CHAPTER 7-- SURFACE WATER-GROUNDWATER INTERACTIONS

This chapter describes the spatial and temporal relationships between surface water and groundwater on Snodgrass. Particularly, we are interested in how increases in surface water (due to ski area development; see Chapter 5) might translate into higher groundwater levels, which would impact slope stability.

7.1 Methods

Surface water data consist of discharge measurements at the Upper Flume and Lower Flume on the axial stream of Snodgrass, as described in the Surface Water chapter. Flume measurements from March 22 through June 2007 were made by manual velocity-area measurements at the future flume sites. After the flumes were installed in July 2007, data were collected via pressure transducers in stilling wells. Groundwater data consist of datalogger measurements of water levels from 16 piezometers (including 3 nested sites), as described in the groundwater chapter.

7.2 Results

7.2.1 Gaining and losing stream sections interpreted from piezometers near streams

Several piezometers (e.g., PZ-5, PZ-6) were installed specifically to see if the water table adjacent to streams was higher or lower than the water in the streams; this would represent gaining and losing streams, respectively. As described in Chapter 6, all streams on the SE flank of Snodgrass Mountain appear to be gaining streams.

7.2.2 Response of the water table to infiltration events

Our data from 16 piezometers spans two surface-water events, the Spring 2007 peak runoff, and several smaller Summer 2007-fall 2008 rainfall events.

7.2.2.1 Response to Spring 2007 snowmelt

We began making surface flow measurements in the axial stream on March 22, 2007. Discharge at the Lower Flume had already begun to rise due to snowmelt prior to the 22nd, and began to rise on March 29 at the Upper Flume (Fig. 7-1a). Flow peaked at both flumes on April 22 (ca. 830 gpm at the Lower

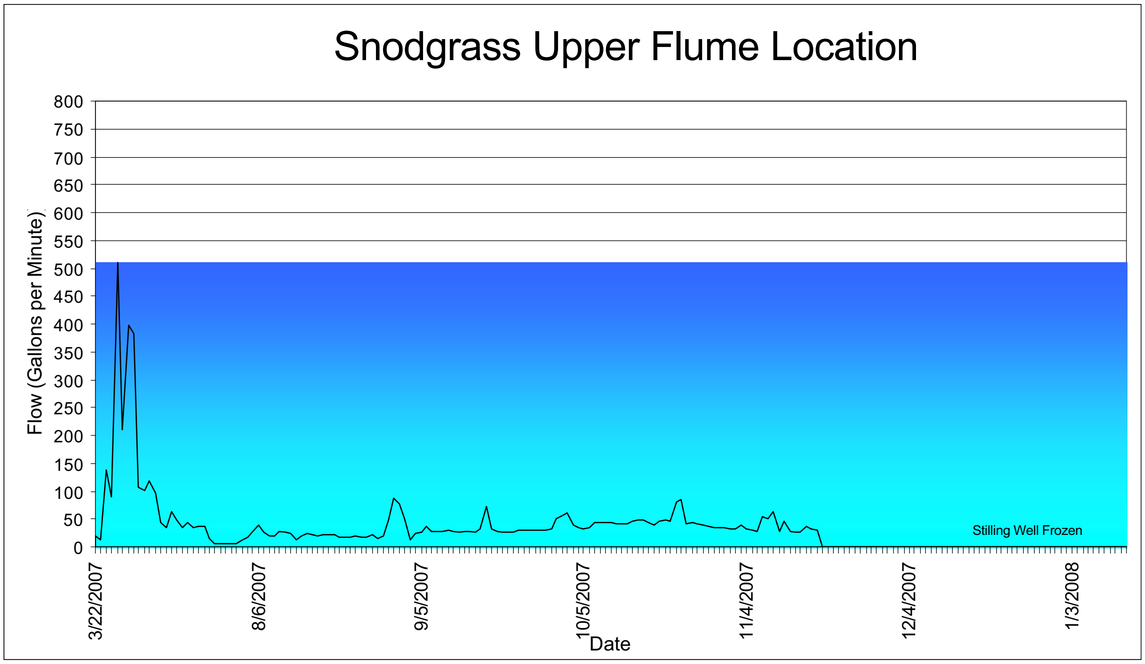

Fig. 7-1a. Weekly peak discharge of the axial stream at the Upper Flume (in gal/min) between March 22, 2007 and Jan. 31, 2008.

