# SLOPE-STABILITY IMPLICATIONS OF GROUND-WATER-LEVEL FLUCTUATIONS IN WASATCH FRONT LANDSLIDES AND ADJACENT SLOPES, NORTHERN UTAH

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## ABSTRACT

Accurate slope-stability analysis of pre-existing landslides and adjacent, potentially landslide-prone slopes requires a realistic estimation of maximum ground-water levels. Previous researchers have documented a long-term rise in ground-water levels since the 1960s in unconsolidated deposits near recently active landslides. Ground-water levels rose mostly during and immediately prior to a wet cycle that started in 1967. Between 1967 and 1998, cumulative excess precipitation totaled about 26 inches in Salt Lake City, coincident with a long-term rise in ground-water levels by as much as 25 feet to historically high levels and active landsliding by the late 1990s.

Ground-water-level monitoring since early 1999 in and near five Wasatch Front landslides shows that seasonal ground-water levels rise in response to snowmelt, and locally to summertime lawn watering and extreme precipitation events. Seasonal ground-water levels during the measurement period fluctuated up to a maximum of 14.6 feet. Our data indicate more variability in seasonal peak ground-water levels than in seasonal low levels in a single well. Ground-water levels rise more rapidly in wet years than they decline in dry years, suggesting that infiltration of water into a slide is a more efficient process than dewatering of a slide. Extensional ground deformation features including fissures, grabens, upslope-facing scarps, and back-tilted surfaces facilitate rapid infiltration of local precipitation and snowmelt.

In the Sherwood Hills landslide in Provo, rising ground-water levels in the lower part of the landslide, accompanied by first declining and then rising levels in the upper part of the slide, preceded the onset of damaging movement in 2005, suggesting a dynamic ground-water-level-fluctuation model for landslide reactivation.

## INTRODUCTION

Limited data exist on ground-water levels and fluctuations in landslides and adjacent slopes in the Wasatch Front, despite the criticality of such information to accurate landslide- and slope-stability evaluation. Most ground-water-level data collected by consultants are limited to a short duration defined by the length of the project. Thus, a limited basis for estimating the probable short (seasonal), intermediate (several years), and long-term fluctuations in ground-water levels in and near landslides exists.

The purpose of this study is to document ground-water-level fluctuations in specific, previously instrumented (with ground-water-level monitoring wells) landslides and adjacent slopes. These data are intended to provide engineering geologists and geotechnical engineers a preliminary basis for estimating design ground-water levels in

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landslide- and slope-stability analyses. In the future, we intend to update this paper as new data provide better information on long-term fluctuations in ground-water levels. Already, preliminary data from monitoring during the early part of 2006 indicate greater fluctuations and higher ground-water levels than documented in 2005.

In this paper, we compile and analyze selected ground-water-level data from three of five monitored Wasatch Front landslides (figure 1), and our results document both seasonal (within a single year) and intermediate-term (over a period of several years) fluctuations in levels. Our study spans a drought that began in 1999 and lasted through most of 2003, and our results document the impact on ground-water levels of successive dry years. We also document the rapid rise in seasonal high ground-water levels that occurred during the last two years of this study (2004 and 2005), which were locally wetter than normal, and this rise continues in 2006.

## PREVIOUS STUDIES

Kaliser and Slosson (1988) documented the rise in ground-water levels in Utah, affecting both confined and unconfined ground water, and the occurrence of perched ground water during the wet years of the early 1980s (1981-1984). Burden and others (2000) documented the rise in ground-water levels in some wells completed in unconsolidated Quaternary deposits in the Wasatch Front to historical high levels in the late 1990s. Ashland (2003) recognized that active landsliding in southern Davis and northern Salt Lake Counties in the late 1990s coincided with historically high ground-water levels in nearby wells. In addition, Ashland (2003) inferred that the rise in ground-water levels documented by Burden and others (2000) was caused, in part, by the infiltration of excess precipitation during a long-term wet cycle (Fleming and Schuster, 1985) that spanned the period between 1967 and 1998. Ashland (2003) also documented a landscape-irrigation-induced rise in ground-water levels at two Wasatch Front landslides and a transient rise in ground-water level due to an intense rainstorm event. Initial ground-water-level measurements at several of the landslides in this study were made as part of landslide-stability-evaluation studies by consultants (Terracon 1998; Terracon Consultants, Inc., 1998; URS/Dames & Moore, 2001).

