An expression for land surface water storage monitoring using a two-formation geological weighing lysimeter

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Abstract

Field studies have demonstrated that ground surface rainfall accumulation can be detected at depth by synchronous increases in static confined groundwater pore pressures. This opens the way for “geological weighing lysimeters” providing disturbance-free water storage monitoring of the surface environment, in effect by weighing a significant land area in real time. Such systems require specific hydrogeological conditions which are not easily verified by field observations and replicated observations from multiple geological formations are a prerequisite for quality control. Given replication over two monitored formations, we introduce an expression which utilises the respective formation piezometric water levels to give an improved combined estimate of the ground surface water budget. The expression utilises raw piezometric levels and has the advantage of direct correction for Earth tide noise, which may sometimes be influenced by local effects in addition to the pure solar/lunar tidal potential. The expression is particularly simple if the two formations have similar (but possibly unknown) undrained Poisson ratios and porosities. Surface water budgets can then be estimated using only the respective formation barometric coefficients and piezometric levels. An example application to two vertically separated confined aquifers at a New Zealand site indicate an improved accuracy over single-formation observations. The two-formation expression for surface storage could find use as an accurate water budget tool with particular application to monitoring diffuse hydrological systems such as wetlands, arid regions, and heavily forested localities.

Key words: weighing lysimeter, water budget, storage estimation

1. Introduction

The Earth's surface is subjected to repeated mass loading from natural phenomena including ocean tides, atmospheric pressure changes, seasonal soil moisture variation, and precipitation events. Loading changes of lesser magnitude may arise from forest biomass variation associated with climatic fluctuations (Rolim et al., 2005; Fearnside, 2004). The elastic response to surface loading may extend to some depth (Pagiatakis, 1990; Schulze et al., 2000, Sophocleous et al., 2006) and can be observed as groundwater pore pressure fluctuations in geological formations with suitable physical properties (Rojstaczer et al., 1989).

Monitoring the elastic response to land surface loading by recording synchronous groundwater pressure changes has attraction as a means of estimating surface and near-surface water storage change as a spatial average, which is not easily amenable to direct field measurement. It was early recognised that a fully confined extensive aquifer is well suited for this purpose (Van der Kamp et al., 1991; Bardsley, et al., 1993) although aquitards also have advantages (Van der Kamp et al., 1997; Barr et al., 2000). The actual land area monitored by deep groundwater pressures cannot be exactly defined but will increase with observation depth and is likely to be in the order of hectares for pressures recorded around 50 meters below ground (Van der Kamp et al., 1997). Larger monitored areas may be achievable in future because surface loading effects have been detected to four kilometers depth (Schulze et al., 2000).

The lack of field development of this interesting approach to land surface water budgets perhaps reflects concerns that the monitored groundwater pore pressures cannot be guaranteed free of formation leakage influence, transient pressure waves, or other dynamic effects which could destroy the simple static/elastic weighing ideal. In order to avoid the erroneous interpretation of transient phenomena or other groundwater water dynamic effects as surface water budget changes, it is essential to demonstrate similar but independent surface water budget estimates derived from pore pressures monitored in separated geological formations with different physical properties. These formations should be vertically separated but still close enough to be independently detecting surface water budget changes taking place within same land surface area.

We assume as a starting point therefore that there are two time series of surface water budget estimates available (estimated storage changes), which have been established as being sufficiently similar to be consistent with geological weighing lysimeter behavior in both formations. The issue then arises over how best to combine both time series to give an improved estimate of the surface water budget. The most obvious approach is simply to average the two estimates and thereby reduce random error. We present here an alternative procedure by which the combined estimate of surface water storage variation is obtained directly from raw piezometric water levels without the necessity for input of an explicit barometric or Earth tide correction. Barometric effects can be easily removed in any case but Earth tides may not always be so readily eliminated because local influences can result in the recorded Earth tide not being a simple function of the solar/lunar tidal potential (van der Kamp and Gale, 1983). Barr et al (2000) were able to filter out Earth tides in their Canadian study site using the theoretical tidal potential but we were unable to achieve this with water level data at our site in New Zealand. Similarly, Sophocleous et al (2006) found it better to use a wavelet filter rather than the theoretical Earth tide to reduce Earth tide effects from well water levels at a site in Kansas.