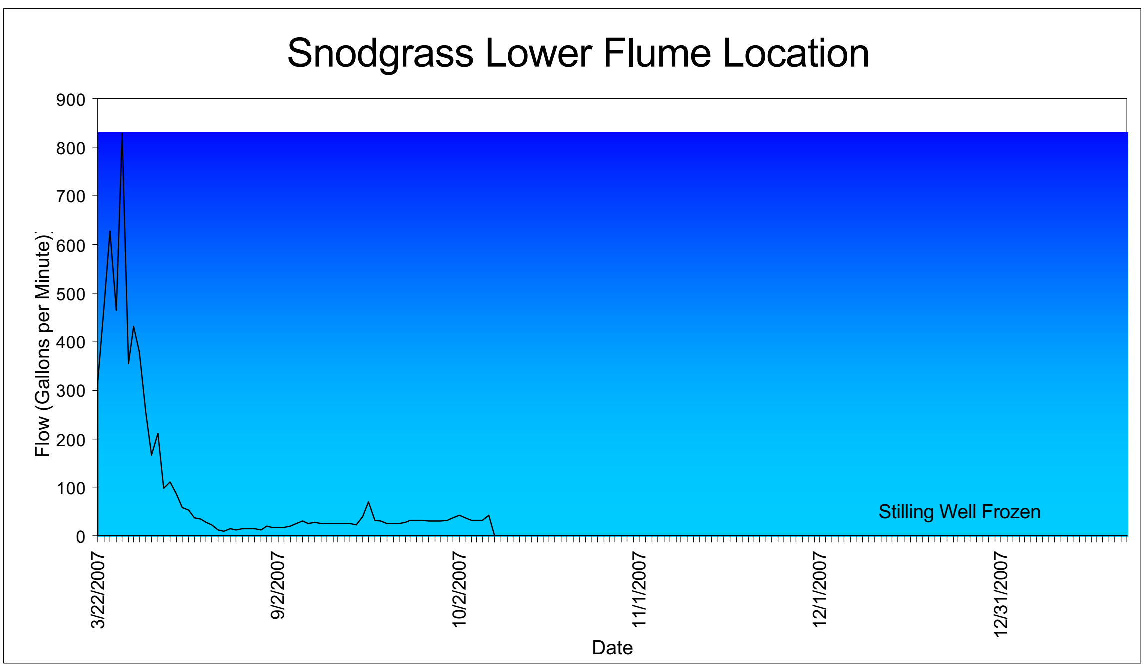

Fig. 7-1b. Weekly peak discharge of the axial stream at the Lower Flume (in gal/min) between March 22, 2007 and Jan. 31, 2008.

Flume, 510 gpm at the Upper Flume). At the Lower Flume, the hydrograph slowly declined to baseflow by late June, whereas at the Upper Flume, flow had declined to baseflow by early June.

The shorter hydrograph duration at the Upper Flume probably results from direct runoff from snowmelt in the upper drainage basin. That basin is underlain entirely by Tertiary laccolith, and soils are thin on steep slopes. Thus, snowmelt water should flow rapidly to the axial stream via overland flow and very shallow throughflow. In contrast, the Lower Flume catches not only the above runoff, but also runoff from the Transition Zone which contains many springs and seeps. Evidently, these springs and seeps are fed by snowmelt water that infiltrates along a deeper flow path, with a resulting longer lag time before the water reappears as surface water at springs.

Five of the 16 piezometers recorded data spanning the peak runoff of April 29, 2007 (Fig. 7-2). Four of these piezometers are on the East Slide (SG-3, -4, -5, PZ-16), and one is on a till-covered toeslope of the Slump Block (PZ-15). The maximum water level rise of +14 ft occurred in the lower middle of the East Slide, with smaller rises in the upper and upper middle parts (+6.5-7.5 ft), and a very small rise at the toe (+1 ft). Water level rise below the Slump Block was also small (+3.5 ft).

On the East Slide, the fact that groundwater rises twice as much in the lower middle (PZ-16) as it does farther upslope, suggests that PZ-16 may be located in an area of upward-traveling groundwater flow (discharge zone). It also suggests that groundwater may be confined at PZ-16, which is near the toe of the young part of the East Slide (Qlsy, polygon 36). This is supported by the +8.5 ft rise in water level between when the well was drilled (-27 ft BGS on Nov. 15, 2006), and when the datalogger was installed 6 weeks later (-18.5 ft BGS, Jan. 9, 2007). This rise was not a seasonal phenomenon, because normally water levels fall between November and January (e.g., water level fell 2 ft between Nov. 2007 and Jan. 2008).