## GROUND-WATER-LEVEL FLUCTUATIONS IN LANDSLIDES AND ADJACENT SLOPES

This study documents and analyzes ground-water-level data collected between late 1998 and 2005. Our data include ground-water levels compiled from other sources (Burden and others, 2000; Terracon, 1998; Terracon Consultants Inc., 1998). The long-term ground-water levels documented by Burden and others (2000) provide the best estimate for the changes in ground-water levels in landslides prior to this study, despite that the measurements were not in wells completed in landslides.

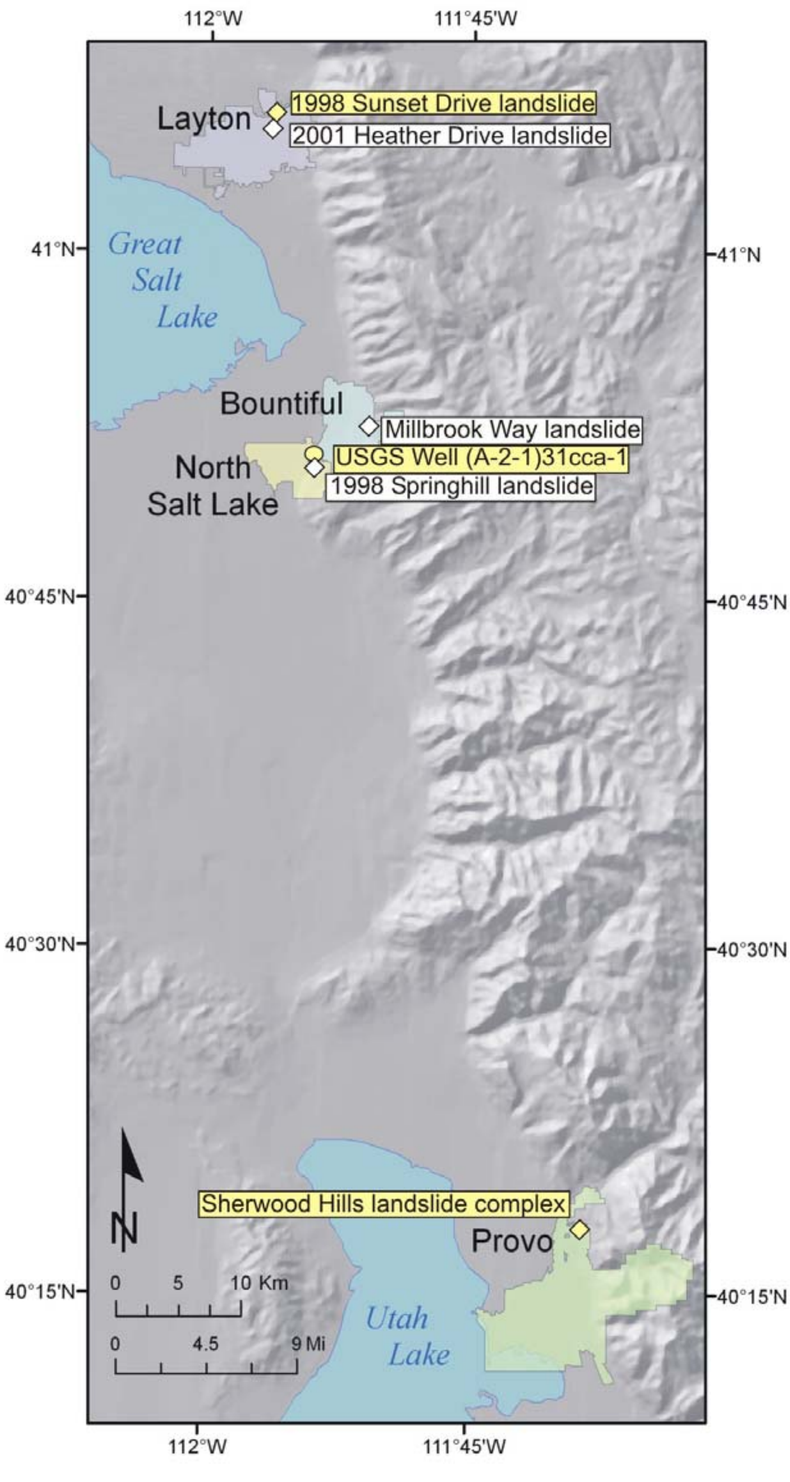


***Figure 1.*** *Location of historical landslides and monitoring wells completed in landslides or adjacent unconsolidated Quaternary deposits. Data from yellow sites are discussed in detail in this paper.*

