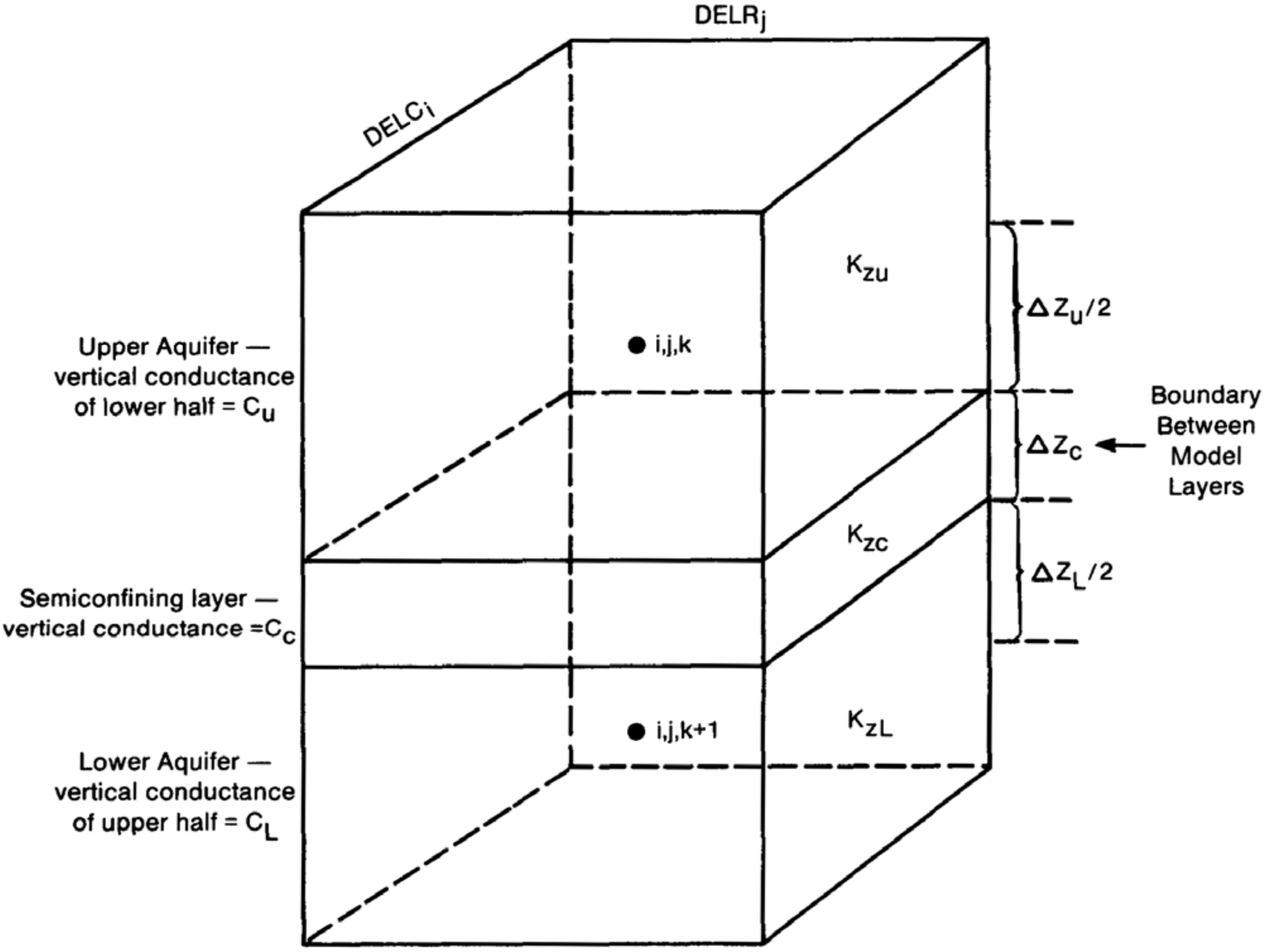
In many applications K_{zc} is much smaller than either K_{zu} or K_{zL}; in these situations the terms involving K_{zu} and K_{zL} are negligible and Vcont can then be reduced to Equation A.2 (McDonald and Harbaugh).

$$Vcont_{i,j,k+1/2} = \frac{K_{zc}}{\Delta z_C}$$

Equation A.2

This equation results in a Vcont term that can be represented by the thickness of the confining layer and the vertical hydraulic conductivity of the confining layer.

Figure 17: Diagram for calculation of vertical leakance, Vcont, between two nodes with a semi confining unit between.



$$\frac{1}{C_{eq}} = \frac{1}{C_u} + \frac{1}{C_c} + \frac{1}{C_L} =$$

$$\frac{1}{DELC_i * DELR_j}\left\{\frac{\Delta Z_u/2}{K_{zu}} + \frac{\Delta Z_c}{K_{zc}} + \frac{\Delta Z_L/2}{K_{zL}}\right\}$$

$$VCONT_{i,j,k+1/2} = \frac{1}{\dfrac{\Delta Z_u/2}{K_{zu}} + \dfrac{\Delta Z_c}{K_{zc}} + \dfrac{\Delta Z_L/2}{K_{zL}}}$$

Use of pumping test data to calculate of Vcont

The definition of Vcont can be described as the ratio of vertical hydraulic conductivity of the confining layer to the thickness of the confining layer as given in Equation A.2. This derivation can be shown to be relevant when compared to the Hantush-Jacob formula which describes flow in a confined aquifer.