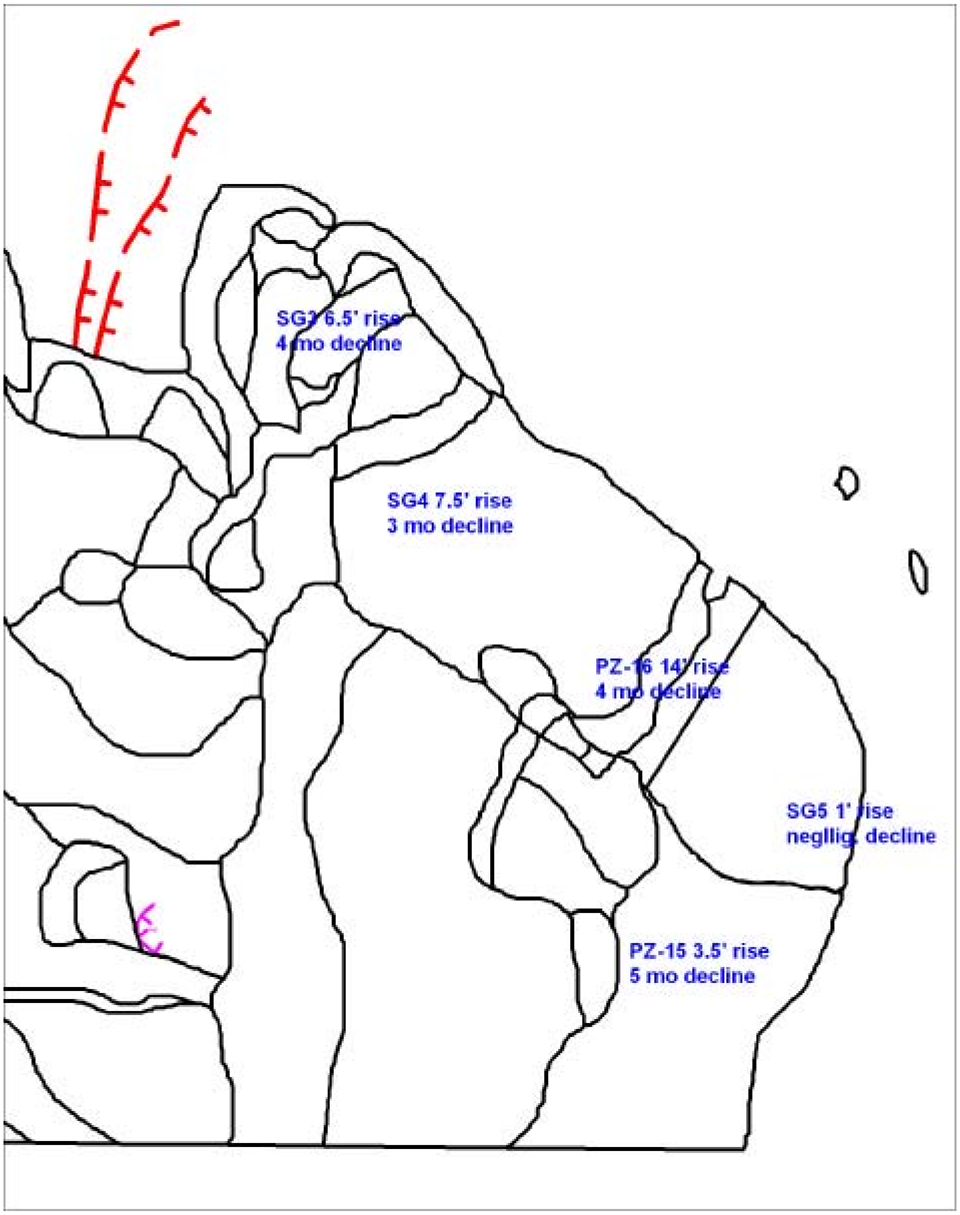

Fig. 7-2. Magnitude of water-level changes coincident with the 2007 snowmelt season, observed in 5 piezometers. First label is piezometer number, second label is magnitude of peak water level rise, third label is length of time it took water levels to decline back to pre-snowmelt levels. Outlines show landslide polygons.

7.2.2.2 Response to Fall 2007 Precipitation

During 5-month period Sept. 2007-Jan. 2008 there were several periods of increased streamflow at the flumes, five of which are highlighted on Figs. 7-3 to 7-4. The trends of water level in piezometers during this period fall into 3 categories (Fig. 7-3): (1) slow decline towards pre-snowmelt levels, on the falling limb of the piezometer “hydrograph”, (2) no fluctuation, or (3) rise in water level beginning after the first or second storm event.

Category 1 wells may display a very small, temporary rise in water level after each of the five events, but these small “bumps” do not disrupt the overall steady decline in water levels. The small rise presumably results from direct downward infiltration of water in the vicinity of the well. Category 2 wells show similar small (to negligible) rises. Our interpretation of these wells is that most of their groundwater is derived from relatively distant recharge of the large Spring snowmelt influx, traveling along relatively deep flow paths.

Category 3 wells also start off with a slow decline in Sept., and may display small rises due to individual storm events. However, once the Fall storms begin, their water levels make a long-lived rise, apparently in response to the cumulative effect of the five short-duration storms. All six Category 3 piezometers are clustered in the central part of the SE slope of Snodgrass (Fig. 7-5). Four of the six (PZ-5, -6, -12, -13) lie close to the axial stream or in topographic low spots at the base of the steep slope band. This coincidence suggests their increased water levels may reflect leaking from the axial stream into the adjacent aquifers (losing stream conditions). The other two sites (PZ-11, SG-4) also lie at the base of the steep slope band, but farther east of the axial stream.