## Long-Term Fluctuations in Unconsolidated Quaternary Deposits near Historical Landslides

Long-term ground-water-level data for Wasatch Front landslides are currently lacking, but our data provide some insight into long-term ground-water-level fluctuations in landslides. In addition, long-term ground-water-level fluctuations in landslides can be inferred from wells in nearby unconsolidated deposits. Figure 2 shows the long-term ground-water-level rise since 1960 in a well completed in lacustrine deposits in southern Davis County near the Springhill landslide that was active in 1998. The historical high ground-water level at this well occurred in 1999, a year after damaging movement of the Springhill landslide. The ground-water level in this well rose almost 22 feet between 1960 and 1999. About 8.5 feet of this rise occurred during a wet cycle (Fleming and Schuster, 1985) between 1967 and 1998 during which almost 24 inches of excess precipitation fell (Ashland, 2003). The wet cycle included three periods characterized by four or more successive wetter than normal years (1967-71, 1980-86, and 1995-98) referred to as precipitation periods (Ashland, 2003). The total rise in ground-water level during the three combined precipitation periods was about 10.5 feet; the 2-foot difference from the rise during the entire wet cycle (8.5 feet) is a result of declines in ground-water levels during intervening dry years (1972-79 and 1987-94). Most of this rise occurred during the last two precipitation periods (4.5 feet during the 1980-86 precipitation period and 4.7 feet during the 1995-98 precipitation period) that each contain one of the two wettest calendar years on record in Salt Lake City (1983 and 1998) (figure 3).

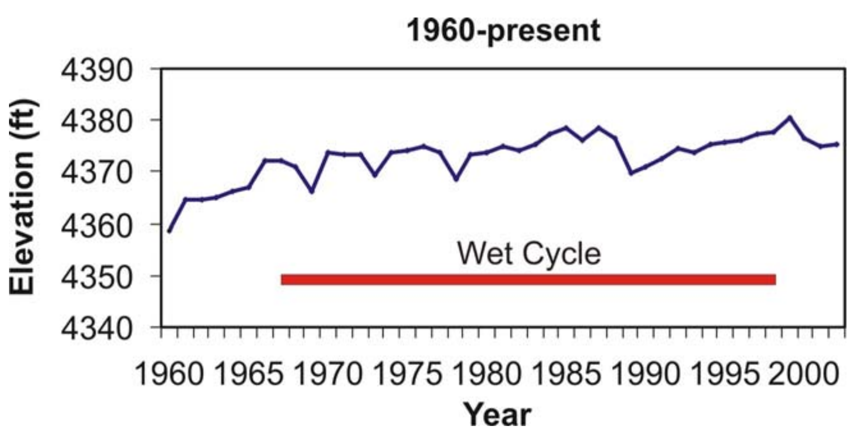


***Figure 2.*** *Long-term ground-water-level rise since 1960 in unconsolidated Quaternary (lacustrine) deposits in southern Davis County. Historical high ground-water level occurred in 1999. USGS well (A-2-1)31cca-1 (Burden and others, 2000). March ground-water level shown. Bar shows time span of wet cycle of Fleming and Schuster (1985) as interpreted by Ashland (2003).*

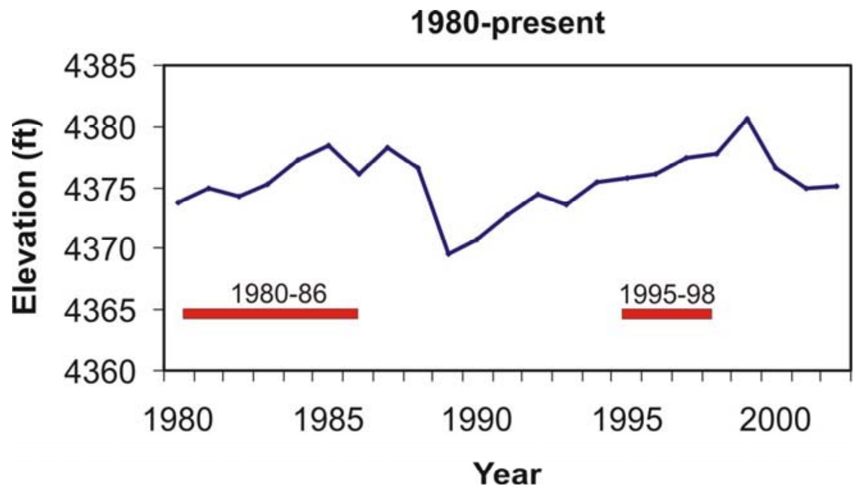


***Figure 3.*** *Detail of figure 2 showing rise in ground-water level during the last two precipitation periods). USGS well (A-2-1)31cca-1 (Burden and others, 2000). March ground-water level shown. Horizontal bars show time spans of the two most recent precipitation periods of Ashland (2003).*

