SNOWMELT-INDUCED GROUND-WATER FLUCTUATIONS IN SELECTED NORTHERN UTAH LANDSLIDES—PRELIMINARY RESULTS FROM THE 2007–08 LANDSLIDE WATER YEAR

by
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ABSTRACT

The relationship between ground-water levels and late winter/early spring snowmelt was evaluated at selected northern Utah landslides where ground-water observation wells had previously been installed. The period of investigation between September 2007 and August 2008 was characterized by generally wetter-than-normal conditions in the fall and early winter and subsequent drier-than-normal conditions. Snowfall in early winter resulted in a sustained snowpack that lasted through early 2008 at low elevation and into the spring at higher elevation. Ground-water levels predictably rose with melting snow, but the proportion of the rise attributable to melting of the winter snowpack varied. Peak ground-water levels consistently followed the onset of snowmelt, and locally occurred subsequent to local snowmelt around the vicinity of the observation well. At some locations, high ground-water levels were sustained for weeks or longer despite dry conditions in the spring and early summer. Differences in the rate of ground-water-level decline appear attributable to local ground-water gradient variations and the proximity of wells to shear zones, but other factors may play a role including variations in local permeability, ground-water compartmentalization by low-permeability clay gouge, and well construction for which detailed data are lacking.

INTRODUCTION

In northern Utah, winter snowpack typically covers most landslides, even those at lower elevations. The primary triggering mechanism of most of these landslides, excluding shallow slides on steep slopes, is a relatively rapid, snowmelt-induced rise in ground-water levels (Ashland, 2003; Ashland and others, 2005, 2006) that occurs in the late winter to spring. The resulting peak ground-water levels are transitory, but sustained above-normal precipitation following the peak levels can prolong the period of elevated ground-water levels (Ashland, 2003, 2007).

Previous research has focused on using temperature data to predict the critical snowmelt period associated with the onset of landslide movement in mountainous areas (Chleborad, 1997, 1998). The focus of this ongoing investigation is to examine the relationship between ground-water levels and the late winter/early spring snowmelt at selected northern Utah landslides where ground-water observation wells had previously been installed. Of particular interest is determining how the magnitude and timing of the transitory peak ground-water level relates to the local snowmelt on each landslide. Ultimately, this may contribute to an improved predictive model for landsliding in northern Utah triggered by snowmelt-induced ground-water-level rise. This report presents the preliminary results of this investigation, spanning most of the 2007–08 landslide water year (September 2007 through August 2008).

METHODOLOGY

The scope of the investigation consists of compiling provisional precipitation data from National Weather Service (NWS) stations near the landslides, collecting field measurements and observations on snow depth and ground-water levels, and data analysis. Provisional NWS data included daily, storm-specific, and monthly precipitation and snow depth data for stations near (typically within a few miles of and commonly in line-of-sight to) the landslides. The use of provisional NWS data allowed for tracking of precipitation concurrent with the fieldwork described below. Table 1 summarizes the type of NWS data available for the selected landslides.

NWS precipitation data were used primarily to determine the prevailing precipitation trend (wetter/drier than normal) and the approximate rain/snow ratio of monthly precipitation. Daily temperature data were also compiled for the Bountiful Val Verda station on dates of field measurements. Limitations of the data included occasional substitutions from sources other than the official station and the provisional nature of the data (possible errors, reporting discrepancies, etc).

Field observations included snow depth measurements from hand-dug snow pits, the relative snow cover, and ground surface conditions (moisture). Sketches of the snow layering were made at each pit as a basis for estimating the snow water equivalent of the snowpack using measured snow densities from other Wasatch Front sites. Ground-water levels were measured using a Heron Instruments water-level meter. With the exception of the well at the East Capitol Boulevard-City Creek (CBCC) landslide in Salt Lake City, the ground-water observation wells were installed previously by others, and detailed well-construction information for these wells is lacking. Table 2 summarizes some of the observation well information.

LANDSLIDE GEOLOGY

The landslides in this investigation are each in a distinct geologic setting and vary in aspect and elevation (figure 1). A brief summary of the geology of each landslide follows.

SunCrest Landslide C

SunCrest landslide C (Professional Service Industries, Inc. [PSI], 2004a) is an elongate, generally south-trending landslide on the south slope of the Traverse Mountains in Draper between approximately 5400 and 5800 feet in elevation (figure 2). The landslide is approximately 2700 feet long, with two clockwise bends in the upper and lower parts of the slide, and is about 500 to 1000 feet wide. Biek (2005) mapped the landslide as being underlain by Tertiary volcanic rocks, but landslide C appears to be part of a landslide complex in which identifying in-place Tertiary rocks poses a significant challenge. Trench excavations (PSI, 2004a, 2004b) revealed ground-deformation features in the lower and middle part of the landslide that consisted mostly of generally north-dipping thrusts on which debris was transported downslope. In the upper part of the landslide, the main scarp zone is dominated by ground-deformation features

Table 1. *Summary of available National Weather Service data types/sources for selected northern Utah landslides.*

Landslide[1]	Location	Daily Precip./SD[2]	Storm-Specific Precip./SF[2]	Monthly Precip./SF[2]	NWS Weathercam
SunCrest C	Traverse Mtns., Draper	NA	P	Y – Alpine P - DPOM	D - SunCrest[3]
CBCC	City Creek, Salt Lake City	Y – SLC WSFO		Y – SLC WSFO	N
Millbrook Way	Bountiful bench, Bountiful	Y - BVV	P – BVV P - BB	Y - BVV	Y - BB
Green Pond	Weber County	NA	P – Snowbasin ski resort	Y - Huntsville	Y – Snowbasin ski resort

[1]Landslides in bold were primary research sites.
[2]Daily and storm-specific NWS data may not be limited to formal station, but may include data from trained weather spotters in general location, Mesonet data, or other sources.
[3]SunCrest weathercam was discontinued during the period of this investigation.
Abbreviations: CBCC – East Capitol Boulevard-City Creek landslide; Y – yes; N – no; P – periodic; D – discontinued; NA – not available; BVV – Bountiful Val Verda NWS station, SLC WSFO – Salt Lake City Weather Service Forecast Office; BB – Bountiful bench; DPOM – Draper Point of the Mountain; SD – snow depth; SF - snowfall.

Table 2. *Summary of ground-water observation-well information.*

Landslide	No. of Wells	Well Depths (ft)	Well-Screen Depth Interval (ft)	Location(s) in Landslide
SunCrest C	2	94.4[1] - ~153[1]	NA	Upper main body
CBCC	1	6.1	2.6-6.1	Toe
Millbrook Way	3	6.2 - 7.8	NA	Head, main scarp, and crown
Green Pond	3	12.4 – 45.6	NA	Inactive lower main body

[1]Initial reported well depths based on information in Professional Service Industries, Inc. (2004b) were 125 and 150 feet.

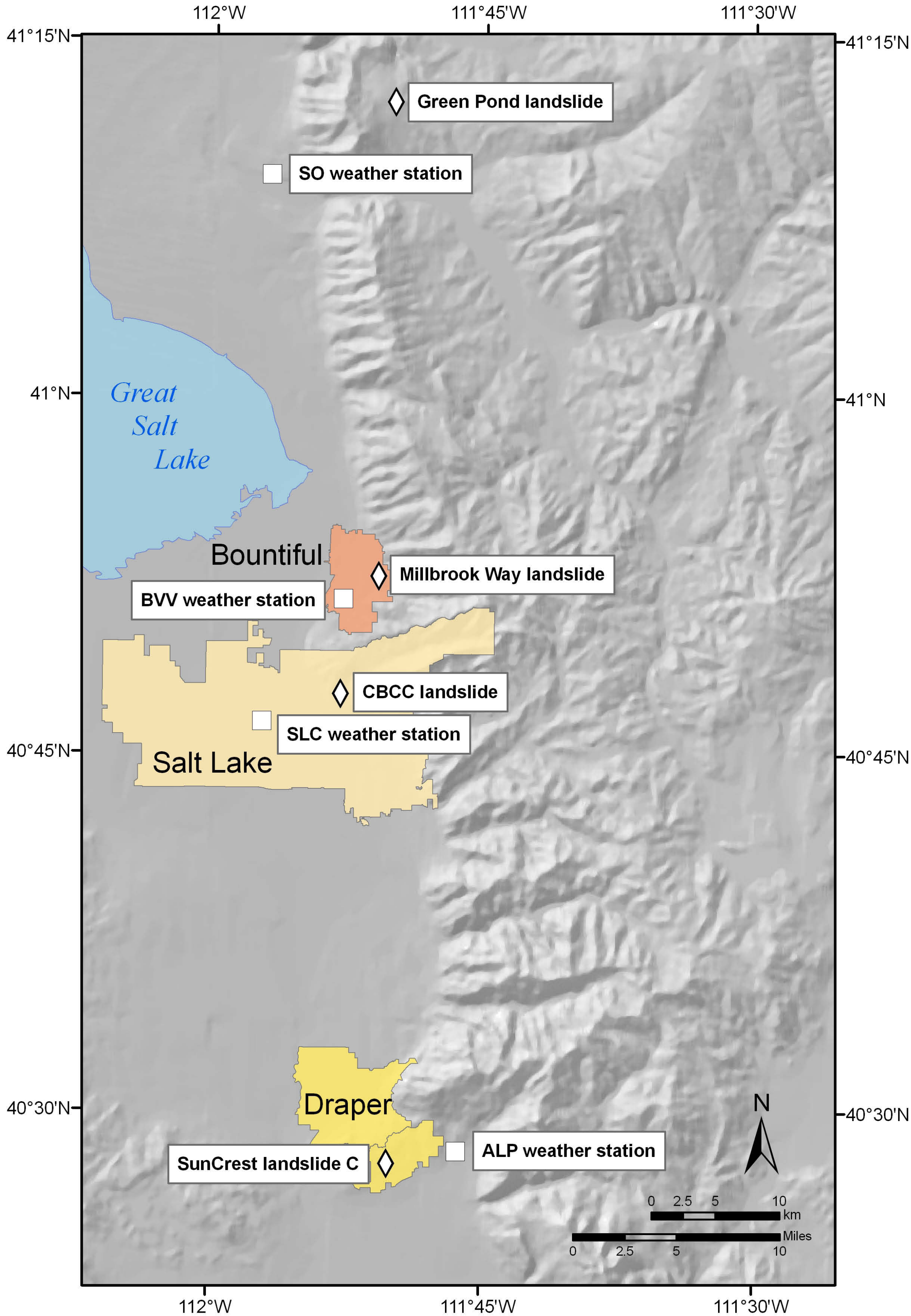

Figure 1. *Location of selected northern Utah landslides (diamonds) and weather stations (squares). Weather station abbreviations: SO – South Ogden, BVV – Bountiful Val Verda, SLC – Salt Lake City National Weather Forecast Office, ALP – Alpine. See text for additional information.*

