LAND SETTLEMENT DUE TO GROUNDWATER PUMPING IN THE LOWER NAMOI VALLEY OF NSW

Ali A[1], **Merrick** N P[1], **Williams** R M[2] , **Mampitiya** D[2], **d 'Hautefeuille** F[2] and **Sinclair** P[3]
1. National Centre for Groundwater Management, University of Technology, Sydney
2. Department of Infrastructure Planning and Natural Resources – Parramatta
3. Department of Infrastructure Planning and Natural Resources – Tamworth

NCGM – UTS, PO Box 123 Broadway, Sydney, NSW 2007, Australia.
E-mails: NMerrick@uts.edu.au
Phone: +61(0)2 95141984 Fax: +61(0)2 95141985

ABSTRACT

A 10-year water sharing plan (WSP) has been developed for the Lower Namoi aquifer that stretches from Narrabri to Cryon in northern NSW. Under the Water Management Act 2000 (WMA), WSPs are being put in place to define the water sharing arrangements between the environment and water users, and between different categories of water users. The plans are designed to provide for healthier rivers and groundwater systems and dependent ecosystems. They provide water users with clarity and certainty about their water access rights.

As part of the WSP, local water level response management is being trialled. Factors considered are land subsidence, groundwater quality, priority groundwater dependent ecosystems and social issues such as bore interference.

In 1974 a series of benchmarks was established from which land subsidence could be monitored. These were supplemented by a more intensive network installed in 1981. Survey levelling of these sites was carried out in 1982, 1987, 1988 and 1990. Subsidence of between 0.08 and 0.21 metres was recorded for the 10-year period 1981 to 1990.

Since that time the volume of groundwater pumping has continued to increase and water levels have continued to fall. A 3-layer regional MODFLOW groundwater flow model for the period 1980 to 1998 has been calibrated, verified, subjected to post audit, and externally reviewed. The model has been used to simulate subsidence, to see if MODFLOW is sufficient for this purpose, and to see if satisfactory calibration is possible with plausible storage and compressibility parameters. Reasonable calibration has been achieved. Subsidence studies overseas have shown that residual compaction can lag far behind water level fluctuations. It is demonstrated here that residual compaction is unlikely for the Lower Namoi aquifer system.

This initial effort at simulating subsidence will guide the approach taken in other valleys in New South Wales, and the lessons learned will be used in the hierarchy of water level response management tools that are to be applied as a secondary consideration to water sharing plans.

INTRODUCTION

The Water Management Act (2000) requires the preparation of water sharing plans (WSPs) for New South Wales aquifer systems, with a tenure of 10 years. WSPs are being put in place to define the water sharing arrangements between the environment and water users, and between different categories of water users. The plans are designed to provide for healthier rivers and groundwater systems and dependent ecosystems. They provide water users with clarity and certainty about their water access rights.

As part of the implementation of the WSP local water level response management is being trialled, in order to protect the local sustainability of the aquifer system. This approach is complementary to sustainable yield management. Local impact management (based on water level response) will be implemented if there is unacceptable hydraulic interference between neighbouring bores, if water quality is in danger of being degraded, if priority groundwater dependent ecosystems require protection, or if excessive pumping is likely to cause permanent compaction of sediments and subsequent land subsidence.

Measurable subsidence has occurred in the Lower Namoi Valley aquifer that stretches from Narrabri to Cryon in northern NSW. This valley hosts the most developed groundwater system in the State, with more than 30 years of irrigated agriculture. Significant quantities of groundwater (along with surface water) are used to irrigate summer crops, predominantly cotton. The aquifer system is highly over-committed and steps are in place to reduce groundwater allocations over the life of the WSP for this valley. In 1974 a series of benchmarks was established from which land subsidence could be monitored. These were supplemented by a more intensive network installed in 1981. Survey levelling of these sites was carried out in 1982, 1987, 1988 and 1990. Subsidence of between 0.08 and 0.21 metres was recorded for the 10-year period 1981 to 1990 (Ross and Jeffery, 1991).

One of the concerns is that the excessive pumping of groundwater in past decades might induce residual compaction. That is to say, that even if water levels can be stabilised, the subsidence might continue for a long time. This lag has been reported for many aquifers overseas.

LAND SUBSIDENCE AND AQUIFER-SYSTEM COMPACTION

Land subsidence is the gradual settling or sudden sinking of the Earth's surface owing to subsurface movement of earth materials. One of the principal causes of land subsidence is the gradual compaction of susceptible aquifer systems that can accompany groundwater level declines caused by groundwater pumping . Detrimental effects of land subsidence include the loss of aquifer storage, increased flooding, cracks and fissures at land surface, damage to man-made structures, and intangible economic costs.