## Short-Term Seasonal Fluctuations

We identify two types of short-term seasonal ground-water-level fluctuations: natural seasonal fluctuations controlled mostly by the late winter/early spring snowmelt recharge and irrigation-induced seasonal fluctuations caused by infiltration of excess water during summertime landscape lawn watering. The former is characterized by a single peak ground-water level that typically occurs before June, whereas the latter results in a bimodal curve where the second seasonal peak ground-water level is induced by irrigation and occurs in the later summer or fall near the end of the landscape irrigation season.

### Natural Fluctuations

Natural seasonal fluctuations of ground-water levels have been identified in several of the landslide areas in this study. At the Sunset Drive landslide, fluctuations in ground-water level in the lower, undeveloped part of the slide are controlled by the snowmelt in late winter/early spring (figure 4). Well B-3 in figure 4 is completed in the lower main body of the landslide. Ground-water-level fluctuations in well B-3 differ from those in wells farther upslope in the slide, so we believe the ground water in this well is hydraulically isolated from the shallow ground water in the upper part of the slide. Our interpretation of the borehole log for this well (Terracon Consultants, Inc., 1998) is that ground water is perched in a silty sand and silt layer overlying a lean clay layer. Since 1999, the peak seasonal ground-water level has occurred sometime between March and May coincident with the snowmelt and the three wettest months of the year (March through May in Salt Lake City), and the low seasonal ground-water level consistently occurred in either September or October following the dry summer months.

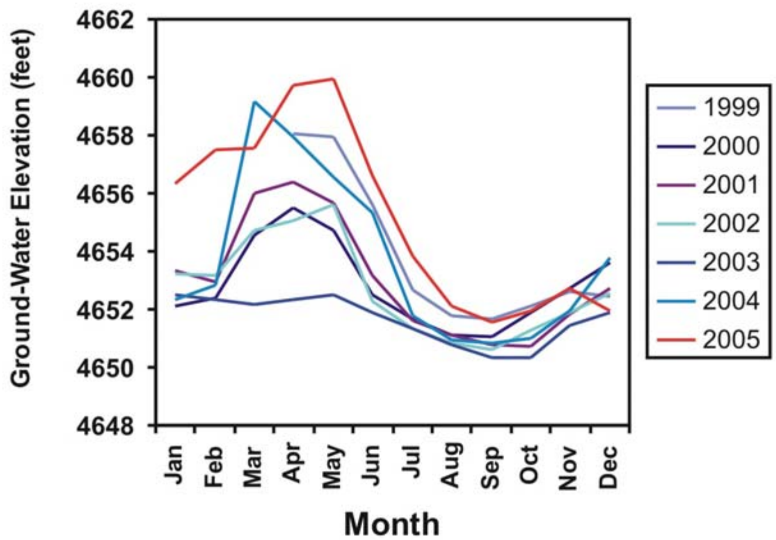


***Figure 4.*** *Natural seasonal fluctuation of the ground-water level in the lower part of the Sunset Drive landslide, Layton. Well B-3 (Terracon Consultants, Inc., 1998).*

Figure 4 also shows different responses in the seasonal peak and low ground-water levels in well B-3 to varying precipitation conditions between 1999 and 2000. During this period, the seasonal peak ground-water level varied by 7.4 feet, whereas the seasonal low level only varied by 1.3 feet. The seasonal peak ground-water level is primarily controlled by snowmelt recharge, and differences in late-winter, low-elevation snowpack are likely the primary cause of the variation. The seasonal low ground-water level in well B-3 is likely controlled by the ground-water gradient and the discharge conditions in the lower part of the landslide. Flowing springs and a seep in the lower landslide dry up by late summer as ground-water levels decline, reducing further lowering of the ground-water level. Somewhat surprising is the limited variation in the low seasonal level despite successive drier than normal conditions for most of the period (particularly from 2001 through 2003). We believe this supports our inference that the low seasonal ground-water level is primarily controlled by the ground-water gradient. In addition to the drying up of the springs and the seep in the lower slope, we infer that a diminishing capacity to lower ground-water levels accompanies a flattening of the gradient as ground-water levels decline in early summer in the upper part of the slope.