Using the data collected from pumping test data, a formula for determining Vcont may be derived from the following Hantush-Jacob formula. The two main assumptions valid for this formula are that no water drains from the confining layer and that groundwater flow in the aquitard is vertical (Fetter, 2001). The formulas are given below:

$$B = (Tb'/k')^{1/2}$$

Equation A.3

$$T = b * k$$

Equation A.4

where

B = leakage factor (m)

b’ = thickness of aquitard (m)

k’ = hydraulic conductivity of aquitard (m/d)

T = transmissivity of the confined aquifer (m^2/d)

k = hydraulic conductivity of confined aquifer

b = thickness of confined aquifer

Substituting Equation A.4 into Equation A.3 and solving for the Vcont term is given below:

$$B^2 = \frac{b * k * b'}{k'}$$

$$\frac{B^2}{k * b} = \frac{b'}{k'}$$

$$Vcont = \frac{k'}{b'} = \frac{k * b}{B^2}$$

Example from pumping test and monitoring bore data

The method described above should be able to be used to derive Vcont values associated with pumping test results in order to interpret the modelling figures presented in this report.

An example is provided here that has been taken from a pumping test analysis conducted by the NSW Office of Water on a property in Zone 6 of the Upper Macquarie alluvium.

A 14-day duration pumping test which used measurements from seven monitoring bores was analysed using AQTESOLV® Version 3.01 Professional. A Theis curve was best fit to the data using the Hantush-Jacob solution. The shape of the data curve indicated a leaky-confined condition as described by Fetter (2001).

The results for leakage factor, r/B, and transmissivity, T, for each monitoring bore are listed for the three best-fitting data in Table 10. Assuming that the vertical leakance terms of the overlying and underlying aquifer layers are negligible compared to the confining bed, the above derivation for Vcont was applied to the data results. The estimated Vcont values based on the transmissivity and leakage factor from the pumping test results are listed in Table 10.

Table 10: Lower Macquarie alluvium pumping test results and estimated aquifer properties and Vcont

Monitoring Bore	r (m)	T (m^2/d)	r/B	k (m/d)	B (m)	B^2 (m^2)	Vcont =T/B^2 (1/d)
gw08464	572	666.5	0.25	11.5	2288	5234944	1.27E-04
test bore4	652	610	0.41	10.4	1590	2528876	2.41E-04
gw036533	852	510	0.46	8.7	1852	3430548	1.49E-04
							Average = 1.72E-04

The estimated Vcont values based on average aquitard thickness, b’, estimated from bore logs and the estimated a hydraulic conductivity, k', from the pumping test results for the confining unit are given in Table 11.

Table 11: Lower Macquarie alluvium pumping test results and estimated aquitard properties and Vcont

Monitoring Bore	b' (m)	k' (m/d)	Vcont = k'/b' (1/d)
gw08464	1.0	1.26E-04	1.26E-04
test bore4	8.6	2.02E-03	2.35E-04
gw036533	12.4	1.84E-03	1.48E-04
			Average = 1.70E-04

An estimated average Vcont value of 1.7E-04 is considered a leaky condition which is consistent with the pumping test results which indicated a leaky-confined aquifer type.

Appendix B: Storage change and leakance diagrams by layer for one year pumping

Figure 18: Vcont value of 1.0E-04 1/d distribution of storage change and leakage (GL) by layer