Compaction of the aquifer system occurs when the hydraulic head or fluid pressure in compressible, fine-grained sediments declines, releasing pore water in the compressible sediments from storage. (Fluid pressure has units of stress and is equal to hydraulic head times the specific weight of water.) For a constant total stress on the aquifer system, the associated decrease in fluid pressure is accompanied by an equivalent increase in the effective or intergranular stress on the granular matrix or skeleton of the aquifer system, resulting in aquifer-system compaction. The magnitude of the compaction is governed by the compressibility of the sediments, which varies by an order of magnitude or more depending on whether the intergranular stress changes are in the elastic or inelastic range of stress for the compacting sediments. Elastic compaction is compaction that occurs when the skeletal structure of the sediments is not permanently rearranged: it can be reversed by an associated rise in hydraulic head. Inelastic compaction is compaction that occurs when there is a permanent rearrangement of the skeletal structure of the sedimentary matrix; it cannot be reversed by a rise in hydraulic head, and, therefore, results in a permanent lowering of land surface and a loss of groundwater storage capacity. The point to which hydraulic heads must decline to cause inelastic compaction in the compressible sediments is termed the preconsolidation head.

In the context of an aquifer system, the past maximum stress, or preconsolidation stress, can generally be represented by the previous lowest groundwater level. For stress less than preconsolidation stress—that is, groundwater level higher than previous lowest groundwater level (preconsolidation stress), the aquifer system deforms elastically, and the deformation is recoverable. For stress beyond preconsolidation stress—groundwater level lower than previous lowest groundwater level, the pore structure of the system’s susceptible fine-grained sediments may undergo a significant rearrangement, resulting in permanent reduction of the pore volume and vertical displacement of the land surface, or land subsidence.

Land subsidence due to groundwater pumping is well documented. There are reports of subsidence of about 9 m in Mexico City and the San Joaquin Valley of California, 7 m in Wairakei New Zealand, and 5 m in Tokyo (Poland 1984). Groundwater-induced subsidence is contributing to the slow demise of Venice in Italy.

Specific Storage

Water released from storage in an artesian aquifer, under the condition of a decreasing head, is from two mechanisms: the compression of the aquifer skeleton caused by an increase in effective stress, and expansion of water caused by decrease in pore pressure.

The specific storage (S_s), is defined as the volume of water released from or added to the unit volume of the aquifer material when the hydraulic head changes a unit amount. It is generally expressed as:

$$S_s = \rho_w g\,(\alpha + n\beta_w)$$

where S_s is specific storage of the aquifer material [L^{-1}], ρ_w is density of water [M/L^3], g is gravitational acceleration [L/T^2], α is compressibility of the aquifer material [LT^2/M], β_w is compressibility of the water [LT^2/M], and n is porosity of the aquifer material.

The term $\alpha\rho_w g$, is the component of the specific storage due to the compression of the aquifer material, caused by unit change in the pressure head, and is controlled by the compressibility of the soil matrix (α). This component is termed the skeletal component of the specific storage (S_{sk}). The term $\rho_w g\, n\beta_w$ is the component of the specific storage caused by the expansion of the water when the pressure head is lowered by a unit amount, and is controlled by compressibility of water β_w, and is denoted as S_{sw}.

The skeletal component of the specific storage addresses the storage change of the aquifer system due to the compression of the soil matrix. Skeletal compressibility of the fine-grained aquitards and coarse-grained aquifers typically differ by several orders of magnitude; therefore, it is useful to define them separately.

The skeletal specific storage of the aquitard, S'_{sk}, is defined for two ranges of stress (σ), elastic and inelastic:

$$S'_{sk} = \begin{cases} S'_{ske} = \alpha'_{ke}\rho_w g, & \sigma' < \sigma'_{(\max)} \\ S'_{skv} = \alpha'_{kv}\rho_w g, & \sigma' > \sigma'_{(\max)} \end{cases}$$

The subscripts *e* and *v* refer to elastic and inelastic properties, respectively. For a change in effective stress, the aquitard deforms elastically when the effective stress remains less than the previous maximum effective stress, σ'_{max}. When the effective stress exceeds σ'_{max}, the aquitard deforms inelastically.

For coarse-grained sediments typically found within aquifers, inelastic skeletal compressibility is negligible; therefore, skeletal specific storage of an aquifer (coarse-grained sediments), S_{sk}, is adequately represented by the fully recoverable, elastic component of the skeletal specific storage, S_{ske}:

$$S_{sk} = S_{ske} = \alpha_{ke}\rho_w g$$

where α_{ke} is elastic compressibility of the aquifer (coarse-grained) material.