From the medium-term response of category 3 wells to groups of storms, it is clear that their aquifers interact with the surface water streams. Category 1 wells apparently derive most of their groundwater from the short-lived influx of March-May snowmelt, moving along deeper flow paths not connected with surface streams. Category 2 wells show no long-term trend that can be associated with a hydrograph shape. This suggests that groundwater flow velocities are very slow, or that flowpaths are very long and attenuated.

Two pairs of nested piezometers yield different patterns of water level change. At PZ-8 in the West Slide area, both 8A (screen at 15-25’) and 8B (screen at 46-56’) show nearly identical declines over 5 months, punctuated by small storm-related rises. In contrast, at PZ-13 in the Older Earthflow, shallow well 13B (screen 7-17 ft) shows no change in level, whereas deeper well 13A (screen 30-40 ft) shows a rise of +2.0 ft in response to the fall storms. The axial stream lies 13 ft below the elevation of PZ-13, so it is not surprising that the shallow well 13B does not show much response to increased flow in the axial stream. The third pair of nested piezometers (6A, 6B) cannot be compared, because 6A is a flowing artesian well for which the pressure head is not measured.

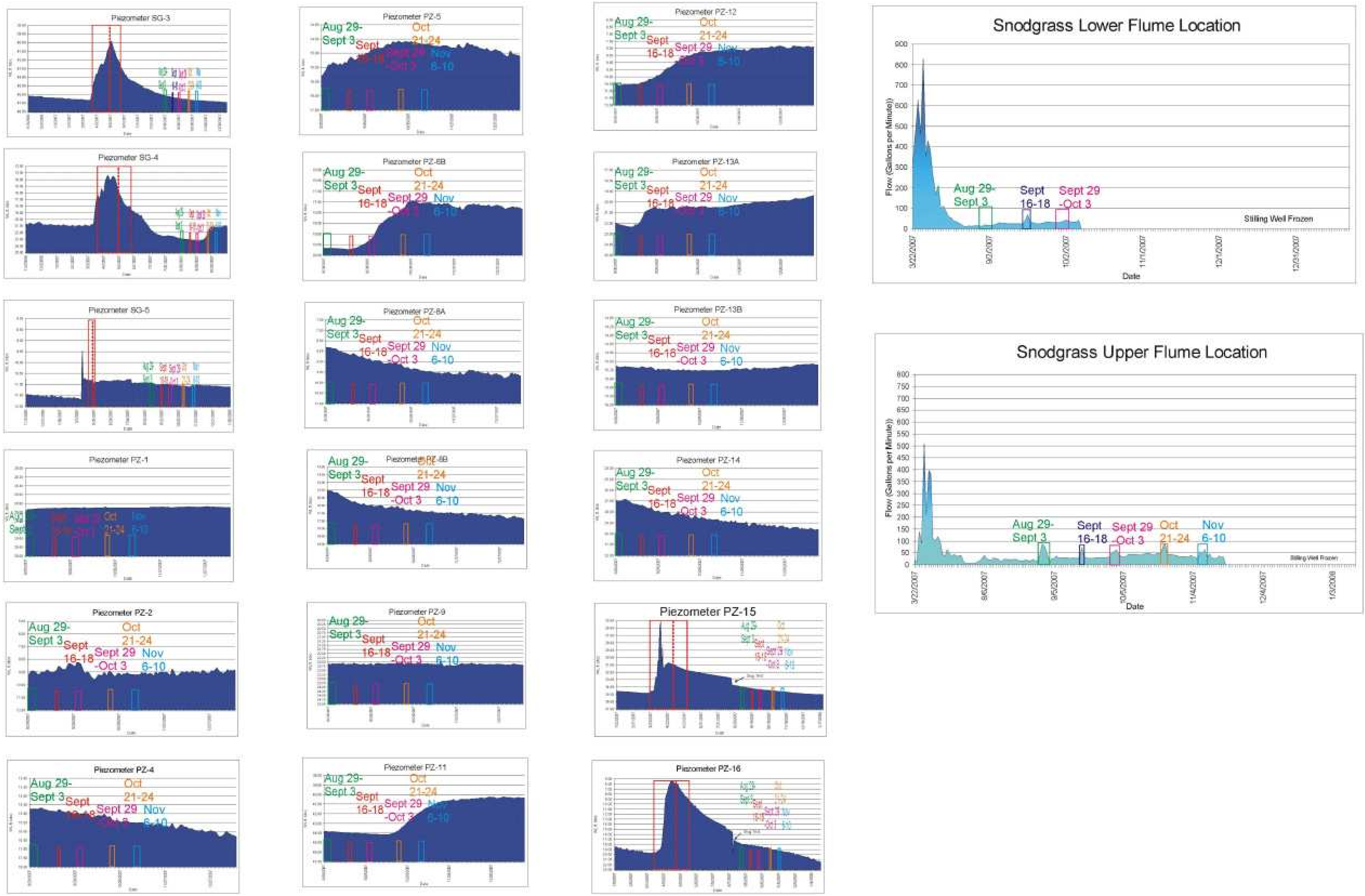

Fig. 7-3. Water levels records from the 18 piezometers (left), correlated with runoff at the flumes (right). Piezometers are arranged by number, with PZ-1 at upper left and PZ-16 at lower right. Runoff events are superimposed on each piezometer record.