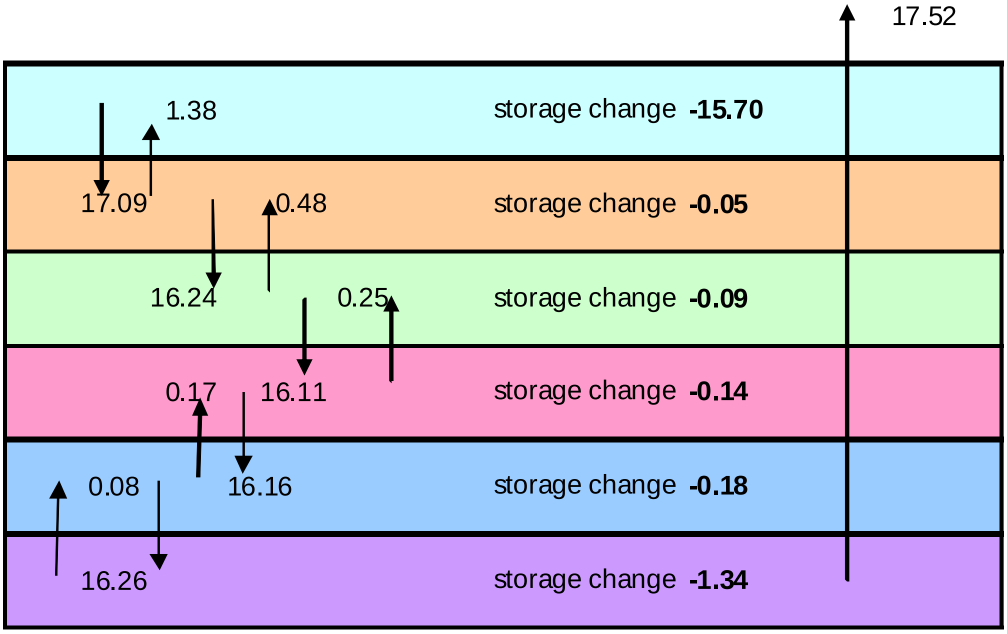


Figure 19: Vcont value of 5.0E-05 1/d distribution of storage change and leakage (GL) by layer

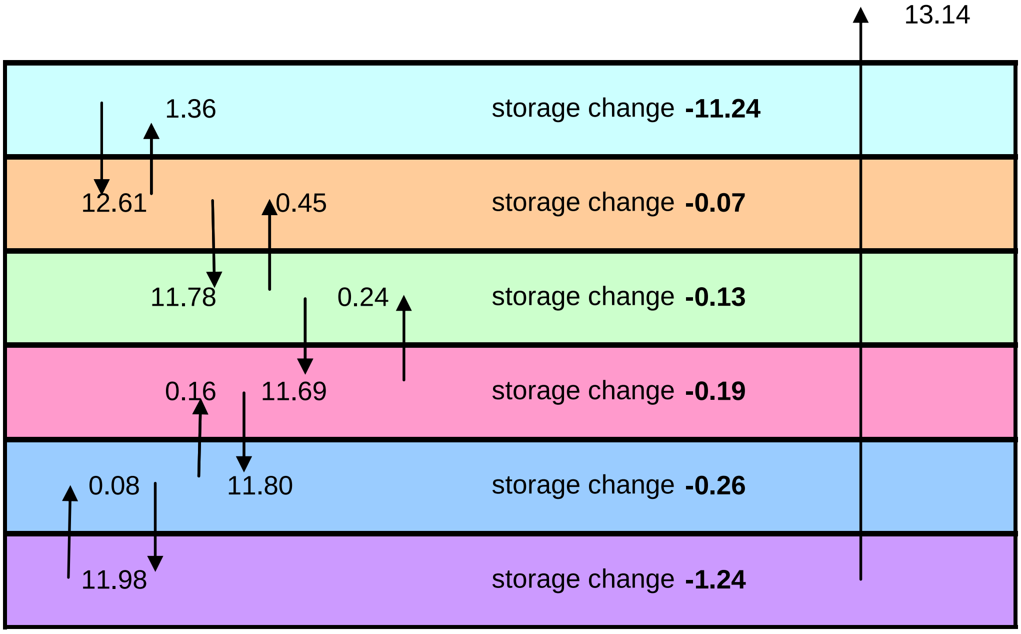


Figure 20: Vcont value of 1.0E-05 1/d distribution of storage change and leakage (GL) by layer