Our alternative approach incorporating two-formation estimation of land surface storage change takes the form of a new storage change expression which self-corrects for both barometric effects and Earth tides. Barometric correction is still required in the initial verification phase, however, in order to confirm that the two time series of water storage estimates do not differ significantly.

2. Field verification through replication

The concept of replicated observations over two different formations is developed in a little more detail in this section with respect to the physical requirements of geological weighing lysimeters. The two formations concerned are assumed to be confined units of significant lateral extent with minimal groundwater flow and leakage, subject only to elastic vertical deformation in response to ground surface mechanical loading, and with granulated lithology such that matrix compressibility is much greater than grain compressibility. This situation should not be uncommon in aquicludes and should also hold for many “stagnant” sedimentary aquifers (Mazor, 1995; Mazor et al., 1995) as well as some confined aquifers with surface outcrop distant from the monitoring site.

We revisit first the case of a single elastic confined formation assumed monitored with an open piezometer. Over some time interval Δt the ground surface water storage change Δs is related to piezometer water level change through the loading effect as (Bardsley et al., 2000):

$$\Delta s = \Delta L_c / (1 - b) \tag{1}$$

where Δs is the area-integrated land surface water storage change in length units of water, b is the static confined barometric coefficient, $1-b$ is the loading coefficient (Jacob, 1940), and ΔL_c is the barometrically corrected change in piezometer water level. The term “surface water storage change” is used here as a convenient way to denote the total water mass change on the actual land surface and also in the soil and in any unconfined aquifer which may be present.

Confirmation that any single formation is acting as a geological weighing lysimeter could in principle be achieved by showing that Δs sequences obtained from Eq (1) are closely similar to corresponding Δs estimates derived from accurate spatial extrapolation of many surface and near-surface point moisture measurements. However, the storage changes estimated from point observations are likely to contain considerable extrapolation error and therefore have limited value for model validation.

A more straightforward approach to the validation issue is to monitor two confined and vertically separated water-bearing formations and check whether respective applications of Eq (1) yields similar Δs sequences. The reasoning here is that it would be unlikely that one or more of the geological weighing lysimeter assumptions should fail in just such a way to cause Eq (1) to give similar Δs sequences from two different formations with different loading coefficients.

2. Derivation

Given that two formations have been established as independently monitoring the same ground surface water loading changes, the respective piezometer water level change in response to a change in surface water storage, atmospheric pressure and Earth tide potential can be written:

$$\begin{aligned} \Delta L_1 &= (1-b_1)\Delta s - b_1\Delta a + \Delta r \\ \Delta L_2 &= (1-b_2)\Delta s - b_2\Delta a + \theta\Delta r \end{aligned} \quad (2)$$

where ΔL_1 and ΔL_2 are the observed piezometer water level changes in the respective formations, Δa is atmospheric pressure change expressed as length units of water, and Δr and $\theta\Delta r$ are the respective components of the water level changes due to Earth tides, with θ a positive parameter. The Earth tides here may be modified by local effects and no assumption is made concerning their relation with the solar / lunar theoretical Earth tide. Solving for Δs then gives the desired two-formation expression for land surface water storage change as:

$$\Delta s = \Delta a[(z_1 - \alpha^{-1} z_2)^{-1} - (\alpha z_1 - z_2)^{-1}] + \Delta L_1 b_1^{-1}(z_1 - \alpha^{-1} z_2)^{-1} - \Delta L_2 b_2^{-1}(\alpha z_1 - z_2)^{-1} \quad (3)$$

where $\alpha = \theta b_1 / b_2$ and $z_i = (1-b_i)/b_i$ for $i = 1, 2$.

Application of Eq (3) is straightforward because aquifer barometric coefficients are readily obtained from standard methods and the parameter α can be estimated by using trial and error values to find the optimal Earth tide correction.

A simplification applies if the two formations are physically similar with respect to porosities and undrained Poisson ratios . In this situation $\alpha = 1$ because $\theta = b_2 / b_1$ (Bredehoeft, 1967) and Eq (3) reduces to:

$$\Delta s = c_1 \Delta L_1 - c_2 \Delta L_2 \qquad (4)$$

where c_1 and c_2 are functions of formation barometric coefficients only, as evident from Eq (3).