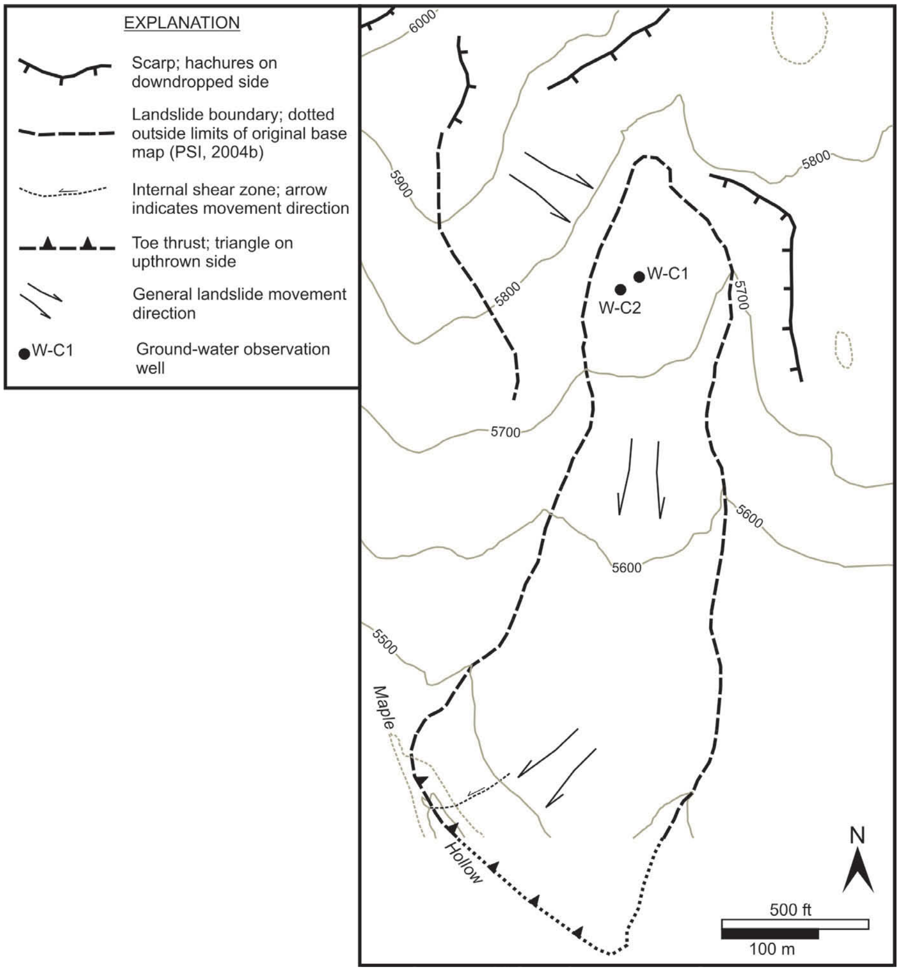

Figure 2. *Provisional sketch map of SunCrest landslide C in Draper. Dashed line shows approximate boundary of main part of landslide, but landslide also includes debris on moderate slopes downslope of scarps. Scarps in uppermost part of landslide possibly extend to north of mapped area. Deflected creek along west edge of toe suggests local historical movement in area bounded on south by internal shear zone. Most of figure modified from PSI (2004b). Southern and northern limits of topography reflect boundaries of original base map (PSI, 2004b). Dashed contour lines added for additional detail of Maple Hollow area and ridges.*

where the sense of the displacement is generally southeast side down. The toe of the landslide is along the east edge of Maple Hollow, where the stream channel appears to be locally deflected southwestward more than 15 feet, suggesting at least partial historical movement of the slide.

East Capitol Boulevard–City Creek Landslide

The East Capitol Boulevard-City Creek (CBCC) landslide (Ashland, 2003) is a persistently moving landslide on an east- to southeast-facing slope adjacent to a perennial tributary of City Creek in Salt Lake City (figure 3). The landslide is roughly funnel shaped in plan view and is about 620 feet long and 430 feet wide at its head, but only 45 feet wide at its toe. The landslide is between approximately 4700 and 4950 feet in elevation. Thinly bedded to laminated lacustrine silt with sparse gravel lenses or layers is exposed in the main scarp of the landslide. Van Horn (1981) mapped the underlying rock as Tertiary tuffaceous deposits. Exposures in cuts downslope of the landslide consist of heterogeneous debris that is likely older landslide deposits. The gray color and clay content of these deposits suggest they are likely derived from the underlying Tertiary rocks.

Millbrook Way Landslide

The Millbrook Way landslide is a relatively small historical landslide on a southwest-facing slope north of Mill Creek in Bountiful between approximately 5060 and 5110 feet in elevation (figure 4). The landslide is about 160 feet long and 140 feet wide at its toe that is along the base of a cut slope on the north side of Millbrook Way. Nelson and Personius (1993) mapped the area including and surrounding the Millbrook Way landslide as landslide deposits, suggesting the historical landslide is a partial reactivation of a pre-existing slide. Mapping by Nelson and Personius (1993) suggests that the prehistoric landslide formed in lacustrine shoreline deposits of Lake Bonneville that are underlain by metamorphic rocks (including amphibolites, schists, and phyllites) of the Precambrian Farmington Canyon Complex. Exposures of metamorphic rocks in cuts and foundation excavations along Millbrook Way indicate the

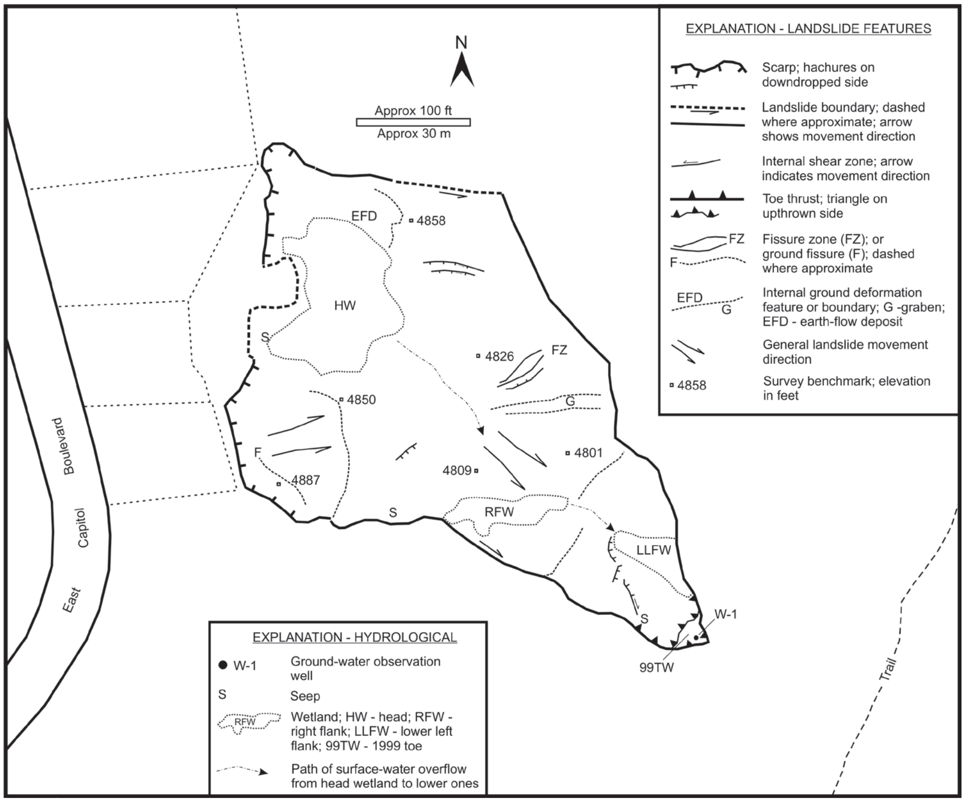

Figure 3. *Provisional sketch map of the East Capitol Boulevard–City Creek (CBCC) landslide in Salt Lake City. Survey points on landslide installed by Salt Lake City Surveyor Lynn Curt. Elevations measured in April 2006. Dotted lines show approximate boundaries of developed portions of residential lots in crown of landslide.*

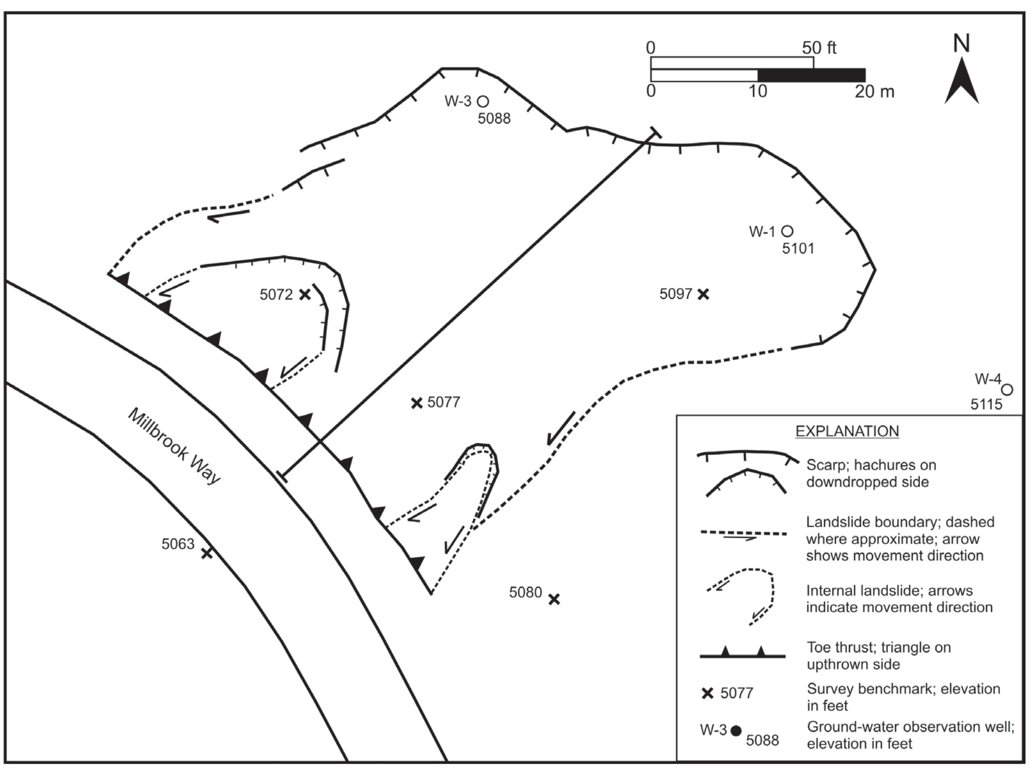

Figure 4. *Provisional sketch map of the Millbrook Way landslide in Bountiful. Ground-water observation wells W-1 and W-3 are near or in the main scarp, respectively. Ground-water observation well W-4 is upslope and east of the main scarp. Two shallow small slides exist in lower part of landslide. Ground elevations measured in 2005. Solid line shows approximate section line in figure 11.*