The component of specific storage that addresses the expansion of water is composed of two parts; the expansion of the water in the aquifer, S_{sw}, and the expansion of the water in the aquitards, S'_{sw}. Thus, elastic specific storage of the whole aquifer system, S_s, can be expressed as:

$S_s = S_{ske} + S'_{ske} + S_{sw} + S'_{sw}$

As only aquitards compact inelastically, and the fact that S_{skv} is much greater than S'_{sw}, the aquitard inelastic skeletal specific storage, S_{skv}, can adequately represent the inelastic specific storage of the whole aquifer system:

$$S_{sv} = S'_{skv} = \alpha'_{skv}\rho_w g$$

where S_{sv} is inelastic specific storage of the aquifer system.

Riley (1998) concluded that, in a typical aquifer system consisting of unconsolidated to partially consolidated late Cainozoic sediment, the inelastic specific storage generally is 20 to more than 100 times larger than elastic specific storage. Water that drains during a permanent compaction event is lost forever and cannot be recharged.

Storage Coefficient

The product of the skeletal specific storage values of the aquitards, or aquifer, and aggregate thickness of the aquitards, $\Sigma b'$, or aquifer, Σb, define skeletal storage coefficient of the aquitards (S'_k), and the aquifers (S_k), respectively:

$$S'_k = \begin{cases} S'_{ke} = S'_{ske}\left(\Sigma b'\right), & \sigma' < \sigma'_{\max} \\ S'_{kv} = S'_{skv}\left(\Sigma b'\right), & \sigma' > \sigma'_{\max} \end{cases}$$

$$S_k = S_{ke} = S_{ske}\left(\Sigma b\right)$$

where S_{ke} is elastic skeletal storage coefficient of aquifers, S_{ke}' is elastic skeletal storage coefficient of the aquitards, and S_{kv}' is inelastic skeletal storage coefficient.

A separate equation relates the fluid compressibility of water to the component of the aquifer storage attributed to pore water, S_w:

$$S_w = S'_{sw}\left(\Sigma b'\right) + S_{sw}\left(\Sigma b\right) = \beta\rho_w g\left[n'\left(\Sigma b'\right) + n\left(\Sigma b\right)\right]$$

where n' and n are porosities, and S'_{sw} and S_{sw} are the specific storage components for water, of the aquitards and aquifers, respectively.

The aquifer system elastic storage coefficient, S, is defined as the sum of the skeletal storage coefficients of the aquitards and aquifers, plus the storage attributed to water compressibility:

$$S = S'_k + S_k + S_w$$

For a compacting aquifer system, the aquitard inelastic skeletal storage coefficient, S'_{kv}, is much greater than S_w, and the inelastic storage coefficient of the aquifer system, S_v, is approximately equal to the aquitard inelastic skeletal storage coefficient:

$$S_v \approx S'_{kv}$$

In a confined aquifer system subjected to large scale overdraft, the volume of water derived from irreversible aquitard compaction typically ranges from 10 to 30 percent of the total groundwater pumped (Riley, 1969).

Effective Stress

The change in water level is a measure of the change in applied stress. At an arbitrary depth plane, the weight of the overlying sediments and water is called the total stress or geostatic pressure. This comprises two components: the effective stress, borne by the solid component of the medium; and the pore water stress, borne by the water.

When groundwater head varies in a confined aquifer, the stress shifts from one component to the other in order to maintain constant geostatic pressure. Assuming the overlying water table remains constant, a decline in head results in an increase of equal amount in effective stress (Poland and Davis, 1969):

$$\Delta\sigma' = -\rho_w g\Delta h$$

where Δh is the change in head [L], negative for decrease and positive for increase.

In an unconfined aquifer, the geostatic pressure will vary as the water table goes up and down. Therefore, a change in effective stress from a given head change generally is different in confined and unconfined aquifers. The resulting change in effective stress in an unconfined aquifer can be expressed as (Poland and Davis, 1969):

$$\Delta\sigma' = -\rho_w g\left(1 - n + n_w\right)\Delta wt$$

where n is porosity [dimensionless]; n_w is moisture content above the water table as a function of total volume [dimensionless]; and Δwt is the change in water table height, positive for raising and negative for lowering of the water table [L].

As the term $(1-n+n_w)$ is less than unity, the change in effective stress is less for an unconfined aquifer than for a confined aquifer.

Compaction

Previous studies (Riley 1969) have indicated that elastic compaction or expansion of sediments is proportional or nearly proportional to the change in effective stress. The elastic compression of the fine-grained sediments (interbeds) in an aquifer is given approximately by:

$$\Delta b = -\Delta h S'_{ske} b_0$$

where Δb is change in thickness [L], positive for compaction and negative for expansion; S'_{ske} is the skeletal component of the elastic specific storage of the interbed [L^{-1}]; and b_0 is the thickness of the interbed [L].