3. Examples

The use of this two-formation estimation approach will be illustrated with application to some hour-resolution archive data from our geological weighing lysimeter site near Hamilton, New Zealand (Fig. 1).

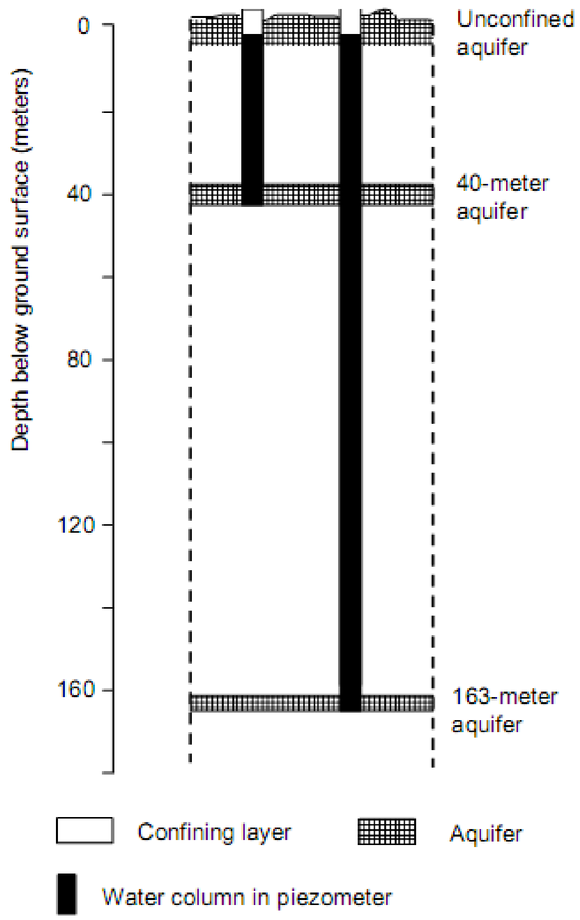

Figure 1. Schematic of the replicated geological weighing lysimeter established near Hamilton, New Zealand. Land surface is 50 meters above sea level.

In setting up the site we elected to seek confined aquifers as the monitoring formations rather than aquitards on the basis that transmissive units are likely to weigh a greater land surface area. The immediate site subsurface comprises a sandy unconfined aquifer extending a few meters below ground surface. The site water table undergoes seasonal fluctuation within this zone. The monitoring formations are two confined gravel-sand aquifers a few meters thick located respectively at 40 and 163 meters depth, with pore pressures monitored as piezometer water levels. The confining units are thick weathered ignimbrites. We had hoped that our drilling would locate an aquifer pair with less vertical separation because the replication is compromised to some extent, with the deeper presumably aquifer responding to surface loading averaged over a larger land area. However, there is probably not a great deal of spatial variation in storage change over and just beneath the pasture grass land surface at this location.