lacustrine deposits are relatively thin and suggest the landslide mapped by Nelson and Personius (1993) may be relatively deep-seated and include the underlying metamorphic rocks. The surface of rupture of the Millbrook Way landslide may also extend into the weathered upper part of underlying metamorphic rocks, based on their shallow depth in the crown, east side, and toe of the slide. Shallow test pits excavated as part of this study revealed a variety of near surface geologic materials in and near the landslide. Brown, matrix-supported, massive sandy silt exposed in the main scarp of the Millbrook Way landslide is probably a previously unmapped Holocene alluvial-fan deposit. On the east side of the landslide, metamorphic rocks are exposed at the surface and in an excavated drainage ditch. Upslope of the landslide, a test excavation revealed well-sorted, brown to light brown, fine to medium sand of probable lacustrine origin. Desiccation cracks occur in areas underlain by alluvial-fan deposits and shallow metamorphic rocks and indicate shallow expansive fine-grained soils.

Green Pond Landslide

The Green Pond landslide is a large, historical landslide crossed by State Route 226 (SR-226) in Weber County, Utah (figure 5). The landslide is elongate, somewhat irregularly shaped, approximately 7800 feet long, and has a length to width ratio that varies between about 78:1 and 7:1. Monitoring and observations indicate that the landslide is persistently moving, but can be subdivided into currently active and inactive parts. The active southeastern side of the landslide has been moving at a very slow rate since, at least, October 2005 when landslide-movement monitoring by the Utah Geological Survey began. Surficial deposits near the landslide consist of glacial debris overlying weathered Tertiary Norwood Tuff. Two borehole logs indicate that the uppermost landslide deposits are derived from glacial debris and extend to a depth of approximately 23 and 30 feet near SR-226. The underlying landslide debris is derived from weathered Norwood Tuff that locally consists of weak lean and fat clays. A shallow auger hole upslope of SR-226 in the inactive part of the landslide revealed the uppermost 3 feet of soil consisted of boulders and cobbles of quartzite in a matrix of fat clay.

2007–08 LANDSLIDE WATER YEAR PRECIPITATION AND SNOWPACK

Precipitation in the Wasatch Front of northern Utah during the 2007–08 landslide water year (LWY) (Ashland, 2003; September through August) was generally above normal for the first six months and subsequently below normal beginning in March (figure 6). However, November 2007 was a notably dry

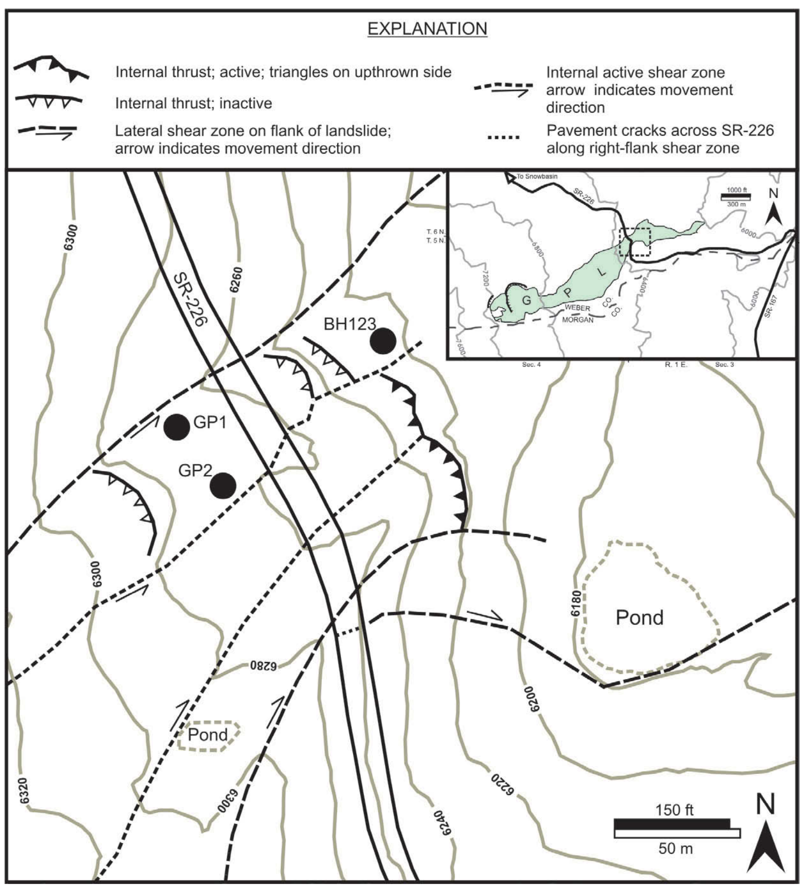

Figure 5. Location of ground-water observation wells in the inactive part of the Green Pond landslide. The three wells are located in the inactive north-western part of the landslide. Inset shows entire landslide. Box in inset shows general location of figure. Modified from Landslide Technology (2002).

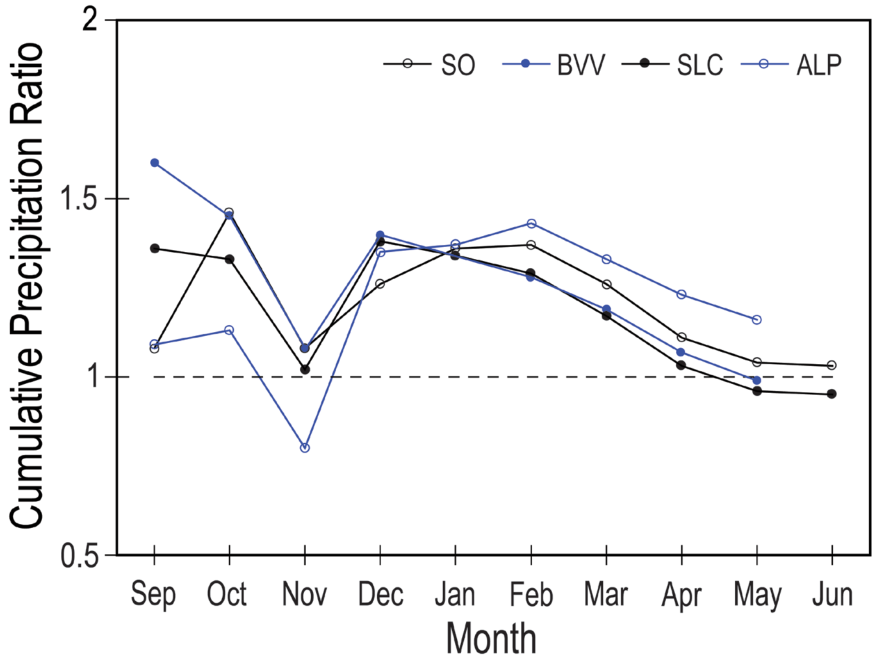

Figure 6. *Cumulative precipitation ratio at four weather stations near selected landslides for most of the 2007–08 landslide water year. The cumulative precipitation ratio is the ratio between the cumulative precipitation for the 2007–08 landslide water year and the normal landslide water year. Cumulative wetter-than-normal conditions generally prevailed between September 2007 and the end of April 2008. Dry conditions beginning in March began a gradual decline in cumulative excess precipitation. Station abbreviations: SO – South Ogden, BVV – Bountiful Val Verda, SLC – Salt Lake City Weather Forecast Office, ALP – Alpine.*

month in the first part of the landslide water year and caused the temporary downward deflection in cumulative precipitation curves in figure 6. By the end of February, cumulative precipitation was 128 percent of normal or higher at the four weather stations, but continuously declined in March, April, and May, which were atypically dry in 2008. Three of the NWS stations in figure 2 (BVV, SLC, and ALP) are at line-of-sight distances from the Millbrook Way, East Capitol Boulevard-City Creek, and SunCrest C landslides, respectively. Precipitation in northern Utah varies by elevation, and higher elevation sites were significantly wetter than lower elevation sites.

The South Ogden weather station (SO) (figure 1), although not near a landslide used as part of this investigation, included a web-accessible daily precipitation dataset that allowed for tracking the approximate percentage of the landslide water year precipitation that fell as snow. In the 2007–08 landslide water year, measurable snow first fell at the South Ogden weather station on October 6, 2007 and the last measurable snowfall occurred on May 1, 2008. Snowfall in October and November (table 3) did not result in a sustained low-elevation snowpack. By December, frequent storms resulted in a snowpack at the station that lasted through early March, and snow remained on low-elevation north-facing slopes into early April. The peak snow depth of 22 inches was reached on February 4, 2008. Snowfall made up approximately 73 percent of the precipitation that fell between September 2007 and May 2008 at the station. However, because the rainfall component of the recorded precipitation was not reported during storms that consisted of rain/snow mixes, the total precipitation was assumed to be due to snowfall. Thus, the estimated snowfall component of the precipitation (73 percent) is a maximum value.

Figure 7 shows the approximate snowfall at the four weather stations during the 2007–08 landslide water year. Little snow fell between September and November, but December and January were snowy months with above-normal precipitation. Thus, a sustained snowpack covered all the landslides by early December. The maximum snow depths recorded during this study occurred in January at the Millbrook Way landslide, and in February at the CBCC and SunCrest C landslides. A lack of evidence of melting of the snowpack at the Green Pond landslide when snow depths were measured in mid-March, suggests the measured snow depths were likely near their maximum. Table 4 summarizes the snowpack measurements at the landslides.

SNOWMELT

The 2007–08 LWY snowmelt can be divided into three parts, melting of fall snow prior to development of a sustained snowpack, melting of the sustained winter snowpack, and melting of late winter/spring snow that fell subsequent to complete melting of the snowpack. Dry conditions from March through May 2008 resulted in the latter contributing only a minor amount to the total landslide water year snowmelt. At the highest elevations on the Green Pond landslide, remnants of the winter snowpack lingered into spring, overlapping with the last of the spring snowfall.