The same assumption can be made when simulating the inelastic compaction of the interbeds—that is, the inelastic compaction or expansion of the sediment is proportional to the change in effective stress:

$$\Delta b^* = -\Delta h S'_{skv} b_0$$

where Δb^* is inelastic compaction [L]; and S'_{skv} is the skeletal component of the inelastic specific storage of the interbed [L^{-1}]. Laboratory studies suggest a better linear relation with the logarithm of the head change (Leake and Prudic, 1991).

MODFLOW IMPLEMENTATION

Leake and Prudic (1991) added the Interbed Storage (IBS) package to the standard MODFLOW code developed by McDonald and Harbaugh (1988). This package requires specification of the following parameters on a cell-by-cell basis within a model layer that contains fine-grained interbeds:

- Elastic storage coefficient;
- Inelastic storage coefficient;
- Initial preconsolidation head;
- Initial compaction.

It is the user's responsibility to aggregate interbed thicknesses spatially, and multiply by estimates for specific storage. Given the lack of data on inelastic values, the user is likely to compute externally the inelastic storage coefficient as a multiple of the elastic storage coefficient. The term 'interbed', where subsidence in aquifers occurs in response to groundwater abstraction, is assumed to be:

- Of significantly lower hydraulic conductivity than the surrounding sediments;
- Of insufficient lateral extent to be considered a confining bed that separates adjacent aquifers; and
- Of relatively small thickness in comparison to lateral extent.

Compaction (Δb or Δb^*) is computed in each cell in each layer at the end of a time step, by multiplying the head change by the appropriate storage coefficient. If the current head is higher than the preconsolidation head, then the elastic value is used. If the current head is lower than the preconsolidation head, then the inelastic value is used and the preconsolidation head is set at the new head value. Land subsidence is computed at a cell by summing the compaction simulated in each of the model layers, and is reported for the model cell at the uppermost layer.

Limitations

The IBS package is limited by the following assumptions:

- Storage values are assumed constant in time;
- Changes in geostatic pressure for an unconfined aquifer are ignored – this will overestimate compaction;
- Aquitard heads are assumed to equilibrate within the time step; that is, aquitards are assumed to drain sufficiently at this time scale in order to dissipate excess pore pressure – this could overestimate compaction at early time and underestimate compaction at late time;
- Inelastic compaction is assumed to be proportional to head change – this will cause an overestimate of compaction.

The modeller must be careful about the choice of time step, as the IBS package assumes that interbed drainage occurs during this time. In addition, if the aggregate interbed storage coefficient (elastic or inelastic) is commensurate with the previously calibrated aquifer storage coefficient, then hydrographic calibration will be upset as simulated water level fluctuations will reduce. The aquifer storage coefficient will have to be reduced by the magnitude of the interbed storage coefficient. However, the latter could fluctuate from elastic to inelastic values during simulation.

LOWER NAMOI VALLEY APPLICATION

The Lower Namoi Valley is an alluviated valley with an area of 5100 km^2 in the semi-arid area of Northern New South Wales, 500 km north-west of Sydney. The valley contains a sequence of non-marine alluvial deposits of Tertiary and Quaternary age, which range in thickness to 120 m as discussed by Williams et al. (1989). The study area is characterised by a narrow palaeochannel, 3 to 10 km in width, passing to the north-west through Narrabri, flanked by a buried basement ridge on its western side and shallow basement with colluvial cover on its eastern side. The channel then trends westerly and subsequently south-westerly towards Cryon (about 30 km west of Burren Junction). It is infilled with fluviatile sediments of the Cubbaroo Formation, up to 60 m thick. The sediments consist of subrounded to rounded sand and gravel with interbedded clay and minor carbonaceous stringers. Sand and gravel zones in the Gunnedah and Cubbaroo Formations provide the main production aquifers. Yields up to 250 L/s are obtained from the Gunnedah Formation at depths of 60-90 m, and from the Cubbaroo Formation at 80-120 m depth as described by Hamilton et al. (1988).

Since its initial development more than 20 years ago, a 3-layer regional MODFLOW groundwater flow model has been calibrated, verified, subjected to post audit, and externally reviewed (Merrick, 2001). The model has been used recently to simulate subsidence, to see if MODFLOW is sufficient for this purpose, and to see if satisfactory calibration is possible with plausible storage and compressibility parameters. The Lower Namoi MODFLOW model has 30 rows and 50 columns of 2500 m cells. The model has been calibrated with monthly stress periods from 1980 to 1998. The model layer associations are:

- Layer 1 – Narrabri Formation;
- Layer 2 – Gunnedah Formation;
- Layer 3 – Cubbaroo Formation.