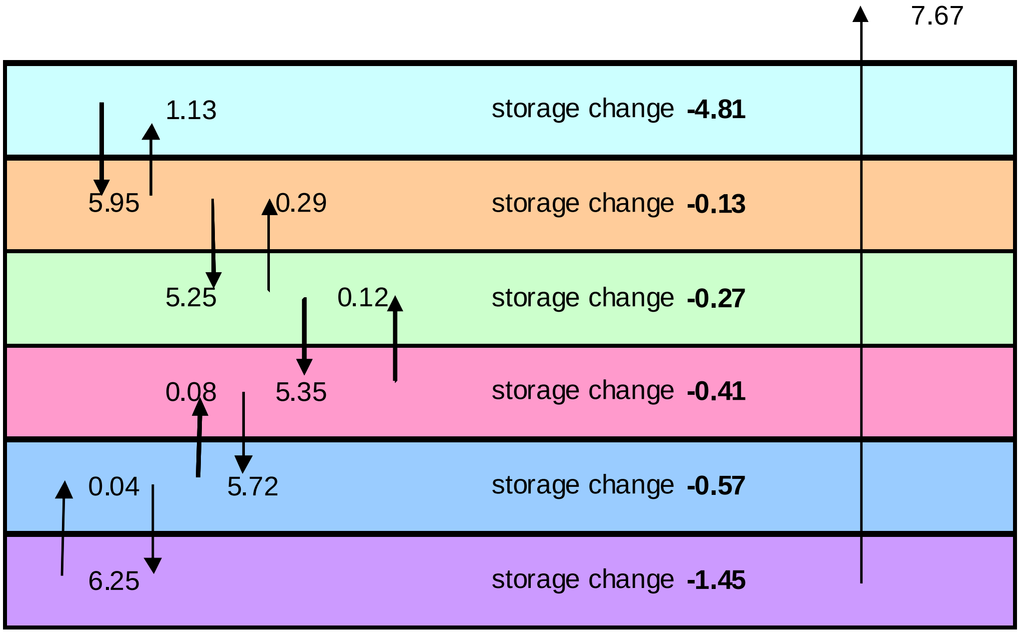


Figure 21: Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

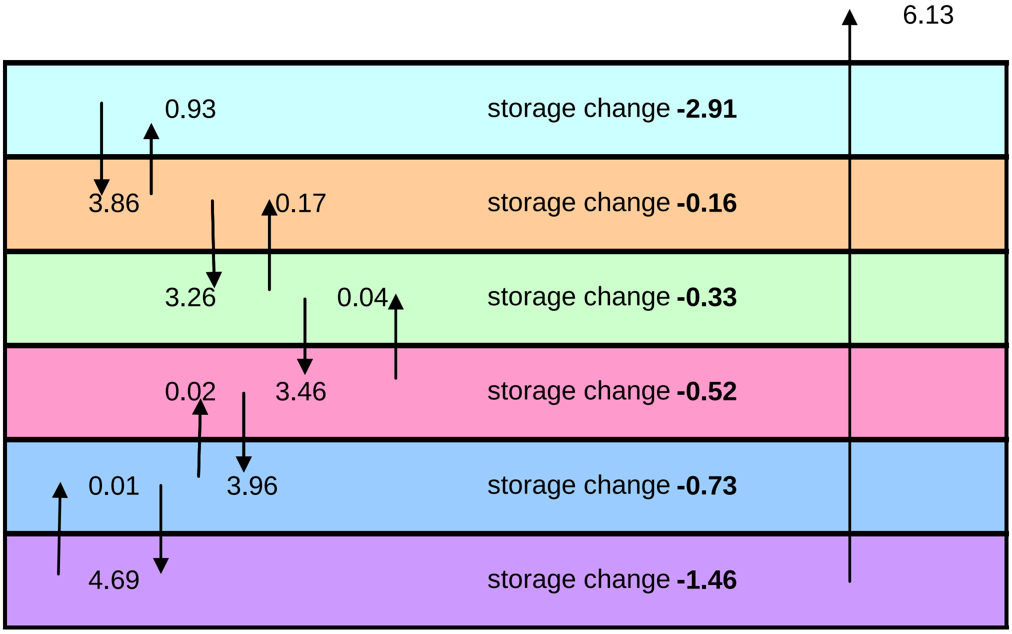


Figure 22: Vcont value of 1.0E-06 1/d distribution of storage change and leakage (GL) by layer

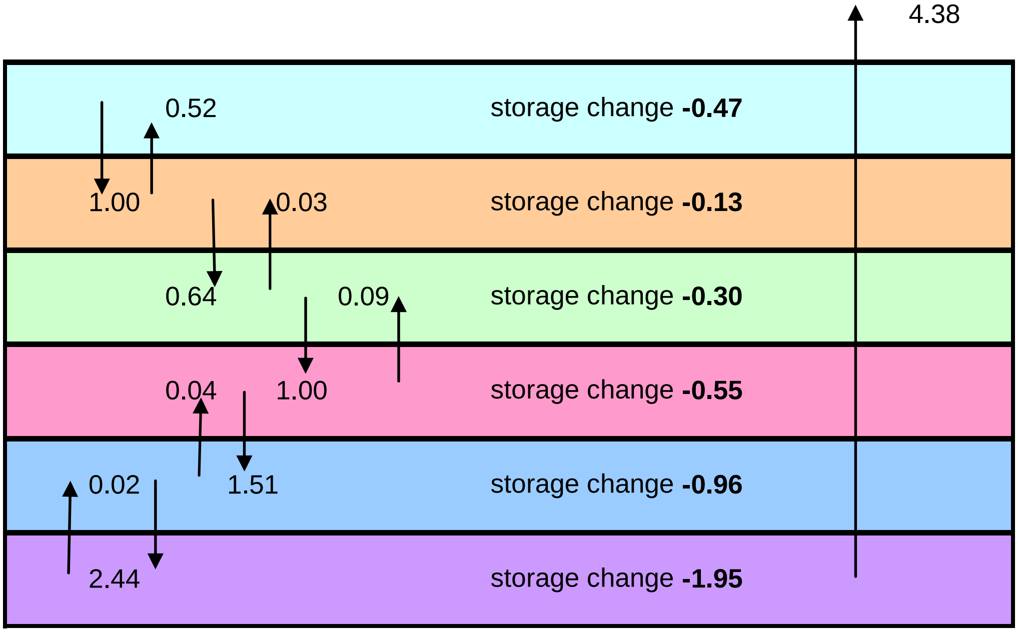


Figure 23: Vcont value of 5.0E-07 1/d distribution of storage change and leakage (GL) by layer