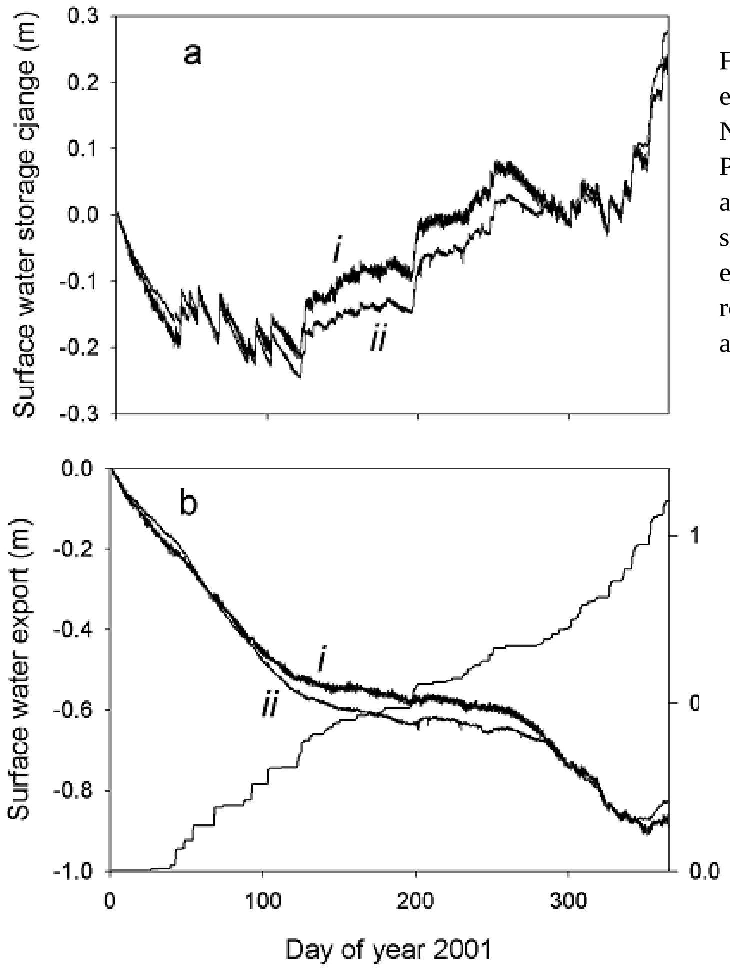

Figure 2. Geological weighing lysimeter estimation of the surface water budget at the New Zealand site through the year 2001. Plots i and ii refer to the 163-and 40 meter aquifers, respectively. (a) surface water storage estimates, (b) total water export estimates and cumulative rainfall. The high resolution variations in the 163-meter aquifer are Earth tides.

The aquifer barometric coefficients were determined as b = 0.11 and 0.31 for the 40- and 163-meter aquifers, respectively. By way of illustration of a replication check over a complete annual cycle, these b values were used in Eq (1) to estimate Δs values at hourly intervals for 2001 (Fig. 2a). There are some evident differences in the storage time series over the winter months but the overall agreement is still sufficiently close to allow interpretation of the plots in terms of surface water budgets. It happened that 2001 was characterised by a dry winter and the limited winter recharge of the soil and unconfined aquifer was evidently only just sufficient to offset the water loss through summer and autumn. However, the effect of high rainfalls toward the end of the year results in a net surface storage gain of about 0.25 meters for the year as a whole. Bardsley and Campbell (2000) present a replicated plot for 1998, which was a more typical year with higher recharge in winter.

An alternative approach to replication verification is to compare the respective surface water export time series (Fig. 2b) as obtained from subtracting recorded cumulative rainfall from the two storage time series. Here too there is quite good replication between the aquifers' two plots, but again with some degree of difference in winter. There is no evident surface drainage at our site so surface water export will represent the net water loss from the combined effect of evaporation loss and any net lateral groundwater change in the unconfined aquifer (the difference between lateral groundwater import and export, measured in length units). The decreased winter gradients of the export plots most likely reflect reduced evaporation rates because of the combined effect of lower air temperatures and less surface water availability from the reduced winter rainfall. Both export curves are quite similar over the year and indicate the total 2001 site water export to be about 0.9 meters. Interestingly, both export plots curve upward slightly at the end of the year. This suggests a brief period of net lateral groundwater gain in the unconfined aquifer of sufficient magnitude to offset evaporation loss.

A feature of 2001 and other years of our record is that there are periods of a few months with particularly high levels of replication. It is these segments of record which are most suited to the application of Eqs (3) or (4) because of near-equivalence of the two Δs estimation series.

One such application is illustrated for the first 100 days of record for 1994 (Fig. 3). Plots *i* and *ii* represent the two independent Δs estimates, from application of Eq (1) to the 163- and 40 meter aquifers, respectively. The evident high degree of replication allows application of Eq (3) to the raw piezometer levels of both aquifers to give the combined estimate of the land surface storage changes. As it happened, trial values of α in Eq (3) gave no evident improvement in Earth tide noise reduction beyond that achieved for $\alpha = 1$, so the simpler expression given by Eq (4) was applied as:

$$\Delta s = 1.55\Delta L_1 - 0.55\Delta L_2 \qquad (5)$$

which is plotted as *iii* in Fig. 3.