Simulation Parameters

Only Layers 1 and 2 have been simulated for aquifer compaction, as most pumping is from the Gunnedah Formation and Layer 3 has limited spatial extent. The preconsolidation head has been set at 1980 observed groundwater levels, to coincide with a period of drought and high abstraction at the start of the simulation.

The total thickness of the aquitards in Layers 1 and 2 was estimated from the percentage of the fine-grained sediments in these layers that was determined from descriptions of the aquifer material noted in drillers' bore logs. Figures 1 and 2 show the clay thickness contour maps for each layer. Separate maps were produced for lithologies described as clay/sand and clay/gravel mixtures.

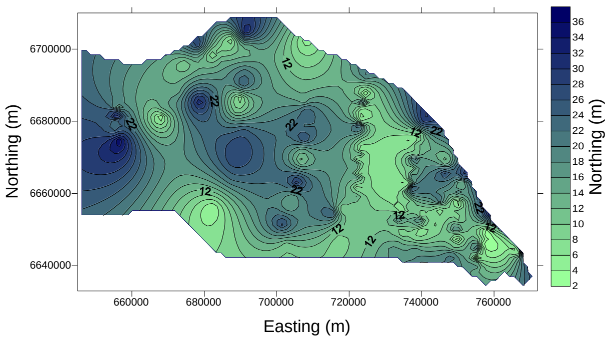

Figure 1. Layer 1 clay thickness (m)

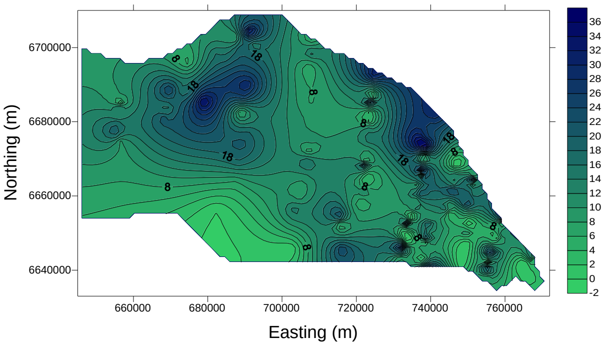

Figure 2. Layer 2 clay thickness (m)

Initial compressibility estimates for each lithology were taken from Domenico and Schwartz (1998), reproduced here as Table 1. The initial skeletal specific storage values for clay, clay/sand, and clay/gravel were estimated as 9.8x10^{-4} m^{-1}, 5.5x10^{-4} m^{-1}, and 4.9x10^{-4} m^{-1}, respectively, and were subsequently varied during calibration.. The inelastic skeletal specific storage was initially taken to be 100 times the elastic skeletal specific storage. These skeletal specific storage values multiplied by the aggregate thickness of each sediment type, were then entered into the IBS package within the PMWIN interface to MODFLOW.

Table 1. Compressibility values (m^2/N)

Clay	$10^{-6} \sim 10^{-8}$
Sand	$10^{-7} \sim 10^{-9}$
Gravel	$10^{-8} \sim 10^{-10}$

Simulation Results

The best combination of parameters was found to be:

- Elastic skeletal specific storage 2.1x10^{-6} m^{-1};
- Inelastic multiplier 75 (specific storage 1.6x10^{-4} m^{-1}).

The elastic value is consistent with the low end compressibilities in Table 1. The simulated distribution of land subsidence at 1998 is shown in Figure 3, where the maximum simulated subsidence is less than 0.5 m.