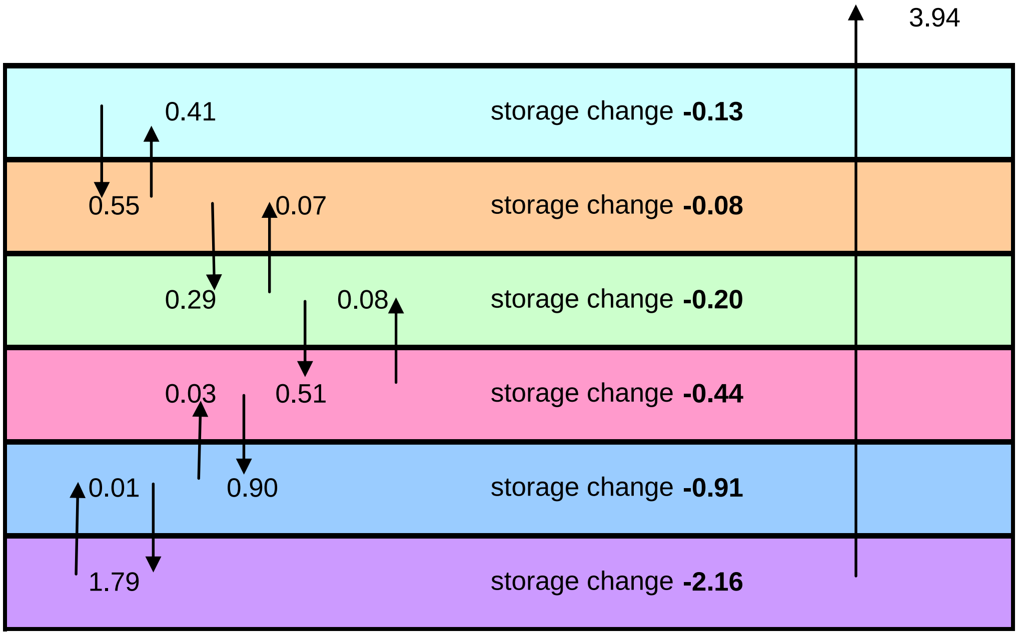
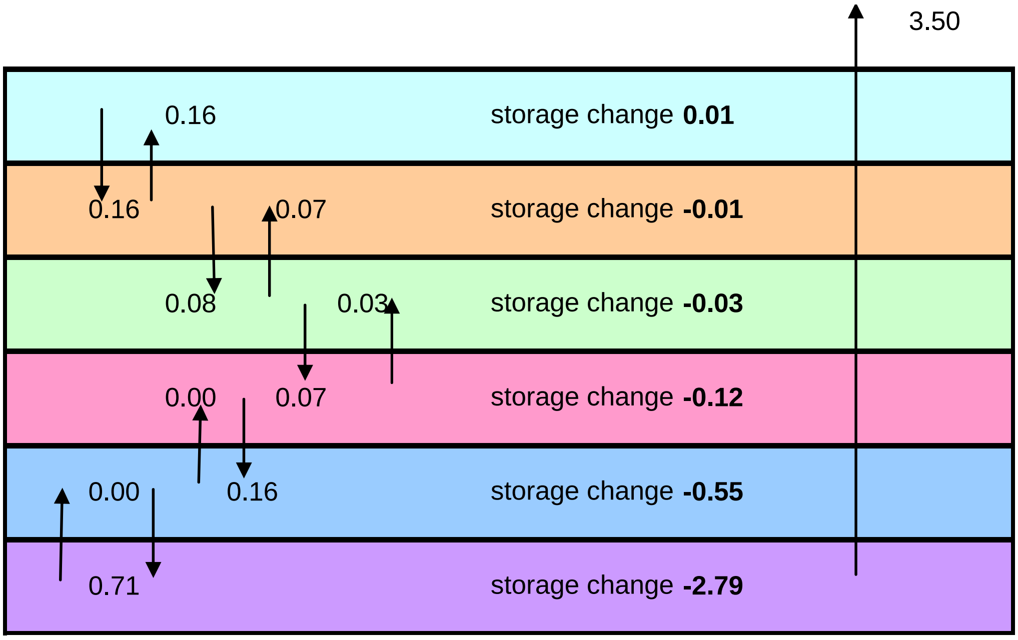


Figure 24: Vcont value of 1.0E-07 1/d distribution of storage change and leakage (GL) by layer



Appendix C: Storage change and leakance diagrams by layer for two, three, four, five, ten, fifteen, twenty and twenty five years of pumping