The c_1 and c_2 constants in Eq (5) are obtained from the relevant terms in Eq (3) for $b_1 = 0.11$ and $b_2 = 0.31$. The ΔL_1 and ΔL_2 values here are the 40- and 163-meter aquifer raw piezometric water level differences, measured from the first recorded water level in the 100-day period in the respective piezometers.

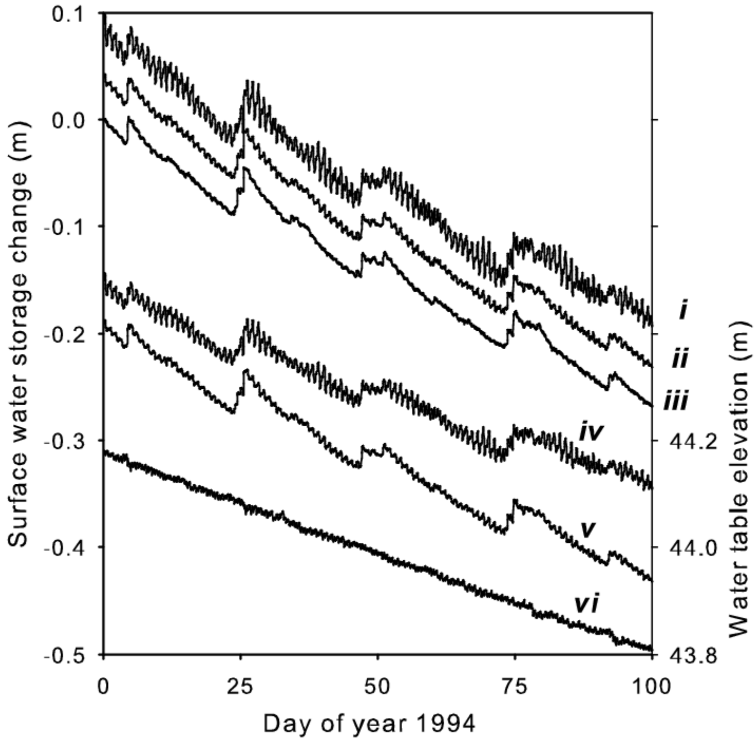

Figure 3. Illustration of application of Eq (5) to replicated surface water storage estimates derived from the New Zealand field site. Plots *i-iii* are individual-aquifer and combined estimates of ground surface Δs. Plots *iv* and *v* are barometrically corrected water levels only and do not have an implication of water storage estimation. Fine scale variations are due to Earth tide effects. All plots have been vertically displaced for ease of viewing. See text for more detailed definitions and discussion. Plot *v* shows the site water table as elevation above sea level.

The Δs sequence of plot *iii* as obtained from Eq (5) gives the anticipated improvement in reducing Earth tide noise. However, in this case Eq (5) is only able to give a modest improvement over the 40-meter aquifer which is characterised by small Earth tide amplitudes. A more striking improvement is likely to have resulted if there had been larger Earth tide effects in this aquifer.

Plots *iv* and *v* have been included in Fig. 3 simply to emphasise that Eq (1) is not just a simple barometric correction of water levels, but rather represents the barometrically corrected values rescaled by (1-b). This rescaling gives the meaning of length units of surface water storage change in the geological weighing lysimeter model (Bardsley and Campbell, 2000). The difference between scaled and unscaled barometrically corrected observations is illustrated by comparing the Fig. 3 plots *iv* and *v* with *i* and *ii*. Plots *iv* and *v* are the respective unscaled barometrically corrected levels of the 163- and 40-meter aquifer water levels and do not show the replication achieved by *i* and *ii*. The lack of replication is to be expected because plots *iv* and *v* do not have any interpretation of geological weighing lysimeter commonality in the sense of being independent measurements of the same surface water storage change.

The saw-tooth effects in plots *i*-*v* in Fig. 3 are due to land surface loading arising from rainfall increments being held for a time in the site soil and subsoil. The water table (recorded at a single observation point) shows no such effects despite being only a few meters below ground surface (plot *vi*). This lack of sensitivity is expected because elastic loading effects generally do not arise in unconfined near-surface aquifers.

Fig. 4a gives greater detail for the first thirty five days of Fig. 3 and the resolution improvement from Eq (5) is more evident. The rainfall loading effect is particularly clear and contrasts with the absence of any rainfall response in the water table (Fig. 4b).