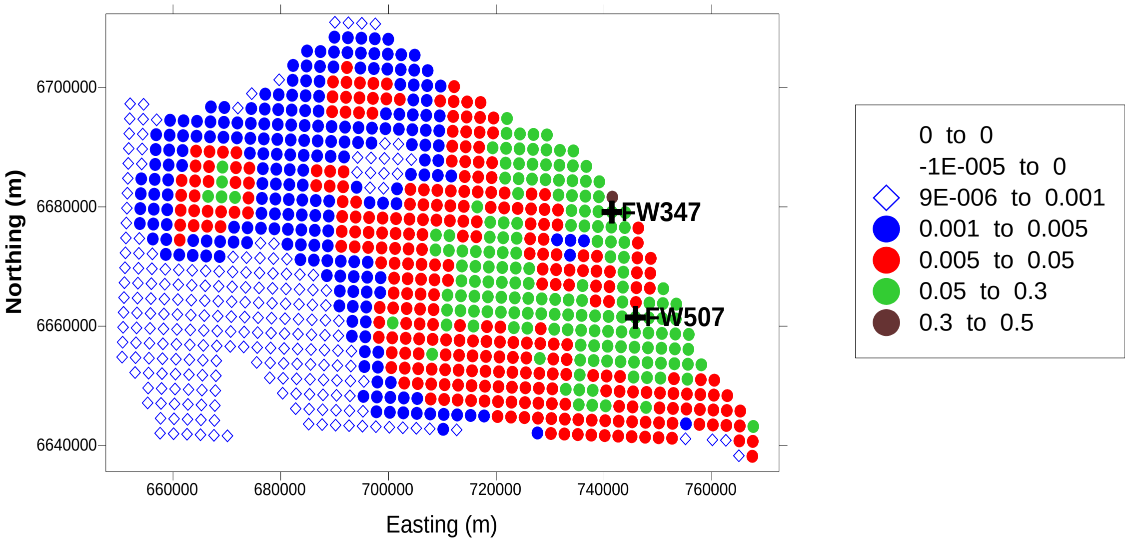

Figure 3. Simulated distribution of land subsidence (m)

The simulated pattern agrees qualitatively with the observed distribution of subsidence at the last measurement event in 1990. Quantitative agreement is best evaluated at representative benchmarks FW347 and FW507 (Figure 3). Time series plots of simulated and observed subsidence are presented in Figures 4 and 5. The paucity of measurement points means that the expected sequence of compaction and uplift events are not adequately captured by the field datasets. Corresponding water level fluctuations are shown in Figures 6 and 7. At FW347, the maximum observed compaction is 0.16 m, for a water level decline of 40 m. At FW507, the maximum observed compaction is less (0.06 m), for a correspondingly lower water level fluctuation (14 m).

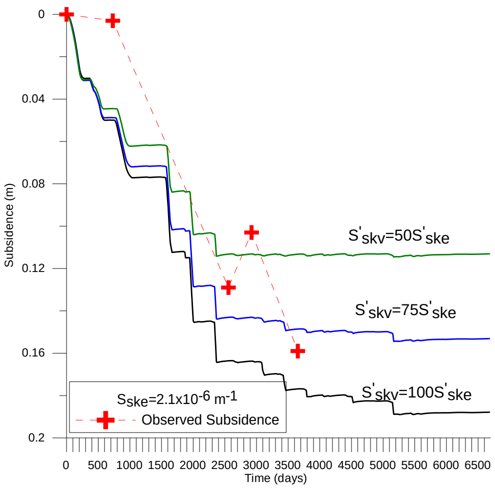

Figure 4. Evolution of subsidence at benchmark FW347

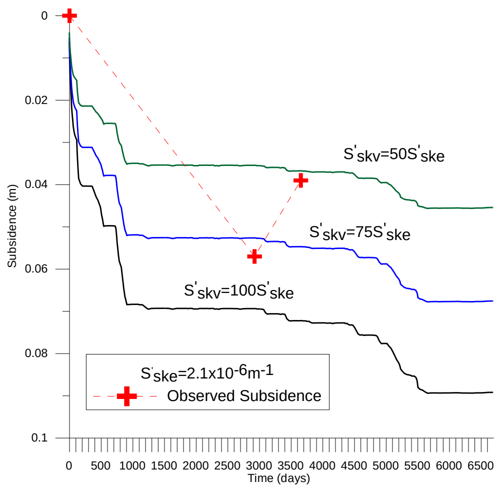

Figure 5. Evolution of subsidence at benchmark FW507

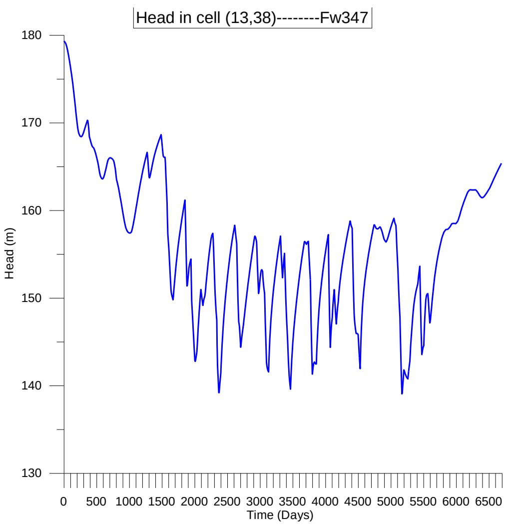

Figure 6. Simulated water level fluctuations at benchmark FW347 (mAHD)