Figure 25: Two years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

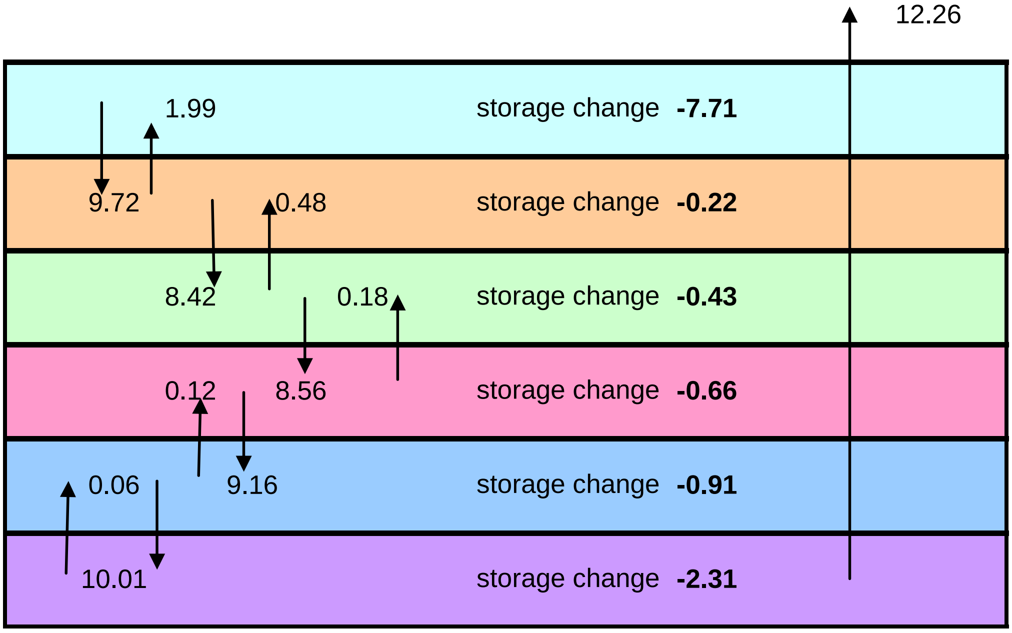


Figure 26: Three years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

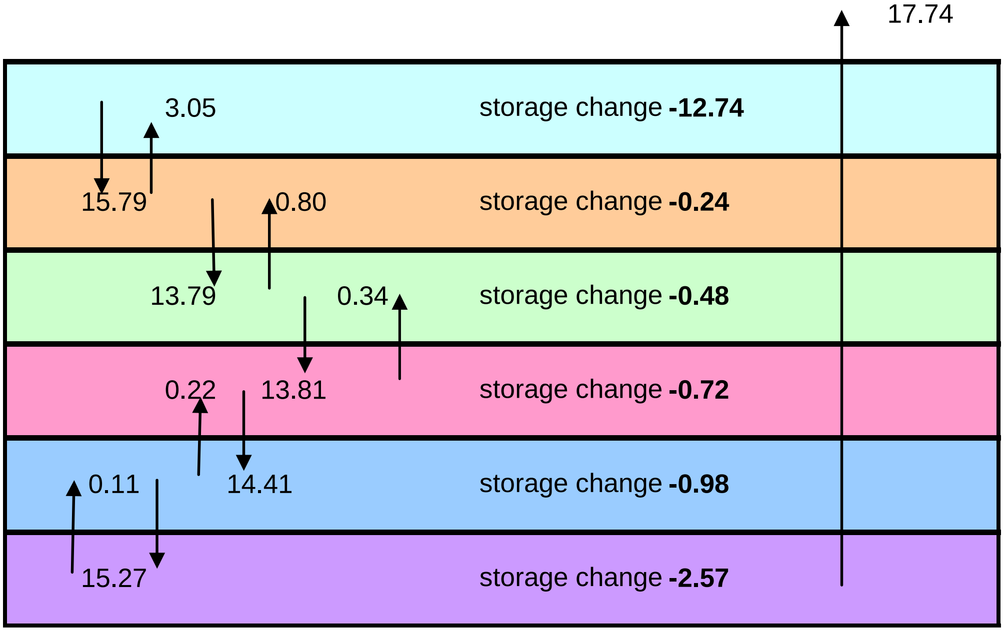


Figure 27: Four years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