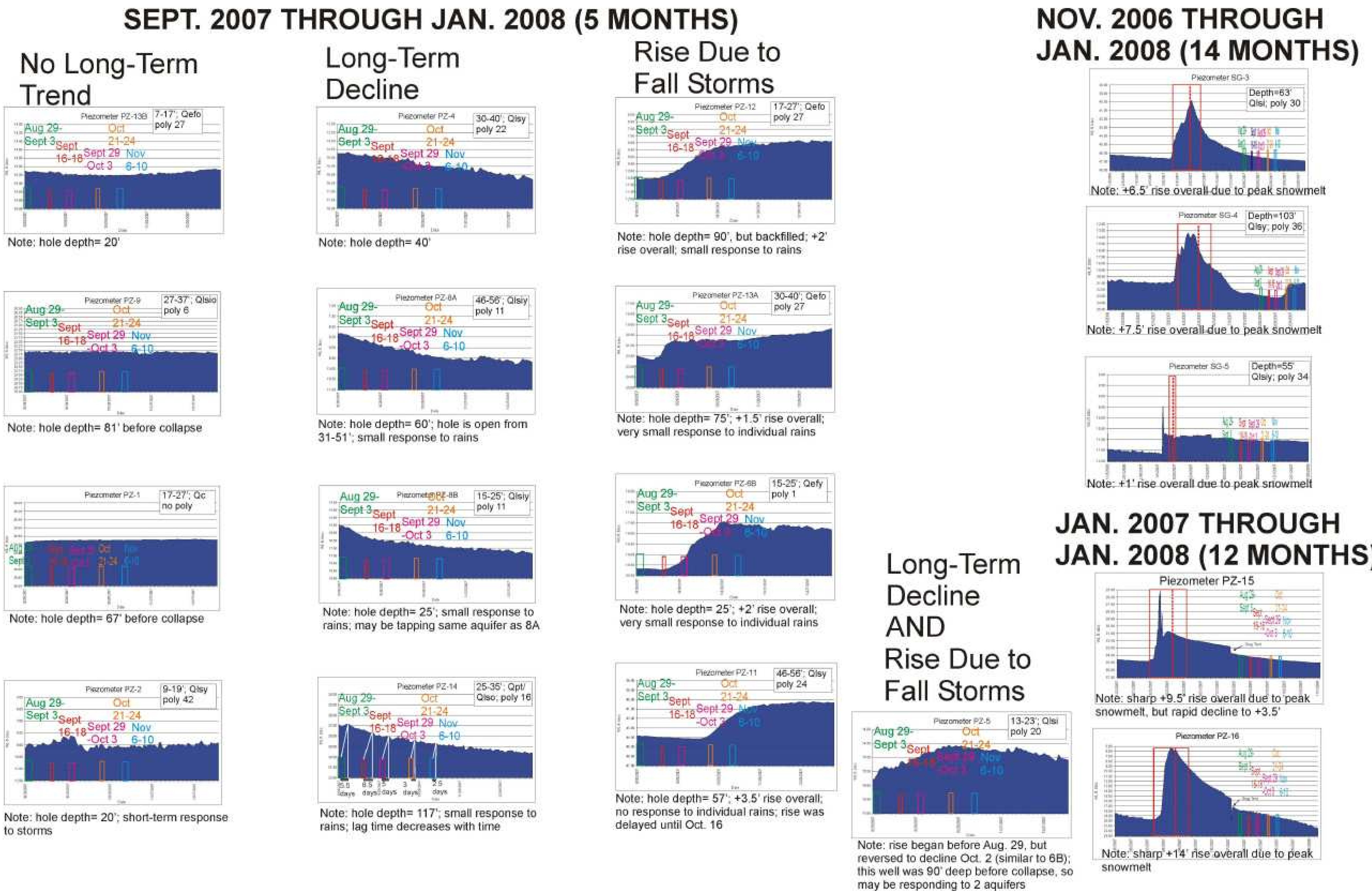

Fig. 7-4. Water levels records from the 18 piezometers (left) correlated with runoff events from flumes (colored rectangles). Piezometers with short (5-month) records are arranged into 3 response groups (at left). Longer records are at right.