Table 3. Summary of precipitation and snowfall at the South Ogden weather station from September 2007 through May 2008.

Month	Total Precip. (in.)	Snowfall (in.)	Snowfall SWE [1] (in.)	Snowfall/Precip. Ratio (%)
September	1.87	T	0	0
October	3.47	4	2.05	59
November	0.90	2	0.43	48
December	3.68	29	3.68	100
January	3.56	44	3.56	100
February	2.66	27.5	2.66	100
March	1.59	11	1.59	100
April	0.89	2	.48	54
May	1.33	0.2	0.02	2

[1]Snow water equivalent amounts are likely maximum values because the rainfall component of daily precipitation was not reported during mixed rain/snow storms and total precipitation was assumed to be due to snowfall.
Abbreviations: SWE – snow water equivalent; T – trace.

Table 4. Summary of winter snowpack conditions at selected northern Utah landslides.

Landslide	Peak Snow Depth (in.)	SWE (in.)	SWE (%AP)	Approx Snowpack Duration
SunCrest C	23.6	4.2 - 5.3 [E]	NA	Dec 07 - Mar 08
CBCC	10.2	3.3 - 3.8[E]	20 - 23	Dec 07 - Feb 08
Millbrook Way	9.1	1.8 - 2.3 [E]	8 - 10	Dec 07 - Feb 08
Green Pond	47 - 57[1]	17.6 - 21.5[M]	NA	Dec 07 - May 08

[1]Range in peak snow depth reflects measurements at two separate locations on Green Pond landslide. Values are average snow depth at each location.
Abbreviations: E – estimated; M – measured (average), %AP – percent of annual precipitation, NA – not available.

Melting of Fall 2007 Snow

In the Wasatch Front area of northern Utah, snowfall in October and November 2007 was followed by warm periods with daily low temperatures above freezing at lower elevations. Only two storms delivered snow to northern Utah in October, and the snow that fell completely melted after each storm (figures 8 and 9). Only minor snow fell in November, and through most of the month no snow covered the landslides for an extended period of time.

Melting of the 2008 Snowpack

At the Wasatch Front landslides (SunCrest C, CBCC, and Millbrook Way), the melting of the winter snowpack had begun by early to mid-February. Locally, some partial melting of the low-elevation snowpack had occurred in the previous two months, even while snow was accumulating. Partial melting of the snowpack in December and January was most notable on south-facing slopes. At the two low-elevation landslides (CBCC and Millbrook Way), a significant partial melting of the snowpack occurred between January 3 and 6, 2008, a four-day period where maximum daily temperatures were above freezing. On January 4, the daily low temperature also remained well above freezing (38°F) at the South Ogden weather station and wind gusts reached 47 miles per hour. Snow depth records at the NWS Bountiful Val Verda (BVV) station showed a 3-inch decline in snow depth between January 2 and 6, 2008, and indicated a snow depth of only 1 inch on the morning of January 6.

In February, the low-elevation snowpack began consolidating and melting faster than the rate of new snow accumulation and a decline in snow depths from their early peak levels was noted at all three Wasatch Front landslides by late February. By mid-March, the winter snowpack had completely melted at the two low-elevation Wasatch Front landslides (figure 9) and melting was well underway at the higher elevation SunCrest landslide C, where snow cover was estimated to be about 40 percent of the entire landslide area by March 19 (figure 8). The winter snowpack on SunCrest landslide C completely melted by April 25.

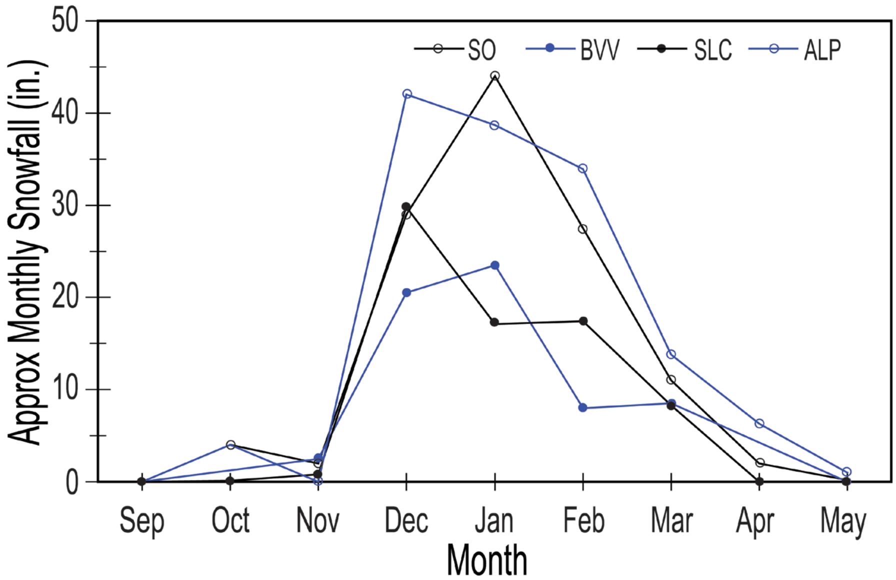

Figure 7. *Approximate monthly snowfall at four weather stations near selected landslides from September 2007 through May 2008. Snowfall at the Bountiful Val Verda station was not consistently reported during the period and likely represents a minimum value. Snowfall amounts estimated using provisional daily reports for Bountiful area and other sources. Station abbreviations: SO – South Ogden, BVV – Bountiful Val Verda, SLC – Salt Lake City Weather Service Forecast Office, ALP – Alpine.*

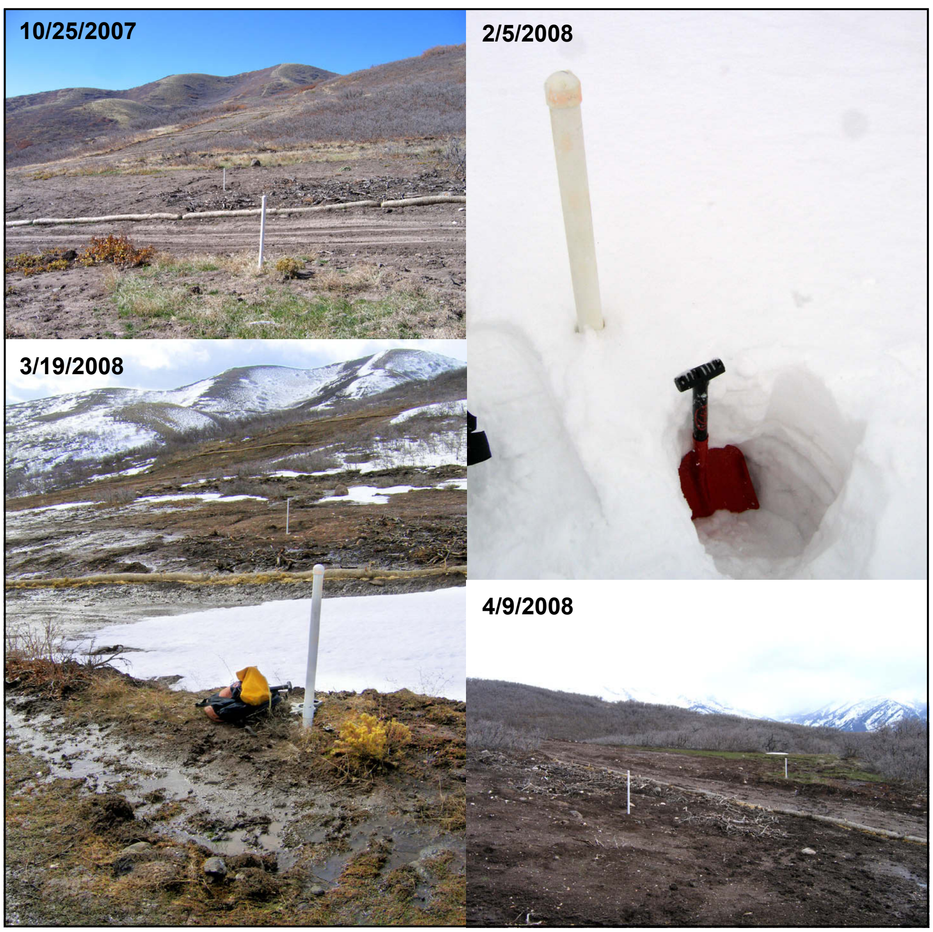

Figure 8. *Chronological photographs documenting the snow cover and snow depth on SunCrest landslide C between October 2007 and April 2008. By December 2007, snow accumulation had begun on the landslide. A maximum snow depth of 24 inches was measured on February 5, 2008. By March 19, 2008, snow covered approximately 40 percent of the landslide. By April 9, 2008, snow covered less than 2 percent of the landslide, mostly on shaded slopes in the head and along the edges of the slide.*

Figure 9. *Chronological photographs documenting the snow cover on the Millbrook Way landslide between October 2007 and March 2008.*

At the highest elevation Green Pond landslide, much of the snowpack in the lower part of the landslide had melted by early May, but local deep patches of snow remained on shaded slopes. By late May, most of the snowpack had melted, but patches of snow remained in the head of the slide on shaded slopes including the large scarps in the head. Snowstorms as late as May 21 continued to deliver some snow to the upper parts of the slide, but by the end of May, snow likely covered no more than a few percent of the entire landslide, restricted to the shaded uppermost areas.

LANDSLIDE GROUND-WATER LEVELS

At three of the landslides, ground water was shallow and unconfined, with depths below the ground surface ranging as shallow as roughly 8 inches at the toe of the CBCC landslide at peak ground-water level to as deep as about 14 feet in the inactive part of the Green Pond landslide. At SunCrest landslide C, ground water was relatively deep with depths greater than 33 feet in both wells, and differentiating whether confined or unconfined conditions existed was not possible. Confined ground water exists locally in the active part of the Green Pond landslide as indicated by artesian flowing conditions observed in vibrating-wire piezometer B208 (Ashland and others, 2008). Simplified geologic cross sections at several of the well sites based on limited subsurface data are shown in figures 10, 11, and 12.

Timing and Relative Magnitude of Ground-Water-Level Rise

Ground-water levels in three of the landslides rose from October 2007 to seasonal peak levels in early to mid-2008. Ground-water levels rose during accumulation of the snowpack at the slides, but the proportion of the rise during the period of snowpack accumulation varied significantly between the three sites (table 5). Ground-water-level measurements were not possible at the Green Pond landslide between January and March 2008, because deep snow buried the wells; thus, the ground-water-level rise preceding the peak snow depth could not be determined.