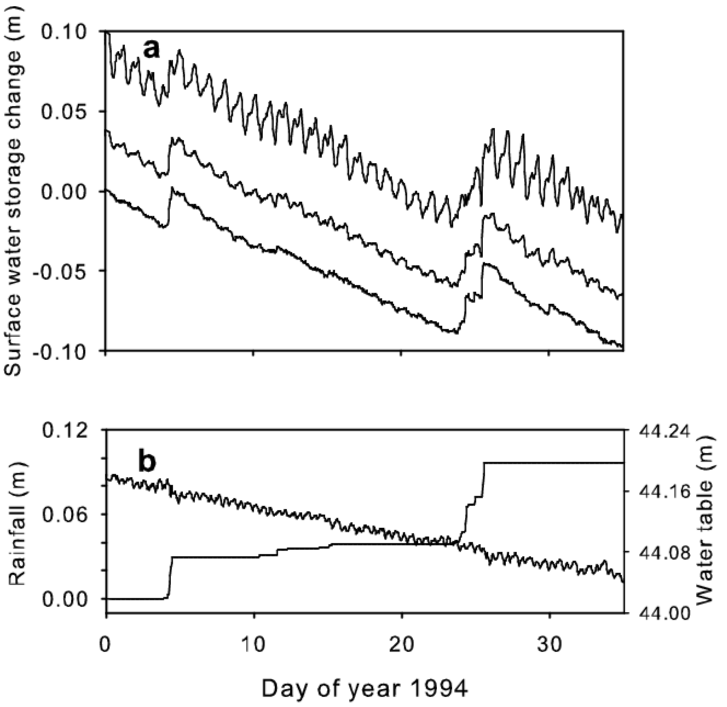

Figure 4. Improved Δs resolution from Eq (5) showing rainfall loading effects for the first 35 days of Fig. 3. (a) plots *i*-*iii* of Fig. 3. (b) site cumulative rainfall (rising plot) and water table elevation (showing steady decline). Earth tides in the 163-meter aquifer are particularly evident.

By way of hydrological interpretation, plot *iii* in Fig. 3 gives the total 100-day storage change as -0.27 meters. Over this period we recorded 0.24 meters of rainfall which defines the site 100-day water loss as 0.51 meters to evaporation and groundwater export. The water table is below the depth of evaporative loss so the linear decline in the water table over the 100 days is consistent with steady net lateral export of unconfined groundwater to the surrounding region.

Use of Eq (5) may improve resolution sufficiently to give some useful insights into more subtle aspects of site hydrology. In Fig. 4a there is a suggestion that water storage declines somewhat more rapidly after significant rainfall events. This is seen more clearly in Fig. 5 which shows a higher resolution view of the second rainfall event in Fig. 4a.

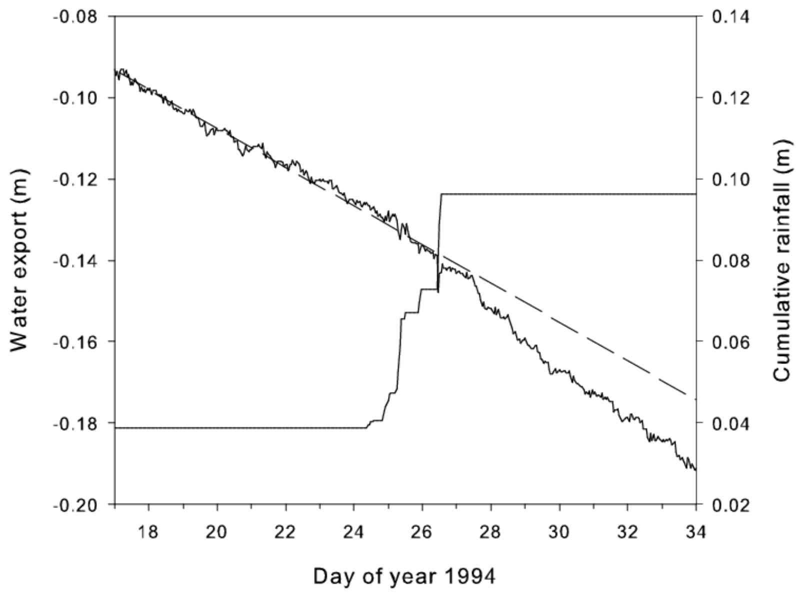

Figure 5. Enlargement of the second rain event shown in Fig. 4, with the water export plot (declining plot) added. Dashed line is the least squares fit to the water export plot over days 17-26, extended to day 34 to illustrate the post-rainfall slope change in the export plot.