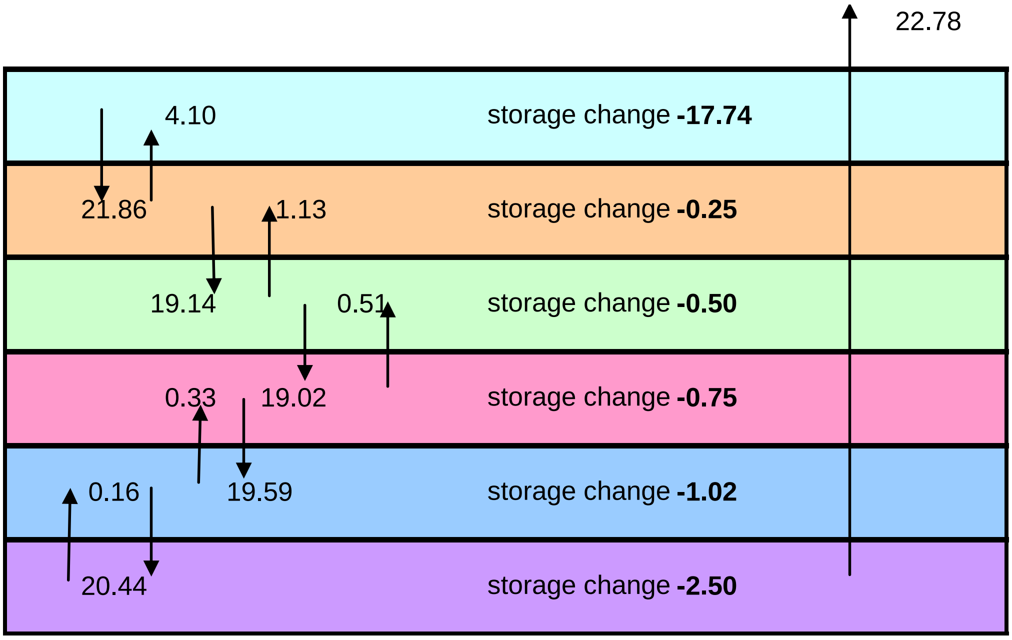


Figure 28: Five years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

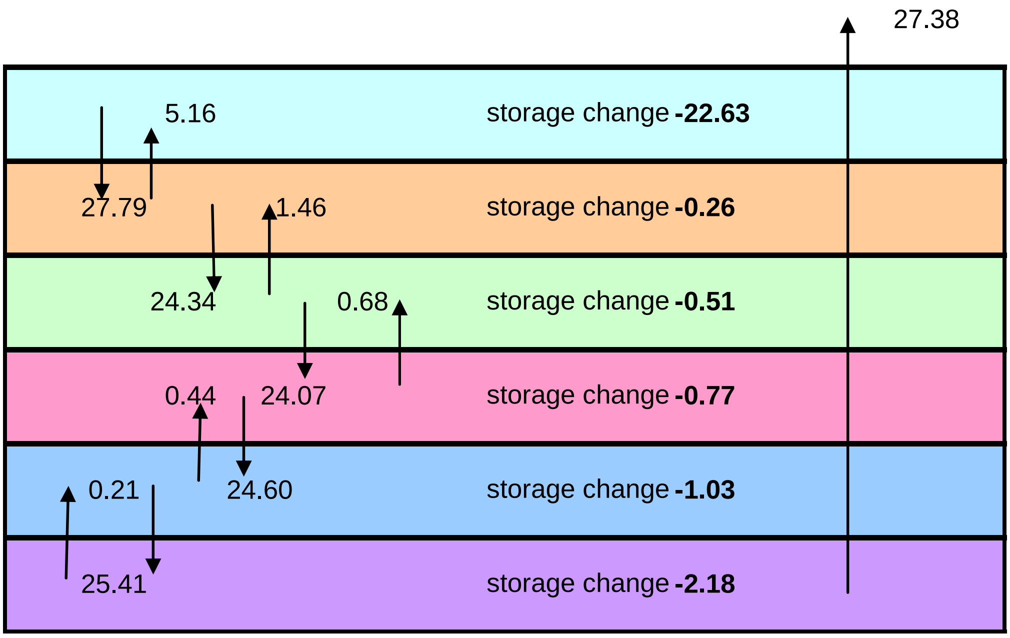


Figure 29: Ten years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

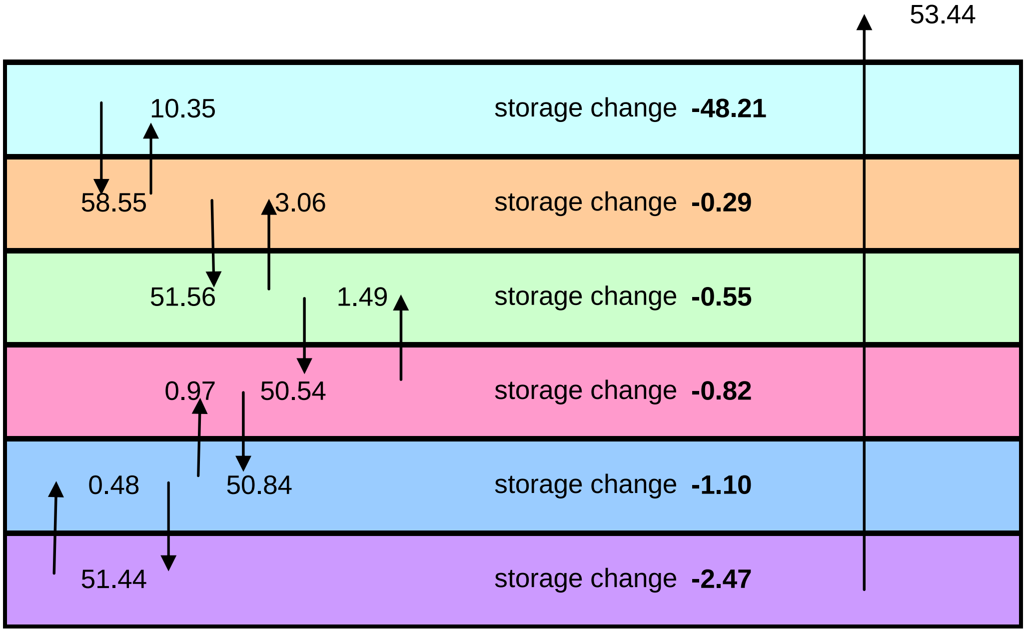


Figure 30: Fifteen years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