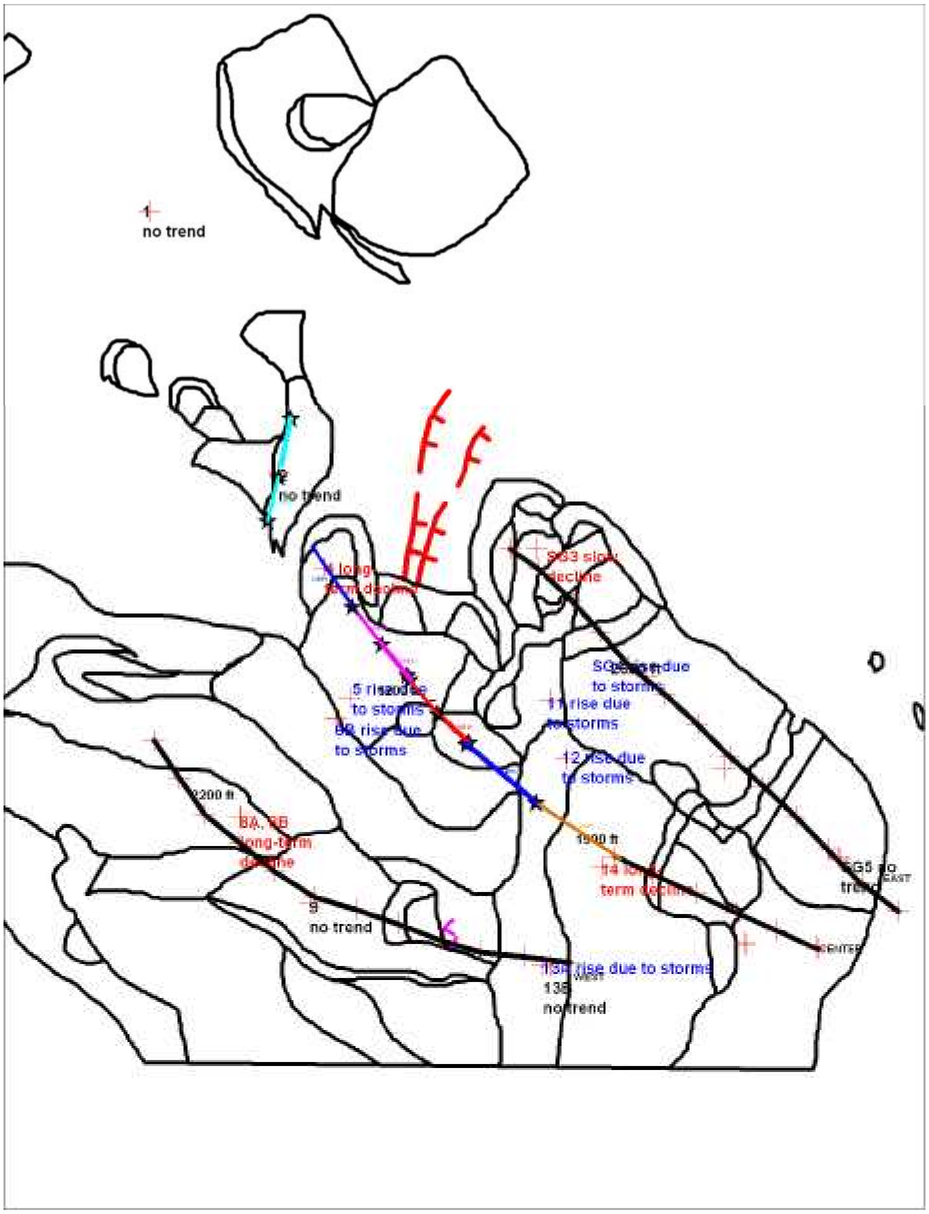

Fig. 7-5. Map of the SE slope of Snodgrass, showing water level trends in the 5-month piezometers. Red, long-term decline; black, no change; blue, rise due to summer-fall rainstorms. Thinner black lines show landslide polygon boundaries. Thicker lines with crosses show locations of geophysics/stability cross-sections (from left to right, West Line, Central Line, East Line).

Table 7-1 summarizes the magnitude of water level changes in the piezometers, in response to short-term (storm), medium-term (groups of storms, falling hydrograph), and long-term (rising hydrograph) infiltration events.

Table 7-1. Magnitude of water level changes in piezometers due to short-, medium, and long-term infiltration events. The fluctuations help define the water levels to use in various landslide stability scenarios. Shaded piezometers are the only ones that recorded the Spring 2007 snowmelt season.

Piezometer	Short-term rise caused by individual storms (ft)	Medium-term rise caused by groups of storms (ft)	Rise caused by Spring snowmelt	Medium-term drop during Autumn dry season
1	<0.05	0	nd	
2	0.5	0	nd	
4	0.25	0	nd	-1.5
5	0.2	+1.2	nd	
6B	<0.1	+2.5	nd	
8A	0.15	0	nd	-1.5
8B	0.2	0	nd	-2.0
9	0.2	0	nd	
11	negligible	+3.5	nd	
12	0.1	+2.5	nd	
13A	0.3	+2.0	nd	
13B	0.05	0	nd	
14	0.3	0	nd	-2.5
15	negligible	0	+9.5 spike (3.5)	-2.0
16*	0.3	0	+14	-4.5
SG-3	negligible	0	+6.5	-1
SG-4	<0.1	+2.0	+7.5	
SG-5	0.15	0	+2	-0.3
Mean	0.15 ft	2.3 ft	7.9 ft	-1.9 ft

* PZ-16 displays the greatest long-term and medium-term fluctuations, and a high short-term fluctuation. It is located in the most active part of the East Slide.