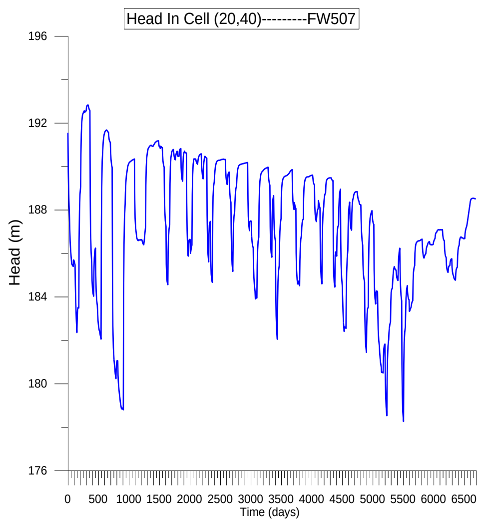

Figure 7. Simulated water level fluctuations at benchmark FW507 (mAHD)

RESIDUAL COMPACTION

Residual compaction can occur long after water levels have stabilised, due to the slow-draining nature of fine-grained sediments. A measure of the time scale for drainage from an aquitard that drains through both upper and lower boundaries is given by the aquitard time constant (Riley, 1969), which can be expressed as:

$$\tau \quad = \quad \frac{S'\,b'}{4\,K'}$$

where S' is the storage coefficient of the aquitard, thickness b', with hydraulic conductivity K'. The time constant is the time by which 93 percent of excess pore pressure has dissipated (Leake and Prudic, 1991). For an aquitard that drains only through the upper or lower boundary, the time constant is 4τ.

As a check on the usefulness of this indicator, independent analytical modelling was done with the dual aquifer model embedded in HotSpots software (Merrick and Merrick, 2002). The code was modified to produce highly-sampled head profiles across an aquitard of specified thickness. Figures 8 and 9 show the head profiles for typical Lower Namoi parameters for aquitards of 1 m and 10 m thickness, respectively, for times varying from 2.4 hours to 1 year. A single bore pumps 10 ML/d from the lower aquifer at a distance of 10 m from the monitoring point. As the aquitard is draining only through the bottom boundary in this example, the corresponding time constants (4τ) are 1 d and 10 d, for specific storage values of 1 x 10^{-3} m^{-1} and 1 x 10^{-4} m^{-1}.

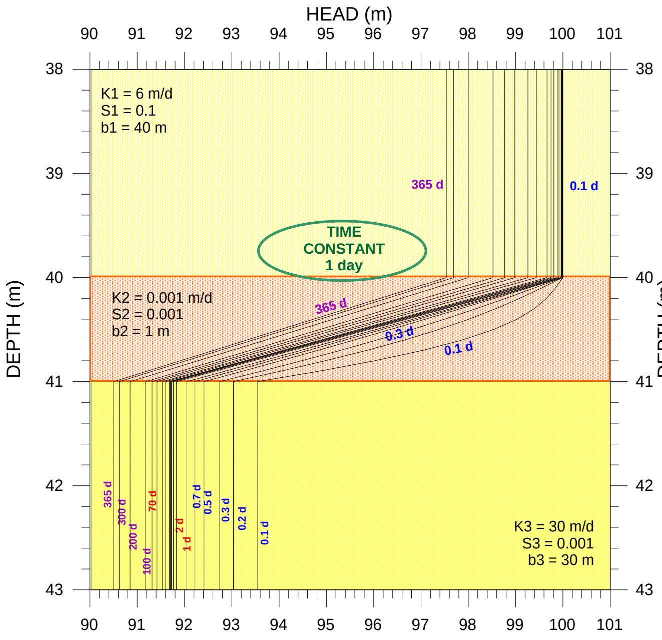

Figure 8. Simulated transient head profiles across a 1 metre thick aquitard

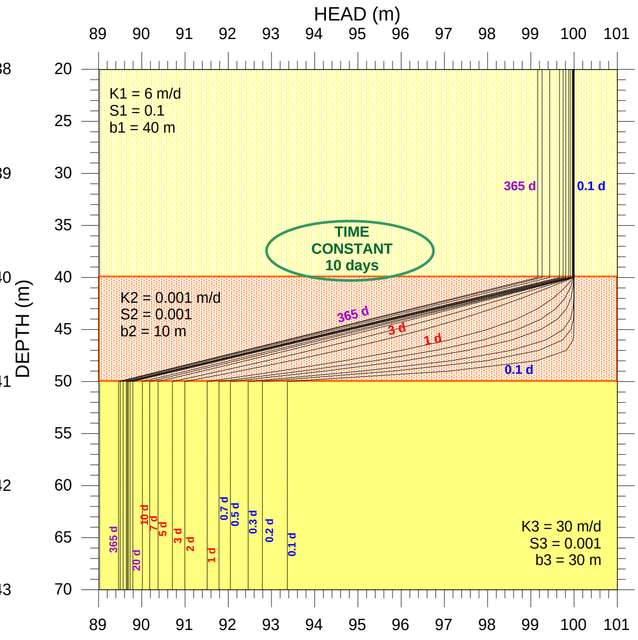

Figure 9. Simulated transient head profiles across a 10 metre thick aquitard

The time constant is a reliable indicator of the time at which equilibrium is almost established in the aquitard, which occurs when the head decline in the aquitard becomes linear. Equilibrium occurs much faster in a thin aquitard. In a thick aquitard, there is insignificant head loss in the upper aquifer until a substantial thickness of the aquitard starts to drain.