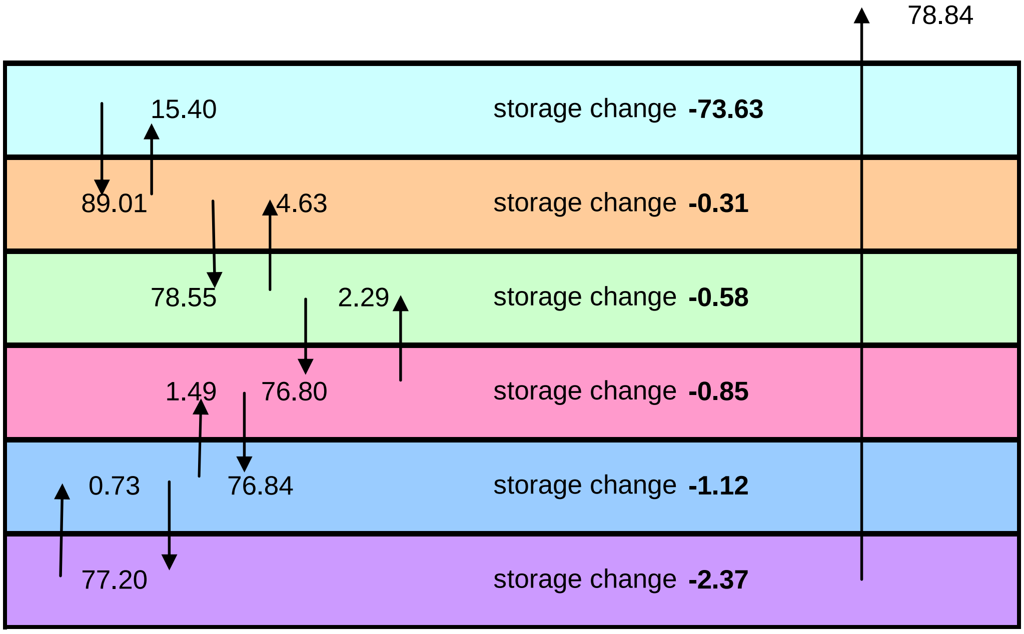


Figure 31: Twenty years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer

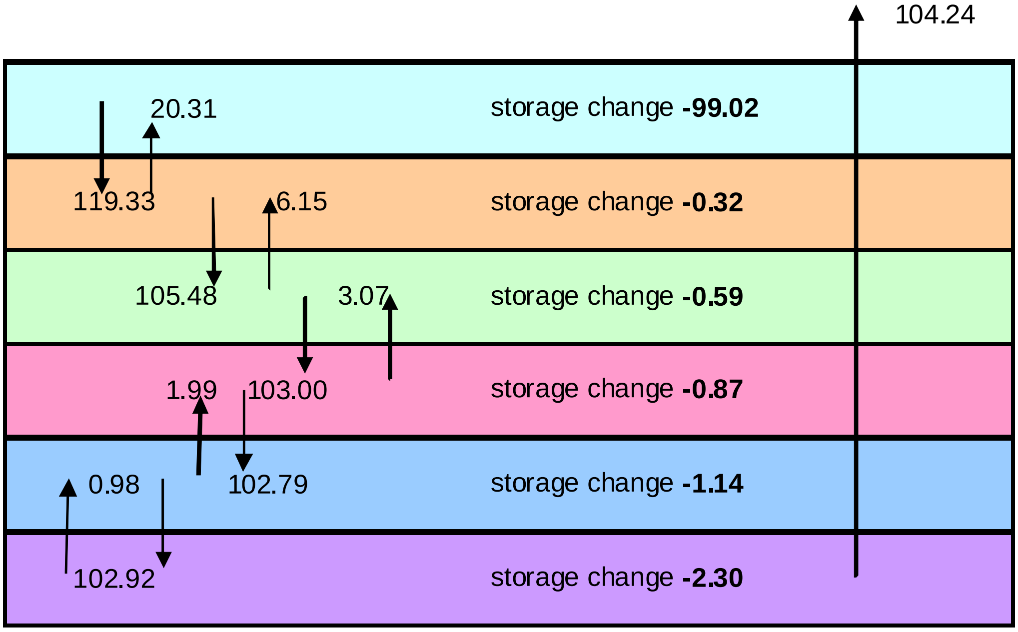


Figure 32: Twenty-five years pumping duration for Vcont value of 5.0E-06 1/d distribution of storage change and leakage (GL) by layer