7.2.3 Estimating Rise in Water Levels Due to Increases in Surface Water

There is no accepted methodology for estimating groundwater rise in slopes as a function of increased runoff in the drainage basin. Therefore, we constructed a simple conceptual model which relies on the conservation of water mass, the type of aquifer in the landslides, and a few other assumptions.

In order to know whether the aquifers in landslides are unconfined or confined, we examined how the water table elevation changed after drilling (Table 7-2). In 9 of the 13 cases, water levels rose after drilling, indicating confined conditions.

Table 7-2. Piezometer behavior as a function of the thickness of the saturated zone, as existed on initial drilling (mid-July, 2007). PZs are grouped into confined conditions (water level rose between drilling and Sept. 2007) and unconfined conditions (water level fell in same time period). Within each group. PZs are listed in order of increasing thickness of the saturated zone.

PZ no.[1]	Thickness of saturated zone (ft)	Deposit	Depth of saturated Zone, July 2007 (ft)	Depth to Water Table, Sept. 2007-Jan. 2008 (ft)	Change in Water Level (ft)	Type of Aquifer
11	2	Qlsy+	-52 to -54	-43.8 to -44.1	rose 8.2	STR CONF
4	3	Qlsy	-38 to -41	-14.7 to -14.9	rose 23.3	STR CONF
16	4	Qlsy	-27 to -31	-18.5 to -5	rose 8.5	STR CONF
2	6.25	Qlsi	-10.5 to -16.75	-9.25 to -8.25	rose 1.25	WK CONF
5	9	Qlsi	-21 to -30	-15.8 to -15.2	rose 5.2	CONF
6B	11	Qefy	-21 to -32	-19.7 to -19.3	rose 1.3	WK CONF
8B	11.25	Qlsiy?	-19 to -30.25	-15.5 to -16.6	rose 3.5	CONF
9	20	Qlsiy?	-26 to -46	-22.6	rose 3.4	CONF
14	34	Qlso	-31 to -65	-26.9 to -28	rose 4.1	CONF
15	12	Qpt	-33 to -45	-35 to -31	stable	UNC
13B	16	Qefo	-11 to -27	-15.1 to -15.2	fell 4.1	UNC
1	25	Qc	-21 to -46	-28.9	fell 7.9	UNC
12	30	Qefo	-10 to -40	-10.6 to -9.9	fell 0.6	UNC

[1] piezometers SG-3, -4, and -5 are not listed, because their well logs from 1995 did not indicate the bottom of the saturated zone

Several trends are obvious in Table 7-2. First, 9 of the 13 piezometers showed a rise in water level between July 2007 when they were drilled, and Aug. 30, 2007 when the piezometers began recording. According to the older piezometers which began recording before the Spring 2007 snowmelt season (SG-3, -4, -5; PZ-15. -16), that time period is on the falling limb of the groundwater hydrograph from spring snowmelt, and water levels should have been declining in all wells. But in 9 of the 13 piezometers, the water level rose after drilling, indicating confined conditions. At the remaining 4 piezometers, water levels fell after drilling, indicating unconfined conditions.

Second, there is a good correlation between the type of aquifer (Unconfined vs Confined) and the geologic deposit. All the confined aquifers are in landslides (Qls*x*), and all the unconfined aquifers are in non-landslide deposits, or in old earthflows. There is little overlap between the 2 groups.

Third, the amount of groundwater rise in the confined aquifers has a strong inverse correlation with the thickness of the aquifer. The thinnest aquifers show the largest rises, indicating the most pressure head. This is a reasonable observation, because if a given amount of groundwater flow were being forced through successively thinner aquifers, pressure heads would have to increase.

Fourth, the amount of groundwater rise in the confined aquifers shows a strong positive correlation with the age class of the landslide. Strongly confined aquifers are only found in Qlsy deposits, whereas confined and weakly confined aquifers are found in progressively older landslides. In non-landslide deposits, aquifers are unconfined. Such a correlation makes sense, if elevated pore pressures are responsible for landslide movement.

7.2.3.1 Estimating groundwater rise as a function of increased runoff

As previously mentioned, there is no accepted methodology for estimating groundwater rise in slopes as a function of increased runoff in a drainage basin. Therefore, we constructed a simple conceptual model which relies on the conservation of water mass and a few assumptions.

First, increases in runoff (from trail clearing and snowmaking) will undoubtedly be accompanied by increases in infiltration. We assume that the ratio of such increases is identical to the ratio of runoff:infiltration in a steady-state drainage basin in the Rocky Mountains. According to Graham Gilbert (pers. commun., 2008), that ratio is 1:1. Therefore, we assume that a (say) 15% increase in runoff in a basin will be accompanied by a 15% increase in infiltration in that basin.