At SunCrest landslide C, the smallest proportion of the ground-water-level rise occurred during the period of snow accumulation and most of the rise was coincident with the snowmelt (table 5). At the Green Pond landslide, ground-water levels in one of the three wells rose slightly (about 1 foot) between October and December 2007, a period that overlapped with the beginning of snow accumulation on the landslide. The one-foot rise represents about 12 percent of the total measured 8.7-foot rise (the measured rise is a minimum estimate because the exact seasonal low ground-water level was not defined by measurements in 2007) to the peak seasonal level, which occurred in early May 2008. The 12 percent rise in the well between October and December 2007 is only a minimum value because most of the snow accumulation on the slide likely occurred after the December measurement, during which some additional rise in ground-water levels probably occurred.

Table 5. *Comparison of the relative magnitude of the ground-water-level rise during snow accumulation and snowmelt.*

Landslide	GWL Rise Before and During Snow Accumulation (percent)	GWL Rise During Snowmelt[1] (percent)
SunCrest C	13-18	82-87
CBCC	90 (75 pre-snowpack)	10
Millbrook Way	65-84	16-35

[1] Includes ground-water-level rise that followed completion of snowmelt.

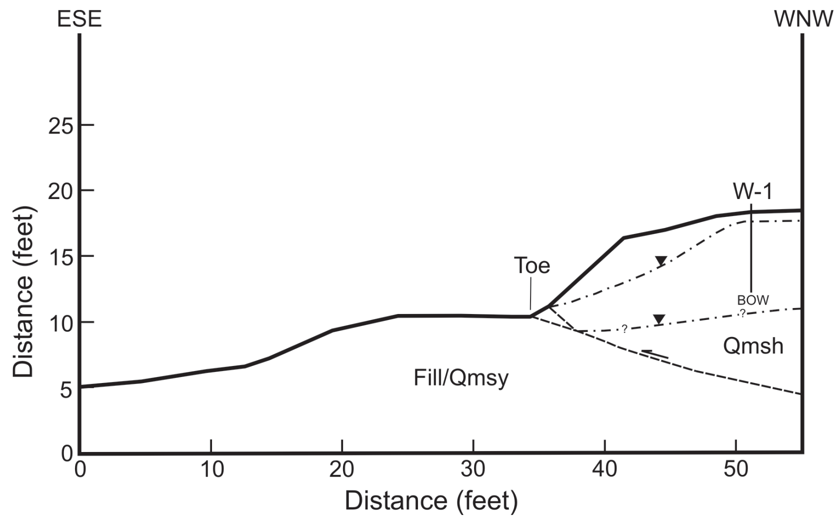

Figure 10. *Simplified geologic cross section of the toe of the CBCC landslide (Qmsh) at well W-1. Dashed line shows inferred basal surface of rupture. Dashed-dotted lines show inferred range in ground-water level in 2008. Query indicates uncertainty in actual low ground-water level, which falls below bottom of well (BOW) during which seepage at the toe stops. Fill and landslide deposits (Qmsy) are overthrust by the toe of CBCC landslide. Figure 4 shows well W-1 location. Section line trend is azimuth 297 degrees.*

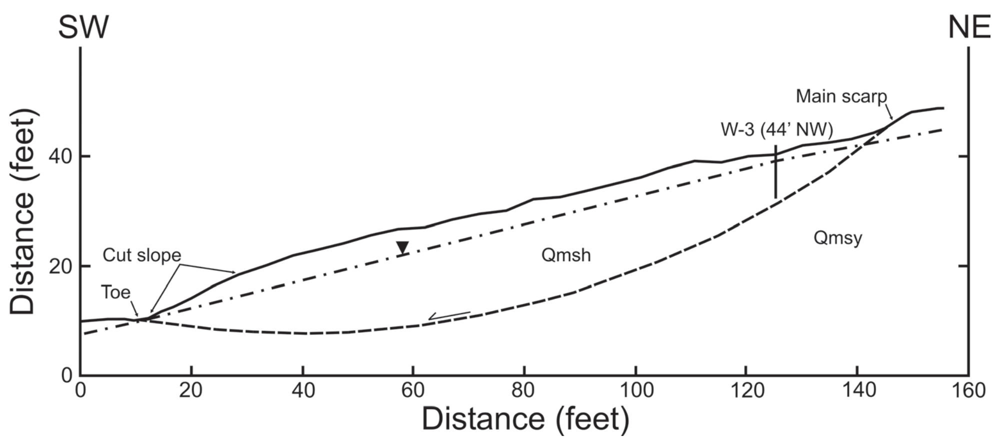

Figure 11. *Simplified geologic cross section of the Millbrook Way landslide (Qmsh). Dashed line shows inferred basal surface of rupture based on site-specific slope-stability analysis (arrow shows movement direction). Millbrook Way landslide is a partial reactivation of a mapped pre-existing landslide (Qmsy) (Nelson and Personius, 1993) that consists of displaced surficial deposits and underlying weathered Precambrian metamorphic rocks. Approximate projected location of well W-3 shown (offset 44 feet northwest of section line). The well is actually located in main scarp free face, thus, the shear zone that forms the scarp intercepts the well. Ground-water level (dashed-dotted line) shown based on highest measured level in well W-3. Figure 4 shows approximate location of section line.*

In contrast at the CBCC landslide, most (75 percent) of the ground-water-level rise preceded the establishment of a sustained winter snowpack (table 5). An additional 15 percent of the rise occurred during the snow accumulation period, but the smallest proportion (10 percent) of the rise to the peak seasonal ground-water level occurred during the snowmelt. As at the CBCC landslide, the largest proportion of the ground-water level rise at the Millbrook Way landslide also occurred before and during the snow accumulation period (table 5).

Timing of the Seasonal Peak Ground-Water Level

The timing of the seasonal peak ground-water level at each landslide varied slightly, but occurred after the onset of snowmelt near the ground-water observation wells (figures 13 through 16). At the SunCrest C and CBCC landslides, the peak ground-water levels occurred coincident with or after the completion of local snowmelt (figures 13 and 14). At the CBCC landslide, the seasonal peak ground-water level occurred nearly coincident with (no more than two weeks after) the completion of local snowmelt (figure 14); however, at SunCrest landslide C it occurred between three weeks to over three months after the completion of local snowmelt (figure 13). At the Millbrook Way landslide, the seasonal peak ground-water level occurred while the snowmelt was still in progress and the remaining snow depth was about 67 percent of the maximum (figure 15). Similarly, the peak ground-water level at the Green Pond landslide occurred after the onset of snowmelt, but prior to completion of snowmelt near the ground-water observation wells (figure 16).

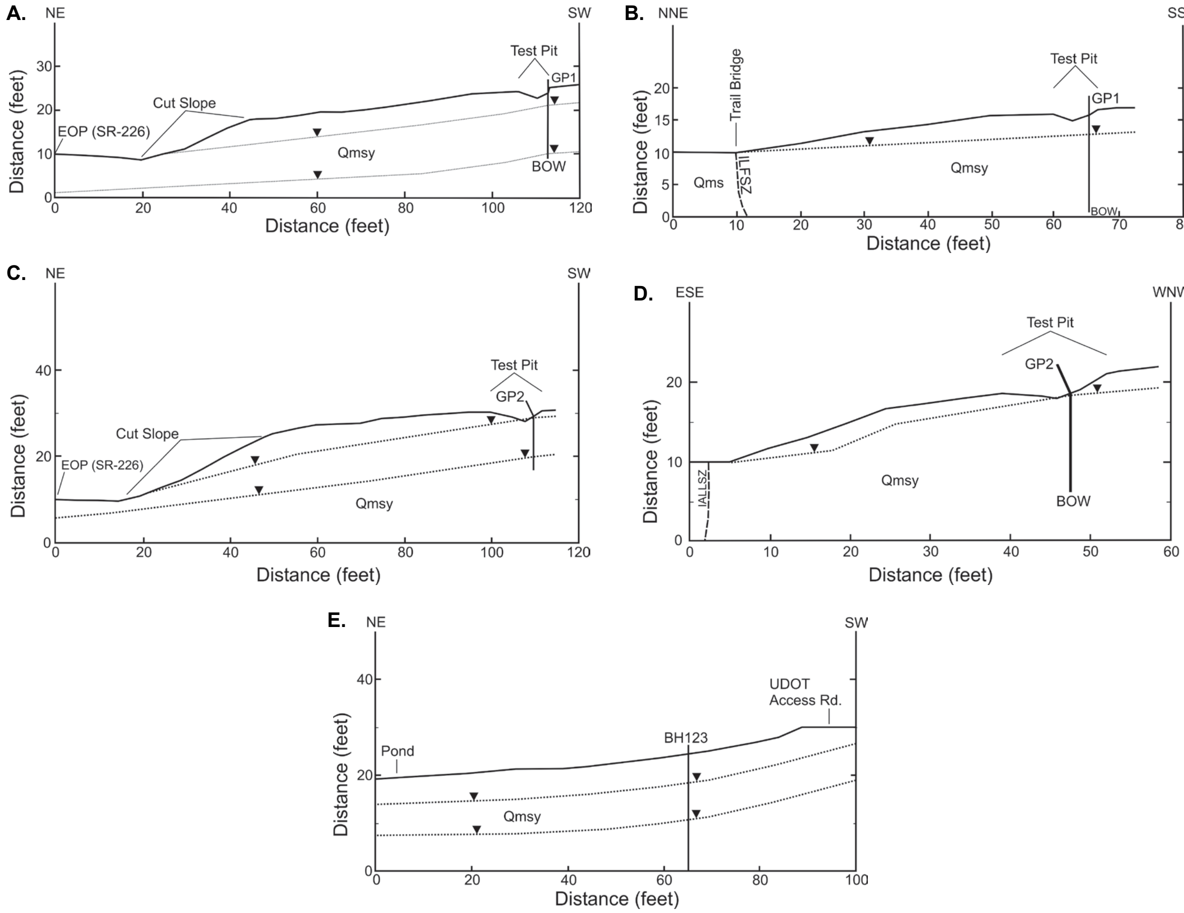

Figure 12. *Simplified geologic cross sections at three ground-water observation wells in an inactive part of the Green Pond landslide. (A) Longitudinal cross section near well GP1 through cut slope along SR-226. Trend of section is azimuth 238 degrees. (B) Cross section parallel to local slope near well GP1. Trend of section is azimuth 190 degrees. (C) Longitudinal cross section near well GP2 through cut slope along SR-226. Trend of section is azimuth 236 degrees. (D) Cross section parallel to local slope near well GP2. Trend of section is azimuth 294 degrees. (E) Longitudinal cross section near well BH123. Trend of section is azimuth 252 degrees. Ground-water levels (dotted lines) in 2008 shown based on measurements in wells and estimated elsewhere based on observed seeps. Seasonal peak and low ground-water levels shown in A, C and E. Seasonal peak ground-water levels shown in B and D. See figure 5 for ground-water observation well locations. Abbreviations: Qmsy – landslide deposits in inactive part of Green Pond landslide, Qms – landslide deposits outside boundary of Green Pond landslide, ILFSZ – inactive left-flank shear zone, IALLSZ – internal active left-lateral shear zone, EOP – edge of pavement (SR-226), BOW – bottom of well.*