The superposed water export plot (derived from subtracting cumulative rainfall from Eq (5) storage values) shows a post-rainfall increase in slope which could be explained as the moistened soil increasing evaporation loss by about 2.5 mm per day. Another interpretation is that at least one of the confined aquifers is subject to leakage and the decline simply represents the inability of the aquifer to maintain the increment of pore water pressure from rainfall loading. However, we believe this to be unlikely in the light of the final example below.

The final illustration of the use of Eq (5) shows a dramatic transformation of the apparently unremarkable segment of our 1993 raw water level data shown in Fig. 6. After an initial check for replication quality, application of Eq. 5 to these two time series of raw observations produces a surface water storage plot which can be overlapped very closely with site cumulative rainfall (Fig. 7). This would appear to confirm that the confined aquifers are indeed watertight because any immediate leakage of rainfall loading pore pressure increments would not result in such close matching.

The water budget interpretation of Fig. 7 is that this period of time coincides with an unusual situation when all non-rainfall surface water balance components happen to sum to zero, allowing the site to function briefly as a giant rain gauge monitoring rainfall accumulation in the soil and immediate subsurface. The more normal situation would be a background trend of storage change from which a cumulative rainfall estimate might be extracted with filtering techniques for subsequent comparison with recorded rainfall (Barr et al., 2000).

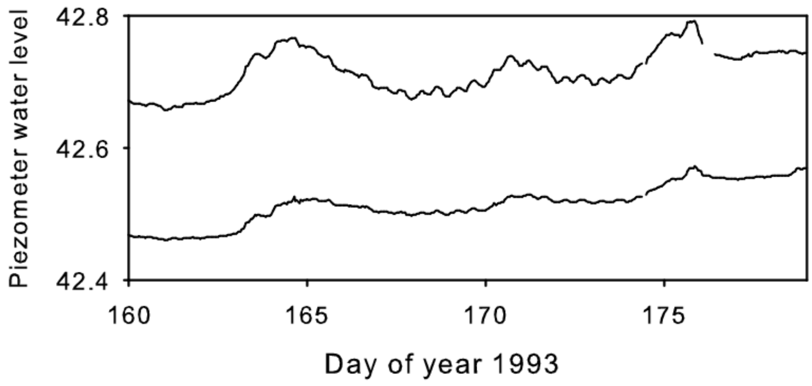

Figure 6. Example segment of recorded raw piezometer water level time series. The 163- and 40-meter aquifer water levels (upper and lower lines respectively) were used in Eq (5) to give the Δs values plotted in Fig. 7. There is a small interval of missing water level record in the 163-meter aquifer.