Second, aquifers only have two ways they can respond to increases in infiltration and the increased groundwater flow. Unconfined aquifers can either thicken and maintain the same hydraulic gradient (slope of water table), or they can remain the same thickness but steepen their hydraulic gradient. Confined aquifers cannot thicken, so they can only transmit more flow by adopting a steeper hydraulic gradient. In this analysis, we assume that unconfined aquifers (found only in non-landslide deposits and older earthflows) will mainly thicken under the same hydraulic gradient. Confined aquifers, present in all the landslide deposits, cannot thicken so they must increase their hydraulic gradients (slope of the piezometric surface).

Third, we assume that the discharge point of the landslide flow systems (springs, seeps) does not increase significantly in elevation, when transmitting the increased flows. That being the case, the piezometric surface can only steepen if pressure heads rise above the existing ones, linearly from the zero at the toe to some maximum value at the head of the flow system.

If we make all these assumptions, then the calculation of groundwater rise at any location along a flowline is a tractable problem. The required inputs are: (1) the location of the head and toe of the flowline (local flow system), (2) the horizontal distance of any point on the flowline from the toe of the flowline, and (3) the percentage of steepening of the piezometric surface due to development actions. For example, in a basin with a confined aquifer and a 15% increase in runoff, we assume a corresponding 15% increase in infiltration. To transmit this increased flow in a confined aquifer, the slope of the water table must also increase by 15% (that is, the tangent of its slope angle must increase by 15%).

Example: landslide polygon 22 and piezometer PZ-4. The local flow system in polygon 22 has an overall length of 300 ft between the headscarp and the toescarp. The piezometric surface (as reconstructed from geophysics Line 2 and piezometer PZ-4) slopes southward and rises 30 ft between the toe and the head. Thus the hydraulic gradient is 30 ft/300 ft, or 0.1. In order to transmit 15% more groundwater flow in a confined aquifer, the piezometric surface must steepen by 15% to a hydraulic gradient of 0.115. Therefore, assuming the piezometric surface at the toe remains at the same elevation, the piezometric surface at the head must rise +4.5 ft to attain this steeper gradient. All intervening points on the flowline must rise a proportional amount, based on their distance from the toe. For example, at piezometer PZ-4, located 120 ft uphill of the toe (120 ft/300 ft. or 40% of the distance to the head), the predicted rise would be 0.4 x 4.5 ft, or 1.8 ft.

Although this approach obeys the conservation of mass and Darcy's Law, it has one major weakness: we do not know if the mountain slope is composed of many small independent flow systems (one per landslide), or one giant flow system (say, spanning the entire Transition Zone between the bottom of the laccolith, and the top of massive Mancos Shale). In the latter example, the flowline in our method could be as long as 2860 ft long (the maximum width of the Transition Zone, from the top of Chicken Bone to the base of the steep slope band) with a drop in the piezometric surface of 570 ft (the same as the elevation drop across the Transition Zone). Given these much larger dimensions, and again keeping the discharge point at a fixed elevation, a 15% steepening of the piezometric surface requires that piezometric surface at the head of the flowline rise by 65 vertical feet! Even at intermediate points along the flowline, such as at PZ-4 (located 1500 ft from the toe on this long flowline; 52% of the distance to the head), the rise would have to be 44.5 ft. Given that the present piezometric surface at PZ-4 is only 15 ft below the surface, this would require that the piezometric surface there rise to 30 ft above the ground surface (strong artesian). At the head of the flowline (bottom of the laccolith, near piezometer PZ-1) it would require a rise of 65 ft, forcing the current unconfined water table (28.9 ft below the surface) to somehow rise 35 feet above the ground surface. Clearly, in an unconfined system such a rise above the ground surface is not possible.

We believe that these scenarios are not realistic, because: (1) groundwater under such high artesian pressures would probably find alternative ways of exiting to the surface; (2) such high pressures would result in factors of safety much less than 1 for almost all mapped landslides, leading to widespread failure; and (3) the year-to-year variation in precipitation over the past two decades here has varied by more than 15%, yet there have been no such widespread failures. Thus, we believe that the SE slope of Snodgrass is probably composed of local flow systems that must be smaller than the entire Transition Zone. These local flow systems respond individually to increases in infiltration and throughflow. The local flow systems may be as small as individual mapped landslides, or groups of landslides interrupted by bands of shallow bedrock (such as mapped in the West Slide complex, over which landslide deposits thin and groundwater is presumably forced to the surface). Delineating the boundaries of each flow system would take many more piezometers than the 16 we have on the mountain and is beyond the scope of this study, if not beyond the capability of wildland hydrologic science at this point in time.

In Chapter 8 (Landslide Stability Modeling), we use this conceptual model as a check on the amount of groundwater rise predicted by the Infiltration Ratio for the proposed action and snowmaking.