The importance of snowmelt recharge on the peak ground-water level is illustrated by the differences between the fluctuations in 2003 and 2004. In late winter 2003, a low-elevation snowpack was absent in the Wasatch Front, but present in late winter 2004. A snowpack measurement on the Sunset Drive landslide on February 5, 2004, indicated a snow-water content of 5.2 inches on the lower part of the slide, or about 32 percent of the normal annual precipitation in Salt Lake City and about 26 percent of the estimated normal annual precipitation in Layton (20.23 inches). The lack of a low-elevation snowpack, and particularly the absence of snow cover on the Sunset Drive landslide, in 2003 resulted in a seasonal peak ground-water level only 1.9 feet above the preceding seasonal low level. In contrast, in 2004 the peak ground-water level was 8.8 feet above the seasonal low. Figure 4 shows that the steepest rise in ground-water level more often coincides with the snowmelt during February and March rather than with spring rainfall during the wet spring months of April and May. By May, ground-water levels are typically declining or have started to decline. Table 1 summarizes the seasonal and total measured fluctuations in ground-water level in well B-3.

***Table 1.*** *Summary of ground-water-level fluctuations in well B-3, Sunset Drive landslide, Layton.*

| | |
|---|---|
| Range in seasonal fluctuation (calendar year) | 2.2 (2003) to 8.3 (2004) ft |
| Mean seasonal fluctuation | 5.4 ft |
| Maximum total measured fluctuation | 9.6 ft |
| Maximum ground-water level | May 2005 |
| Minimum ground-water level | October 2003 |

## Fluctuations Induced by Landscape Irrigation

Landscape irrigation (lawn watering) in the Wasatch Front diverts a considerable amount of water into hillslopes and infiltration of excess lawn water recharges the shallow ground-water table. In some Salt Lake City residential areas, homeowners apply up to 200 inches of water a year to their lawns despite the need for only 30 inches a year to sustain a healthy lawn (Hayes, 2003). This amount of landscape irrigation water is equivalent to roughly 12 times the annual precipitation (16.18 inches) in Salt Lake City.

A summertime rise in the shallow, unconfined ground-water table has been identified in wells in the upper, developed parts of two Layton landslides: the Sunset Drive and Heather Drive landslides. At both landslides, fill soil exists in the upper part of the slide and crown area upslope of the main scarp. The main scarps of both landslides occur in residential areas where landscape irrigation (lawn watering) occurs upslope of the slides. Figure 5 shows the seasonal fluctuation in ground-water level of well B-107 completed in the crown of the Sunset Drive landslide. Well B-107 is completed in interlayered lean clay and sand in the crown of the landslide and is surrounded by a residential area. The upper part of the borehole may be in clay fill, a result of hillslope grading prior to development, although fill is not identified in the borehole log of Terracon (1998).

In all but 2003 and 2004, ground-water-level curves in figure 5 are bimodal. Since 1999, peak seasonal ground-water level varies between spring and late summer, occurring in the latter in four of six years of measurement. All four years were drier than normal which likely promoted excess landscape irrigation during the summer. The peak ground-water level coincided with snowmelt recharge in only two years, 1999 and 2004. In both years, cumulative precipitation beginning September 1 (the informal landslide water year of Ashland, 2003) was near or above normal through most of the late winter and spring. Table 2 summarizes the seasonal, irrigation-induced, and total measured fluctuations in ground-water level for well B-107.

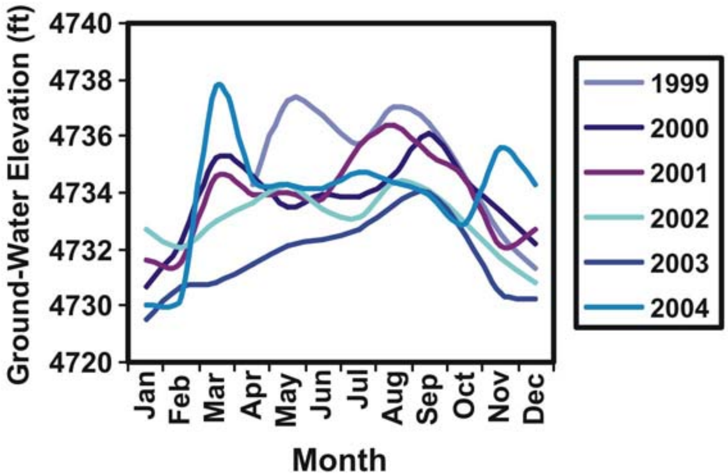


***Figure 5.*** *Landscape-irrigation-induced fluctuation of the ground-water level in the crown of the Sunset Drive landslide, Layton. Ground-water-level curves are bimodal except in 2003 and 2004. The first ground-water-level peak coincident with snowmelt recharge occurs in March through May and a later irrigation-induced peak occurs in August and September. Well B-107 (Terracon, 1998). Third peak in 2004 follows extreme precipitation in October 2004 during which about 7.5 inches of precipitation fell.*