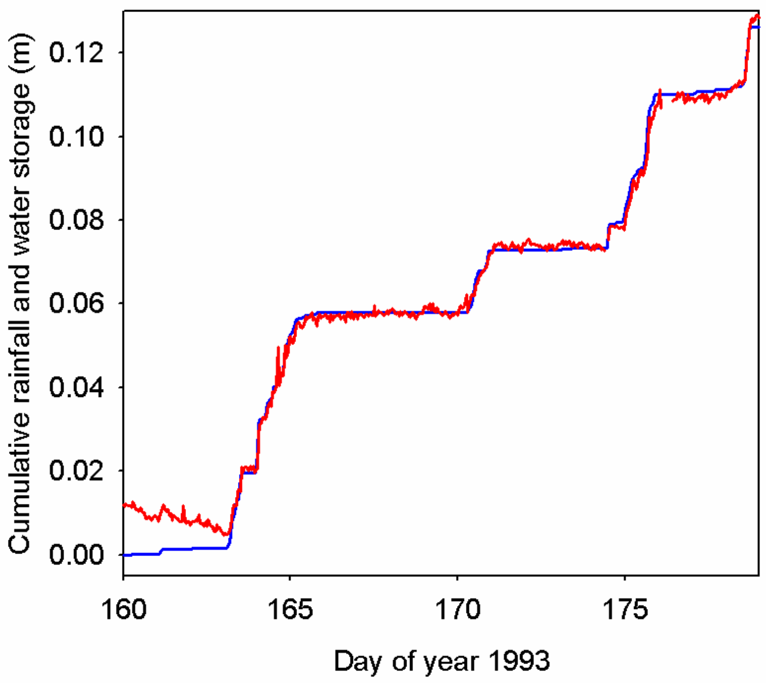

Figure 7. Correspondence of Δs values from Eq (5) and recorded cumulative rainfall. The storage change values (red) were calculated using the paired raw water level data series shown in Fig. 6, vertically displaced to illustrate overlap with cumulative rainfall (blue).

It is interesting in Fig. 7 that the evident matching of storage change to cumulative rainfall appears to be initiated by the first major rainfall event. Unfortunately, site meteorological records are not available for this time but we speculate that water export may have been initially dominated by evaporation loss, reflected in the small storage decline from day 160. The main rain event then marks the onset of weather conditions with minimal evaporation and total site water export almost ceases except for some initial evaporation loss in the first part of the main rain event. Thereafter the dominant change in the site water budget is only rainwater accumulating in the soil and subsoil.

This scenario may or may not reflect the actual situation as it happened. However, the point is made that combined paired-formation geological weighing lysimeters do have the potential to monitor land surface storage changes to a degree of accuracy sufficient to suggest specific directions for further analysis. One particular area of further investigation could be to create groundwater export plots. The rate of lateral groundwater export or import will change only slowly in sites such as ours with low-relief and permeable land surface. Assuming the gradient of the total export plot at night reflects only lateral groundwater effects, it may be possible to average the night gradients of the export plots over a number of consecutive nights to build up the groundwater export function as a running mean. The difference between the total export plot and the groundwater export plot would then represent the cumulative evaporation loss.

4. Discussion and conclusion

There is a definite need for further emplacements of paired-formation geological weighing lysimeters to demonstrate accurate ground surface water monitoring. Our New Zealand site gives a good level of replication through seasonal cycles and very good replication over time periods of a few months. There seems no reason why similar paired monitoring systems could not be set up at suitable localities elsewhere. Indeed, we would hope that the degree of replication would be even better at new sites which are able to establish monitoring geological units in closer vertical proximity. It would probably be advisable to have monitoring formations located at greater than 100 meters below ground surface for sites where there is a well defined seasonal cycle of surface and near-surface water storage change. This is because shallow monitoring may be influenced by transient pressure waves of seasonal duration, depending on the hydraulic diffusivity of the confining material (Van der Kamp et al., 1991; Roeloffs, 1996). Such effects can be useful for making inferences on formation physical properties (Timms et al., 2005) but represent undesirable dynamic effects from the viewpoint of geological weighing lysimeters.

There would appear to be considerable potential for replicated geological weighing lysimeters to yield useful water budget information in various contexts. For example, seasonal rainfall forecasts might be aided by early detection of area-integrated soil moisture changes at indicative continental localities (Koster, et al., 2004). Area-integrated storage change monitoring could have particular value in studies of diffuse surface hydrological systems such as arid regions, tundra, wetlands or forest sites where clearly defined drainage boundaries are absent. It may even happen that Eq (3) could find immediate application to fortuitous paired-formation data collected in other contexts such as seismological monitoring of groundwater pressures.

The specific hydrogeological requirement of hydraulically isolated paired formations does mean that Eq (3) will not find universal application as a tool for surface water storage monitoring. No such restriction applies to Δs estimates from satellite gravity measurements, which can be viewed as the large-scale equivalent of geological weighing lysimeters. However, current satellite technology cannot resolve water storage changes at distance scales less than about 400 km or time scales less than 10 days (Rowlands et al., 2005), with future improvements constrained by the need to maintain satellite elevation against atmospheric friction. We express the hope that the two systems of spatially-averaged water storage monitoring will evolve in a complimentary way, with the satellites aiding regional hydrology and replicated geological weighing lysimeters providing more detailed local water budgets at representative sites in various biomes.

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