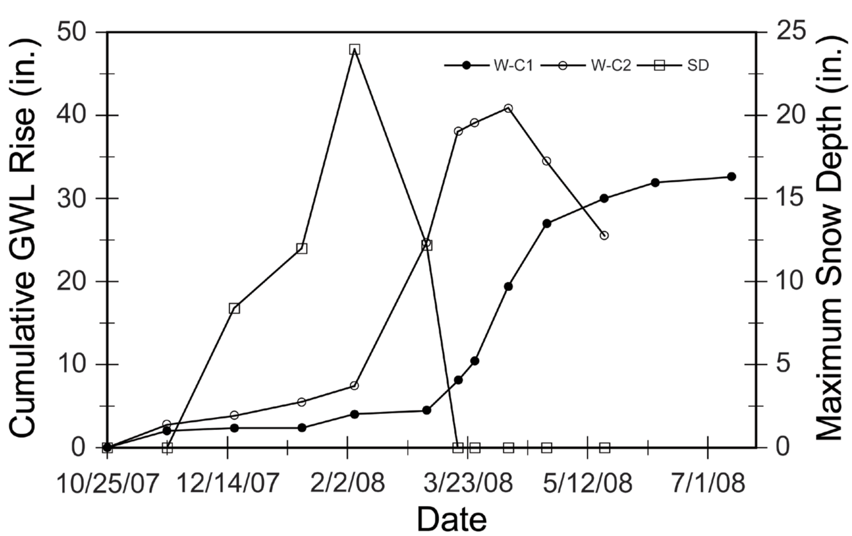

Figure 13. *Plot showing cumulative ground-water-level (GWL) rise (circles) and maximum snow depth (MSD; squares) at SunCrest landslide C. Wells W-C1 and W-C2 are only 52 feet apart and at approximately the same ground elevation; however, well W-C1 is shallower in total depth.*

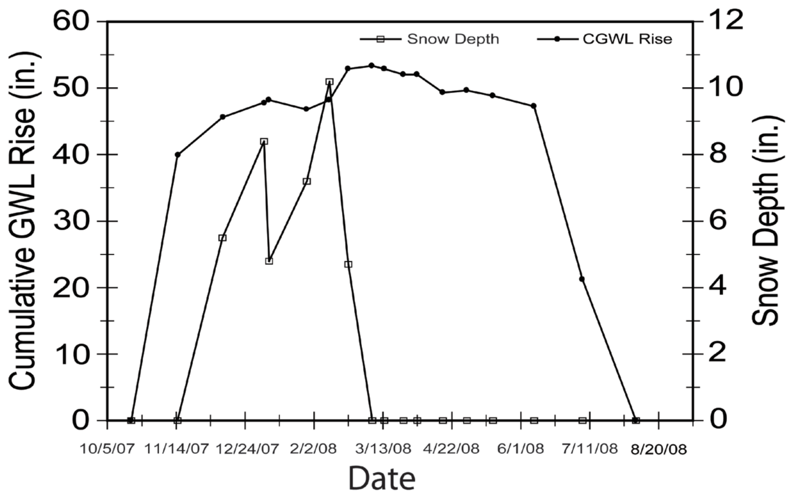

Figure 14. *Plot showing cumulative ground-water-level (GWL) rise (circles) and local snow depth (squares) at the toe of the CBCC landslide. A sustained high ground-water level occurred between December 2007 and early June 2008.*

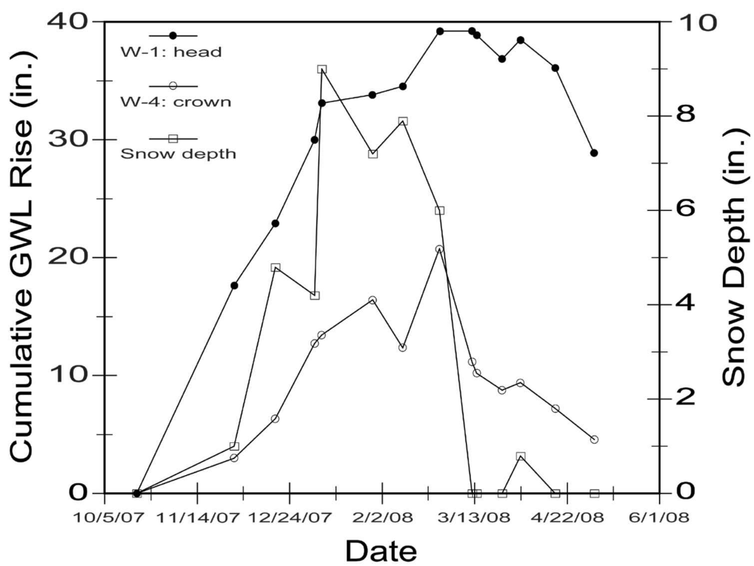

Figure 15. *Plot showing cumulative ground-water-level (GWL) rise (circles) and local snow depth (squares) at the Millbrook Way landslide. Snow depth measured near observation well W-1.*

Sustained High Ground-Water Level

Subsequent to the seasonal peak ground-water level, a relatively high ground-water level was sustained at two of the landslides. This occurred despite a drier-than-normal period that lasted from March through June in 2008.

SunCrest landslide C

At SunCrest landslide C, the ground-water level in well W-C2 declined at an apparently uniform rate following the peak level (figure 13). In about six weeks, the ground-water level declined approximately 15 inches, or about 38 percent of the total measured rise in the well since October 2007. A relatively high ground-water level was sustained for about three weeks immediately preceding the seasonal peak ground-water level, during which the ground-water level was no more than approximately 3 inches below the peak level. The seasonal peak ground-water level in well W-C1, occurred in July, too late to assess the rate of decline in this study.

East Capitol Boulevard–City Creek landslide

Figure 14 shows that the ground-water level in the toe of the landslide declined only slightly, approximately 6.1 inches, during the first three months following the seasonal peak level. Interestingly, during the two months preceding the seasonal peak level, the ground-water level rose approximately the same amount (5.5 inches) that it declined in the three months following the peak level. Figure 14 also shows that a relatively high ground-water level, no more than 8 inches below the peak level, was sustained for about six months between December

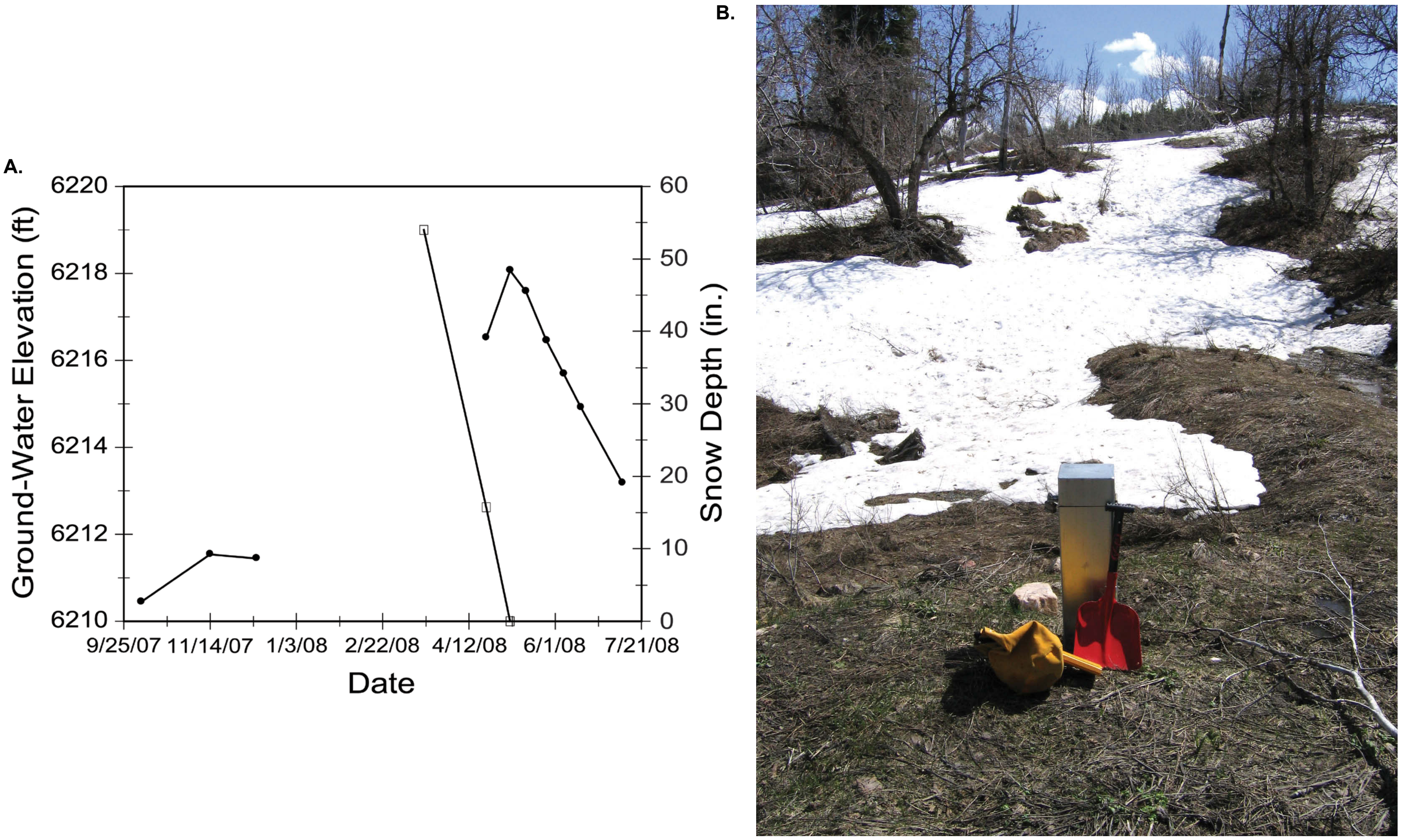

Figure 16. *Plot (A) showing cumulative ground-water-elevation rise (circles) in well BH123 and local snow depth (squares) at the Green Pond landslide. Snow depth measured near well BH123. Excessive snow depth prevented ground-water-level measurement between January and March 2008. Photograph (B) shows snow cover on May 6, 2008 when the seasonal peak ground-water level occurred in well BH-123 (metal protective well casing in foreground). Local snowmelt is complete around well.*

2007 and June 2008. By June, a sharp decline in ground-water level began, similar to the sharp rise that occurred between October and November 2007.