***Table 2.*** *Summary of natural seasonal and landscape-irrigation-induced ground-water fluctuations in well B-107, Sunset Drive landslide, Layton.*

| | |
|---|---|
| Range in natural seasonal fluctuation (calendar year) | 3.6 (2002) to 10.4 (2005) ft |
| Mean natural seasonal fluctuation | 6.0 ft |
| Range in irrigation-induced fluctuation (calendar year)[1] | 3.6 (2002) to 5.7 (1999) ft |
| Mean irrigation-induced fluctuation[1] | 4.8 ft |
| Maximum total measured fluctuation | 11.7 ft |
| Maximum ground-water level | June 2005 |
| Minimum ground-water level | January 2003 |

[1]Difference between seasonal low and irrigation-induced peak ground-water level.

## Intermediate-Term Fluctuations

Over an intermediate term (periods of roughly a year or more in length), ground-water levels generally declined during the drier than normal years between 1999 and 2003. Subsequently however, at the Sunset Drive landslide, a rise in ground-water levels occurred in 2004 and 2005 in response to a return to wetter conditions.

Figure 6 shows April ground-water levels since 1999 in two wells at the Sunset Drive landslide in Layton. Both plots show a general decline in the April ground-water levels between 1999 and 2003 and rapid rebound in the levels beginning in 2004 following a low in 2003, suggesting the response of levels to the return to wet conditions is faster than the response to dry conditions.

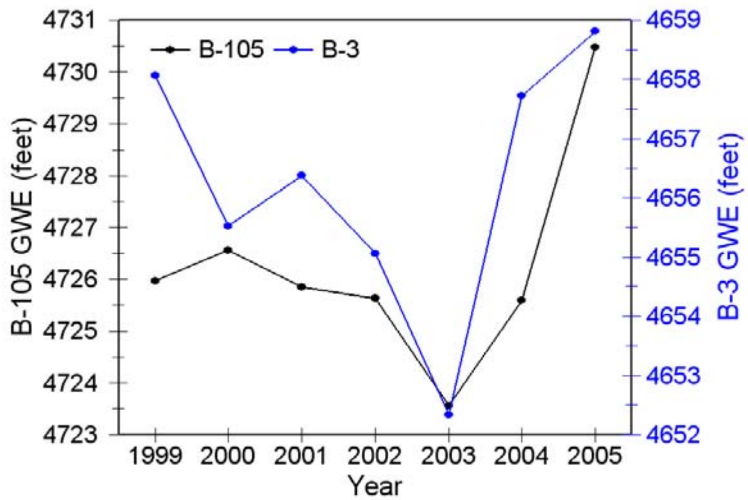


*Figure 6*. *April ground-water levels in the lower (B-3) and upper (B-105) parts of the Sunset Drive landslide, Layton between 1999 and 2005. Abbreviation: GWE – ground-water elevation.*

Figure 7 shows the decline in ground-water level in the active (upper) part of the Sherwood Hills landslide complex in Provo between March 2000 and March 2005. The total decline during this period is about 13 feet. Subsequently, the ground-water level rose 14.6 feet between March and August 2005, the highest seasonal fluctuation in ground-water level recorded at any of the landslides in the study.

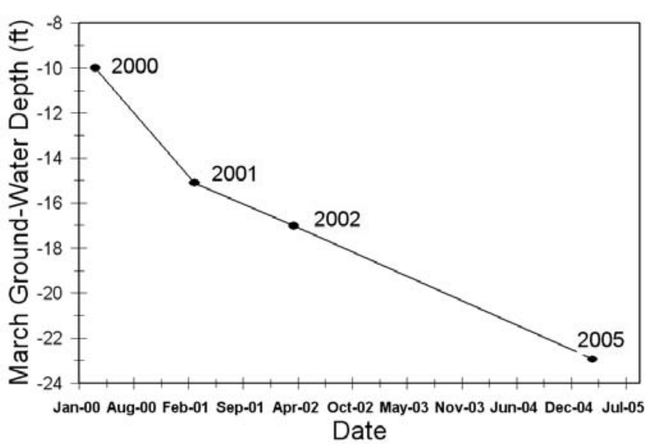


***Figure 7.*** *Decline in March ground-water level in the active part of the Sherwood Hills landslide complex, Provo, between 2000 and 2005. Total decline in ground-water level in well SH-1 was about 13 feet. Well SH-1(URS/Dames & Moore, 2001) is in upper main body of landslide and in the central part of the active area of the slide.*