For the Lower Namoi aquifer, the calibrated inelastic specific storage (1.6x10^{-4} m^{-1}) is similar to the case shown in Figure 9. The aggregate aquitard thickness, however, can be much greater than 10 m, as shown in Figure 2. But it is the maximum thickness of a single aquitard that will determine the time lag, as multiple thin interbeds will drain rapidly. It is likely that subsidence in the Lower Namoi Valley will occur within the same season as the causative pumping. Long-term residual compaction is unlikely.

CONCLUSION

The Interbed Storage Package within MODFLOW is a simple but adequate algorithm for simulating and predicting layer compaction and land subsidence in a regional aquifer system, provided that individual fine-grained interbeds are relatively thin (say, less than 10 metres). The module requires very little data, as textbook compressibility ranges should be adequate to constrain parameter estimates during calibration. However, it is essential that the spatial distribution of fine-grained sediments be well known. It appears that drillers' logs will be adequate for this purpose. A history of survey levelling is necessary for reliable calibration. The modeller must be careful to choose a time step size that is compatible with the aquitard drainage time scale, and should also be aware of the other limitations of this approach.

In places where a MODFLOW model has not been developed, or a quick assessment is needed, it would be possible to add a subsidence module to HotSpots software. This could show the transient head profiles across a representative aquitard, so that the risk of residual compaction can be assessed. A similar compaction algorithm to that employed in the Interbed Storage Package would account for elastic compaction and rebound, and inelastic compaction, for simple or complex water level fluctuations.

For the Lower Namoi Valley, it is concluded that subsidence has occurred contemporaneously with water level fluctuations, and there is little risk of residual compaction in the future.

REFERENCES

Domenico PA and Schwartz FW (1998) Physical and chemical hydrogeology, Second Edition, John Wiley & Sons, 506 p.

Hamilton S, Ross .B and Williams RM (1988) Narrabri Hydrogeological Map (1:250 000 scale map). Department of Water Resources of New South Wales, Hydrogeological Series SI 55-7.

Leake SA and Prudic DE (1991) Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6, Chapter 2, United States Geological Survey, Washington.

McDonald MG and Harbaugh AW (1988) MODFLOW: A modular three-dimensional finite-difference ground-water flow model. United States Geological Survey, Scientific Publications Co., Washington.

Merrick NP (2001) Lower Namoi Groundwater Flow Model: Calibration 1980-1998. Insearch Limited Report for NSW Department of Land and Water Conservation, Project No. C99/44/001, August 2001, 91p.

Merrick NP and Merrick DP (2002) A dual aquifer analytical model with rain and river recharge. CD Proceedings of the IAH International Groundwater Conference, Darwin, Australia, 12-17 May, 2002.

Poland JF and Davis GH (1969) Land subsidence due to withdrawal of fluids. In: Varnes DJ and Kiersch G (eds.) Reviews in Engineering Geology, v2, Geological Society of America, 187-269.

Poland JF (1984) Guidebook to studies of land subsidence due to groundwater withdrawal. UNESCO Studies and Reports in Hydrology no. 40, American Geophysical Union, New York

Riley FS (1969) Analysis of borehole extensometer data from central California. In: Tison LJ (ed.) Land Subsidence, v2, International Association of Scientific Hydrology Publication 89, 423-431.

Riley FS (1998) Mechanics of aquifer systems--The scientific legacy of Joseph F. Poland. In: Borchers JW (ed.), Land subsidence case studies and current research: Proceedings of the Dr Joseph F Poland symposium on land subsidence, Association of Engineering Geologists Special Publication No 8, 13-27.

Ross JB and Jeffery L (1991) Ground Subsidence and Bore Hole Collapse associated with Groundwater Withdrawals—Namoi Valley NSW, Technical Services Division, Hydrogeology Unit.

Williams RM, Merrick NP, and Ross JB (1989) Natural and induced recharge in the Lower Namoi Valley, New South Wales. In: SharmaML (ed.), Groundwater Recharge, Proceedings of the Symposium on Groundwater Recharge, Mandurah, 6-9 July 1987. A.A.Balkema, Rotterdam, 239-253.