Millbrook Way landslide

At the Millbrook Way landslide, the duration of a relatively high ground-water level depended on the location of the well in the landslide. Figure 15 shows that in well W-1 located in the head of the slide, the ground-water level remained within a few inches (3.1 in.) of the seasonal peak level for approximately 50 days. In contrast, in well W-4 located in the crown of the slide, the ground-water level declined to half of the total rise to the peak level within about two weeks. Table 6 shows that the magnitude of the ground-water-level decline for specific time periods was different in each well in the slide, despite their proximity. The greatest decline in ground-water level through June 2008 occurred at well W-3 located in the main scarp of the landslide. However, in two of the wells, a high ground-water level was sustained, remaining within 0.6 inch of the peak seasonal level for 16 days. Subsequent to that initial period, the magnitude of the ground-water-level decline was greatest in well W-3 that likely penetrates the shear zone that forms the main scarp.

Green Pond landslide

At the Green Pond landslide, ground-water levels declined relatively rapidly following the seasonal peak level (table 7, figure 16). Ground-water levels declined between 1.6 and 4.0 feet in the first 11 days and between 2.4 and 5.6 feet in the first month following the peak level. The magnitude of the decline in the first month was equal to between 28 and 47 percent of the total estimated rise from the seasonal low ground-water level in 2007 to the seasonal peak ground-water level in May 2008.

INTERPRETATION

At each of the landslides, rising ground-water levels coincided with melting of the winter snowpack; however, the proportion of the rise at each site coinciding with snowmelt varied (table 5). At two of the four landslides, both at relatively low elevation, the largest proportion of the seasonal-ground-water-level rise occurred prior to and during the period of snow accumulation at the site. However, at the other two higher elevation landsides, the largest proportion of the seasonal ground-water-level rise occurred during snowmelt. The seasonal peak ground-water

Table 6. *Summary of ground-water-level decline following the seasonal peak groundwater level at the Millbrook Way landslide. See figure 4 for well locations.*

	Ground-Water-Level Decline (feet)		
Time Period/Well No.	**W-1** (head)	**W-3** (main scarp)	**W-4** (crown)
1st 16 days	NC	NC	0.9
Peak - Apr 2008	0.3	1.5	1.1
Peak - Jun 2008	2.9	6.5	1.9

Abbreviation: NC – nominal change (less than 0.05)

Table 7. *Summary of ground-water-level decline following the seasonal peak groundwater level at the Green Pond landslide. See figure 5 for well locations.*

	Ground-Water-Level Decline (feet)		
Time Period	**GP1**	**GP2**	**BH123**
1st 11 days	2.9	4.0	1.6
1 month	4.0	5.6	2.4
2 months	7.4	8.9	4.9

level that followed the onset of the snowmelt was transitory at each site, but the duration of relatively high ground-water levels varied considerably. In addition, where multiple wells existed in close proximity, the subsequent decline in ground-water levels was not uniform or even consistent. Further discussion regarding these observations and results follows.

Fall 2007 Ground-Water-Level Rise

At three of the landslides and in one well at the fourth, ground-water levels rose prior to the period of snow accumulation and a sustained winter snowpack, indicating infiltration of mixed precipitation from fall storms. Field observations in the summer of 2008 showed that drying of surficial soils was accompanied by shrinkage that formed polygonal desiccation cracks, possibly resulting in enhanced infiltration capacity by the onset of wetter conditions in the fall. Nevertheless, at the two landslides where the most expansive clay soils exist in the near surface, the Green Pond and SunCrest C slides, the smallest proportion of the ground-water-level rise occurred during the fall and early winter (table 5). One explanation for the minor fall rise in ground-water levels at these slides is the possibility that the desiccation cracks heal rapidly with the return of wet conditions in the fall. Another possibility is that because the desiccation cracks penetrate only short distances (typically only several feet) into the landslide and the crack tips (bottom of the crack) are underlain by clay, water that fills the cracks wets near surface soils, but fails to or is slow to infiltrate and reach the ground water. Thus, the presence of low-permeability clayey surficial soils, regardless of their expansive nature, inhibits infiltration of fall precipitation.

A combination of permeable surficial soils and ground-deformation features that inhibit runoff likely promoted infiltration in the upper parts of the two low-elevation landslides (CBCC and Millbrook Way). Surficial soils in the upper parts and crown of the two lower elevation slides consist mostly of permeable lacustrine and/or alluvial silt and sand that likely have a higher infiltration capacity than the clayey surficial soils in the higher elevation slides. In addition, both lower elevation landslides are historical, and ground deformation features, particularly at the recurrently active CBCC slide, disrupt slopes and drainages, inhibiting runoff and promoting infiltration as water ponds behind ridges or antithetic scarps and is intercepted by open ground cracks.

Somewhat enigmatic is the very high proportion of the ground-water-level rise that occurred in the fall of 2007 prior to the initiation of snow accumulation at the CBCC landslide in Salt Lake City. Between mid-October and mid-November 2007, the ground-water level in the toe of the landslide rose over 40 inches (a minimum value because the ground-water level drops below the bottom of the well in late summer), approximately 75 percent of the total measured seasonal rise (53.4 inches). Prior to this rise, cumulative precipitation in September through October 2007 was 133 percent of normal, but the cumulative excess precipitation total was less than an inch, insufficient to explain the magnitude of the measured ground-water-level rise. Precipitation in November was only 38 percent of normal, likely contributing to the decline in the rate of ground-water-level rise that directly followed the mid-November level measurement (figure 14).

Another possible explanation is that the fall ground-water-level rise is due to infiltration of excess landscape-irrigation water on lots in the crown of the slide. Landscape irrigation typically occurs throughout the summer months and into the early fall, particularly if the water source is culinary water as it is in Salt Lake City. Excess landscape-irrigation water would likely infiltrate into the permeable lacustrine silts and gravels in the crown of the landslide and intercept the landslide at springs in the main scarp or in the subsurface below the main scarp free face. The funnel shape of the landslide in plan view (figure 3) suggests ground-water flow lines would likely converge toward the narrow toe of the slide. Thus, a ground-water pulse related to infiltration of landscape-irrigation water from above may be seasonally directed toward the toe area, resulting in a rise in ground-water levels in the lower part of the slide. In other northern Utah landslides, a landscape-irrigation-induced ground-water-level rise is characterized by a second transient peak in late summer or early fall (Ashland and others, 2005, 2006), and not the sustained late fall rise seen at the toe of the CBCC landslide. However, a landscape-irrigation-induced ground-water-level rise has not been observed in the toe of any other Utah landslide to date, and thus, a direct comparison to the observed rise at the CBCC landslide is not possible.

Evapotranspiration may be another cause for the observed relatively rapid ground-water-level fluctuations. The fall ground-water-level rise occurred at the end of the growing season for the vegetation on the toe of the CBCC landslide that includes reeds, Russian olives, and oak trees. Thus, the fall rise in ground-water level may be due to the suspension of evapotranspiration at the end of the growing season. Similarly, the rapid decline in the ground-water level beginning in June 2008 coincided with rapid growth of reeds surrounding the well and the onset of evapotranspiration. The magnitude of the ground-water-level fluctuations in the well is within the range of evapotranspiration-related ground-water-level fluctuations reported by Laczniak and others (1999) for a site with some of the same vegetation types in southern Nevada.

Snowmelt Component of Ground-Water-Level Rise at Higher Elevation Landslides

The higher proportion of the seasonal ground-water-level rise attributable to snowmelt at the two higher elevation landslides is most likely due to the larger snowpack (due to elevation and also above-normal snowpack at higher elevations in 2008). In the 2007–08 water year, snowpack at moderate to high elevation in the Wasatch Range of northern Utah locally reached over 150 percent of normal. In mid-March at the Green Pond landslide, the average snow water equivalent of the peak snowpack was between about 18 and 22 inches near the observation wells (measured between approximate elevations of 6160 and 6520 feet) (table 3). Thus, a considerable amount of water likely infiltrated into the landslide in the subsequent weeks during snowmelt. The difference in the snow water equivalent of the peak snowpack at SunCrest landslide C and the lower elevation slides was only a few inches, but possibly sufficient to explain the larger proportion of the rise occurring during snowmelt. Although not measured, observations indicated that the snowpack along the ridgeline directly above SunCrest landslide C was considerably higher than that on the landslide and likely contributed somewhat to the rise in ground-water levels as runoff from above infiltrated into the slide or ground water intercepted the main scarp zone.

Locally Sustained High Ground-Water Levels Following the Seasonal Peak Level

Despite dry conditions between March and June 2008, relatively high ground-water levels were sustained locally in some of the landslides for several weeks or longer. At the CBCC landslide, the sustained high ground-water level in the toe of the landslide is even more enigmatic because it initiated prior to the accumulation of the winter snowpack and remained well past the completion of local snowmelt. Figure 14 shows that the ground-water level remained within 8 inches of the peak seasonal level from December 2007 through early June 2008. In the first month following local snowmelt, the ground-water level declined by approximately an inch. The sustained high ground-water level occurred despite below-normal precipitation following snowmelt, suggesting precipitation was not the cause of the sustained high level.

The location of the well in the toe of the landslide may explain the sustained high ground-water level. As indicated previously, the landslide is funnel shaped in plan view, narrowing downslope to a width of approximately 45 feet at the toe. Ground water in the landslide is thus likely directed and concentrated in an increasingly narrower area as it flows downslope from the head to the toe (figure 3). The recharge area in the head of the landslide is considerably larger than the discharge area in the toe. Thus, an imbalance between the volume of water infiltrating in the head of the landslide and the discharge capacity at the narrow toe may occur during snowmelt. In the head, ground-water infiltration is accommodated by open ground fissures and scarps, whereas discharge in the toe occurs along less permeable shear zones (thrusts) characterized by clay gouge. Ground water likely flows, perched above the clay gouge, along the base of the sheared debris above each thrust. This probable imbalance in efficiency between infiltration and discharge in the landslide may account for the sustained high ground-water level in the toe. With the added component of evapotranspiration by wetland vegetation near the toe tipping the balance, ground-water levels begin to decline in early summer. If wet conditions had occurred in spring 2008, a sustained high ground-water level may have been longer in duration and the peak level been higher.