## GROUND-WATER-LEVEL FLUCTUATION MODEL AT MOVEMENT INITIATION

Ground-water-level fluctuations were documented over a period of time in 2005 that bracketed the initiation of movement at two nearby landslides in northern Provo. Prior to landslide movement of the northern of the two landslides, ground-water levels began rising initially in the lower part of the Sherwood Hills landslide to the south. Observations indicating increased damage to roads and foundations suggest initiation of movement of the Sherwood Hills landslide likely occurred during this time period as well. Table 3 summarizes the observed ground-water-level fluctuations that bracket movement initiation in the first half of March 2005. Prior to movement initiation, ground-water levels had risen by more than a foot in the lower part of the landslide, but were declining in the upper part and head of the slide. By April, a month after movement initiated, ground-water levels were rising in the entire slide, but did not rise globally above the February levels until May (figure 8).

***Table 3.*** *Ground-water-level fluctuations in the Sherwood Hills landslide in 2005. Landslide movement initiated in early March.*

| Well | Location | Ground-Water-Level Fluctuation (feet) | | | | | Peak Month |
|---|---|---|---|---|---|---|---|
| | | Jan-Feb | Feb-Mar | Mar-Apr | Apr-May | May-Jun | |
| B-8 | Lower | 0.2 | 1.5 | 1.9 | 0.5 | 1.4 | June |
| B-1 | Middle | 1.4 | -1.6 | 1.0 | 1.7 | -2.7 | May |
| SH-1 | Upper | -0.03 | -0.02 | 4.2 | 6.1 | 3.6 | August |
| B-2 | Head | 0.3 | -0.9 | 0.3 | 1.6 | -0.6 | May-July |
| B-7 | Head | -2.3 | -0.1 | 1.9 | 1.7 | 0.8 | July |

The observed ground-water level distribution in the Sherwood Hills landslide occurred in other Wasatch Front slides in 2005, suggesting a dynamic ground-water-level-fluctuation model for movement initiation. Stretching deformation that typically occurs in the upper part of landslides (Baum and Fleming, 1991) results in transmissive extensional deformation features that facilitate infiltration of snowmelt water into the slide mass. However, deformation features associated with shortening in the toe of the landslide typically consist of low transmissivity thrusts and folds, the former commonly consisting of clay gouge zones. The initial rise in ground-water levels in the lower part of a landslide may result from the inability of the toe thrust system to dewater the slide at the same rate as water is infiltrating into the slide mass through upslope extensional deformation features. Rising ground-water levels in the lower slide result in a reduction of effective stresses and frictional resistance at a time where shallow soils in the upper slide are increasing in density due to snowmelt-induced wetting. Possibly, as ground water flows downgradient and backs up behind the toe thrust system, rising ground-water levels propagate upgradient. This sequence may represent the triggering mechanism process of many clay-soil landslides in Utah.

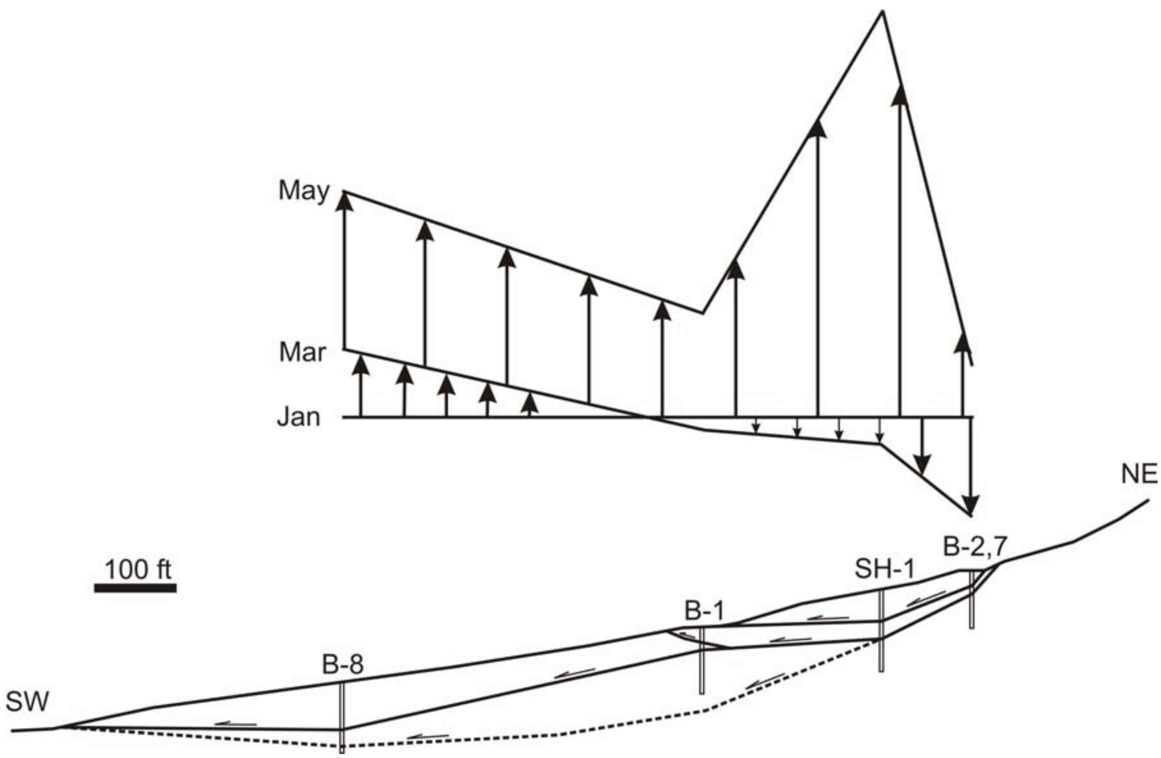


***Figure 8.*** *Geologic cross section of the Sherwood Hills landslide and plot showing ground-water level fluctuations bracketing the onset of damaging movement. Reactivation of this and a neighboring landslide in March was preceded by decreasing ground-water levels in head of landslide, but rising ground-water levels in lower part of slide. By April, ground-water levels were rising in all parts of the landslide, but were not universally higher than the January levels until May. Geologic cross section based on inclinometer data provided by Terracon (Rick Chestnut, written communication, 2005). Vertical arrows in upper plot show scaled relative rise or fall in ground-water levels from January 2005 level.*

## CONCLUSIONS

Our data document seasonal and intermediate-term ground-water-level fluctuations that can be used to estimate design ground-water levels in landslide- and slope-stability analyses. The data span a relative drought period (1999-2003), but locally document the effects of wetter than normal precipitation on ground-water levels in 2004 and 2005. Based on nearby ground-water-level data from unconsolidated surficial deposits (Burden and others, 2000), our initial ground-water-level measurements likely directly followed historically high levels in the late 1990s that coincided with active landsliding (Ashland, 2003).

At the Sunset Drive landslide in Layton, seasonal ground-water levels fluctuate in response to both late winter/early spring snowmelt (natural seasonal fluctuation) and locally to summertime landscape irrigation (lawn watering) (irrigation-induced fluctuation). We measured seasonal ground-water-level fluctuations ranging from about 2.2 to 10.4 feet. More variability exists in the natural seasonal peak ground-water levels than in the seasonal low levels in a single well. The timing of seasonal peak ground-water levels varies depending on the contribution of the infiltration of landscape irrigation water (lawn watering) on ground-water levels. Natural seasonal peak ground-water levels typically occur in late winter/early spring (March through May), whereas irrigation-induced peak seasonal ground-water levels mostly occur in later summer.

Our data quantify, in a preliminary manner, intermediate-term fluctuations in ground-water levels in landslides, but more data are needed over a longer period. The measured total fluctuation at the Sunset Drive (Layton) landslide reached a maximum of 11.7 feet. A decline in ground-water level of 13 feet occurred in a well in the upper part of the Sherwood Hills landslide complex, between 2000 and 2004. Measurements of same-month and/or peak levels showed that ground-water levels generally declined over the drought period (1999-2003), but locally rose in response to wetter than normal conditions in 2004. Preliminary data suggest the rebound in ground-water levels in wet periods is more rapid than the decline during dry periods.

The initial movement of clay-soil landslides in Utah may be associated with a sequence where ground-water levels begin rising in the lower part of slides upgradient of low transmissivity toe thrust systems followed by an upgradient-propagating rise in ground-water levels.

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