At the Millbrook Way landslide, high ground-water-levels were sustained for about 16 days in the two wells located within the boundary of the slide. Seepage occurred from the upper head area near the wells during and shortly following this high ground-water-level period. Most of the precipitation that fell in March came after ground-water levels began to decline in the middle of the month. Thus, March precipitation unlikely sustained the levels in the wells. Mapping by Nelson and Personius (1993) showed lacustrine deposits, which a shallow test excavation showed to be mostly sand, extending about 1000 feet upslope of the main scarp of the pre-existing landslide deposits. Therefore, upslope infiltration of snowmelt water may have helped sustain ground-water levels in the landslide, if ground water flows downslope through the lacustrine deposits into the older landslide deposits of Nelson and Personius (1993), which surround the Millbrook Way slide. However, the well in the crown showed an immediate decline, likely in part due to the presence of a local drainage ditch that probably limits the maximum height of ground water in the well and prevents a sustained peak level by intercepting shallow ground water.

Differences in the Rate of Ground-Water-Level Decline

At three of the landslides with multiple, closely spaced wells (SunCrest C, Millbrook Way, and Green Pond), the decline in ground-water levels following the seasonal peak level was not uniform, but the reason for the differences may vary at each slide. A lack of well-construction and subsurface-condition information increases uncertainty in interpretation.

At SunCrest landslide C, the ground-water fluctuations following the completion of local snowmelt varied significantly in two ground-water observation wells separated by only 52 feet and at about the same elevation, but completed to different depths. Differences in ground-water levels between the two wells, which ranged from approximately 17.5 and 21.5 feet (figures 13 and 17), suggest some sort of compartmentalization of ground water. The timing of the seasonal peak ground-water level in the deeper, western ground-water observation well W-C2 about a month after local snowmelt, but prior to completion of snowmelt on the entire landslide, suggests the peak level occurred mostly in response to local snowmelt. However, the continued rise of the ground-water level in the shallower eastern well W-C1 into the summer, at a declining rate of rise, suggests the influence of a more distant recharge area on the ground-water level. Exactly why the deeper of the two ground-water observation wells responded more directly to local snowmelt remains unclear.

Trenches (PSI, 2004a,b) excavated near the ground-water observation wells indicate they are located in a structurally complex transition zone between the northwestern part of the main scarp zone and the upper main body of the landslide. To the south and downslope of the wells, the general landslide fabric consists of moderately northwest-dipping debris separated by thrusts with similar attitudes. Directly to the west and northwest of the wells, the northwestern part of the main scarp zone is characterized mainly by down-to-the-southeast stretching-related deformation features. Thus, the ground-water observation wells are located in a zone where the movement of debris changes from a southeastward direction to a southward one (figure 2). In the borehole log for ground-water observation well W-C2 (PSI, 2004b; well CB-1), a thick clay zone (probably along a thrust) is described at a depth of approximately 65 to 73 feet and several thin clay zones are indicated below to a maximum depth of about 123 feet. The clay zones may vertically compartmentalize ground water in the landslide, explaining the significant ground-water-level difference between the two closely spaced wells. One explanation for the apparent local response to snowmelt of the deeper well is the possibility that the local recharge area for the saturated debris beneath the confining clay zone is downslope of the well (figure 17), particularly given the upslope (northwest) dip of the clay zones along the thrusts.

At the Millbrook Way landslide, differences in the amount of ground-water-level decline may be due to variable distances of the observation wells from shear zones and permeability differences of various near-surface geologic materials. The greatest decline in ground-water level, excluding that in the short-term (16-day decline), was in well W-3 that possibly penetrated the shear zone that formed the main scarp, suggesting the shear zone may locally enhance dewatering of adjacent soils. The ground-water-level decline in well W-1, located in

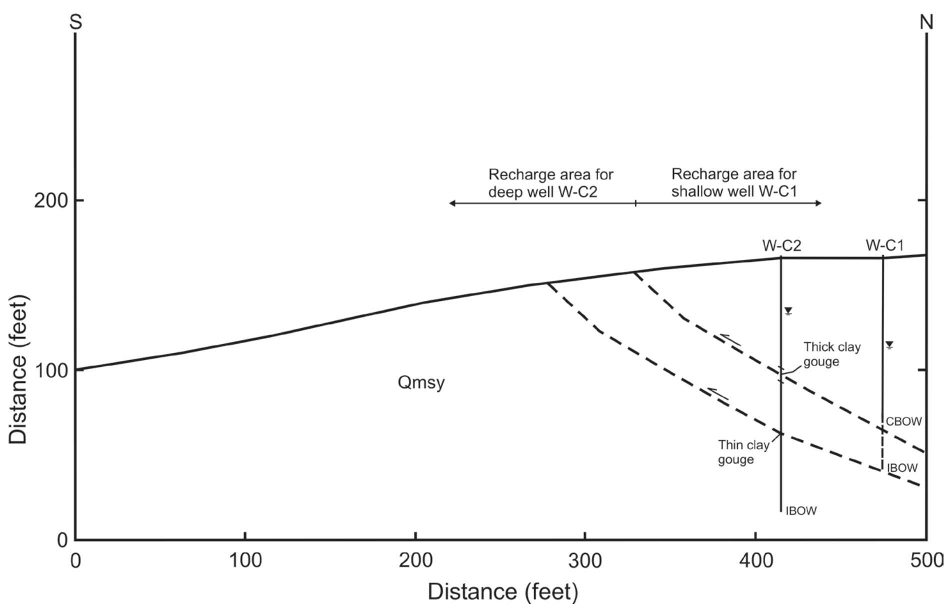

***Figure 17**. Simplified longitudinal geologic cross section near two ground-water observation wells in SunCrest landslide C showing possible recharge areas. Clay gouge along generally north-dipping thrust faults may hydraulically isolate well-screen portions of the two wells. Shallow well W-C1 may measure ground-water level in saturated debris above thrusts, whereas deep well W-C2 may measure ground-water level in saturated debris below and between thrusts. The ground-water level in well W-C2 ranged between 17.5 and 21.5 feet higher than that in well W-C1 during the measurement period. Probable recharge area for well W-C1 is upslope of where thrust intercepts ground surface. Probable recharge area for well W-C2 is downslope of where upper thrust intercepts ground surface. Topography and depth of probable thrusts based on data in PSI (2004b). Abbreviations: IBOW – initial bottom of well, CBOW – current bottom of well (possibly due to siltation in well), Qmsy – landslide deposits (SunCrest landslide C). Depth of landslide unknown.*

the head and directly downslope of the main scarp, but also close enough to the scarp for the lower part of the well to intercept the shear zone, was less than half that in well W-3 by June 2008. The smallest decline in ground-water level occurred in well W-4, outside of the landslide, which is likely completed in low-permeability metamorphic rocks. The main scarp of the Millbrook Way landslide forms a discontinuity that severs, to some extent, the near-surface geologic materials within the slide from those in the crown. However, the observed seepage in the head of the landslide that continued after the completion of local snowmelt suggests some hydraulic connection between shallow surficial deposits upslope and those in the landslide.

At the Green Pond landslide, the differences in the amount of ground-water-level decline (table 7) may be due to local ground-water gradient differences (figure 12). The most rapid decline occurred in well GP2, which has the steepest local ground-surface slope of the three wells. The smallest decline in well BH123 may be attributable to the relatively flat local slope, and inferred flatter ground-water gradient directly downslope of the well. Additionally, a cut-slope directly downslope of wells GP1 and GP2 may increase the efficiency of ground-water discharge because thrusts along which ground water flows may daylight in the cut face.

SUMMARY AND CONCLUSIONS

The results of this ongoing investigation, although preliminary and subject to limitations (see below), reveal the contribution of snowmelt to rising ground-water levels that can trigger landslide movement. This phase of the ongoing investigation specifically examined snowmelt during the 2007–08 landslide water year, which was generally wetter than normal from September through February, and drier than normal beginning in March 2008. Precipitation in northern Utah varies by elevation, and higher elevation sites were significantly wetter than lower elevation sites. A sustained winter snowpack began developing in December 2007 and lasted into early 2008, depending on elevation and aspect.

Locally at all four sites, mixed (snow and rain) precipitation in fall 2007 contributed to a slight rise in ground-water levels. The most dramatic rise during this period occurred in the toe of the CBCC landslide where landslide shape, upslope summer/early fall landscape irrigation, and the suspension of evapotranspiration may have played roles in the measured ground-water-level rise.

At the two low-elevation landslides (CBCC and Millbrook Way), most of the ground-water-level rise preceding the seasonal peak level in early 2008 occurred prior to and during the period of snow accumulation, and the smallest proportion of the rise is associated with melting of the winter snowpack. At the higher elevation landslides (SunCrest C and Green Pond), the snow water equivalent of the peak snowpack was higher than at the low-elevation slides and snowmelt resulted in the highest proportion of the ground-water-level rise that preceded the seasonal peak level.

Locally, high ground-water levels were sustained for various periods bracketing the seasonal peak ground-water level at the two low-elevation landslides, but generally declined immediately following the seasonal peak ground-water level at the higher elevation slides. Most notably, a relatively high ground-water level, no more than 8 inches below the peak level, was sustained at the toe of the CBCC landslide for about six months, including the three drier-than-normal months following the peak level. The funnel shape of the landslide, which narrows downslope, and an imbalance between the efficiency of ground-deformation features that facilitate infiltration in the head and dewater the slide at the toe, in favor of the former, may explain the sustained high ground-water level.

Finally, the observed decline in ground-water levels, following the seasonal peak level, was not uniform in landslides with multiple, closely spaced wells. Some possible explanations include variation in local ground-water gradients, enhanced local dewatering by shear zones, local variations in permeability, and compartmentalization of ground water by clay zones.

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LIMITATIONS

The most significant limitations of this investigation are the limited subsurface data and lack of well construction information for wells at all but the CBCC landslide. Borehole logs were available for only two of the wells used in this investigation and well depth information was not always consistent with measured well depths. Particularly important is information on well-screen interval. The lack of this type of information increases the uncertainty regarding the observed differences in ground-water conditions. The shallow depth of several of the wells precluded measurement of the seasonal low ground-water level and, thus, limited the ability to fully quantify the total rise in ground-water level. The locations of all but the UGS well at the CBCC landslide were determined by others, and were not necessarily ideal for the research objectives of this investigation. Future UGS research will attempt to address some of these shortcomings.

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