CHAPTER 9—CONCLUSIONS AND RECOMMENDED MITIGATION

9.1 Conclusions

Based on the stability cross-sections down the SE flank of Snodgrass Mountain, most landslides on low- to –moderate-gradient slopes have acceptable stability (Factors of Safety >1.3) in both the pre-development and post-development condition. However, Factors of Safety approaching the threshold of stability are indicated where landslides lie on abnormally steep slopes (steep slope band, polygons 9, 21; south slope of the Slump Block, polygon 14), where groundwater is strongly confined to artesian (young earthflow, polygon 1), or where water table seasonally reaches very high piezometric levels (East Slide, polygon 36). These locations coincide with the youngest-looking evidence for slope movement on Snodgrass (i.e., historic landslides, Qlsh).

These steep-slope landslides are not currently sliding as blocks, according to the survey stake and inclinometer data (with the possible exception of polygon 36). Therefore, their Factors of Safety are currently >1.0. Computer stability analysis based on conservative input values (ones that tend to consistently skew the result to lower Factors of Safety) indicates Factors of Safety around 1.10.

The effect of the proposed development is severe where trail clearing and snowmaking are concentrated in the vicinity of these metastable landslides, such as on the steep slope band below Ken's Crux. In that area, proposed development actions are predicted to cut the margin of safety in half for landslides on steep slopes, decreasing it from about 1.10 to about 1.05.

The computer models were deliberately configured to yield conservative results, and predict that the proposed actions will not quite cause landslide reactivation on these steep slope bands. However, given the spatial variability of material properties and groundwater levels, there is some irreducible uncertainty in the computer models. When you combine this uncertainty with the uncertainty in future climate over the project life (50 years), it would be prudent to try to increase the stability of these metastable prehistoric landslides on steep slope pockets by mitigation actions.

The ground surface is slowly creeping downslope in most of the geological "Transition Zone" on Snodgrass Mountain, between the bottom of the Snodgrass laccolith and toe of the Slump Block, based on stake and inclinometer measurements. The spatial pattern of stake velocities and the inclinometer deflections indicate that most, if not all, of this movement is surficial soil creep limited to ca. 2 feet below the ground surface. The average velocity over the past 11 years has been 0.03-0.04 ft/yr (0.36"-0.5"/yr). The maximum surface velocity occurs on the East Slide, and may have a component of landslide movement in it; it is 0.14 ft/yr, or 1.7"/yr.

9.1. Western Cross-Section

MITIGATION:

We recommend an array of horizontal drains, 350 ft long, to decrease the groundwater pore pressures in the vicinity of polygon 9 on the steep slope band (Fig. 9-1).

9.2 Central Cross-Section

MITIGATION: Surface Water Management:

First, we recommend the construction of a ditch carrying runoff from the Chicken Bone meadow to Snodgrass Road. This ditch would, at a minimum, intercept overland flow from about 26% of the drainage basin above Ken's Crux, and route it east and then south along the existing Snodgrass Road. At the base of Snodgrass, this ditch flow would be routed westward into the reservoir in North Village, thus creating a closed loop for snowmaking water (returning it to its point of origin).

Second, we recommend a low debris flow deflection berm at base of steep slope band, to protect the two lift terminals that will sit on the Old Earthflow (Fig. 9-2).

MITIGATION: Groundwater Management:

The landslide polygons listed below have low estimated Factors of Safety, with safety margins that would be cut in half by the proposed action, if no mitigation were performed. For each of them, we propose an array of horizontal drains drilled northward from the base of the steep slope band, as shown in Fig. 9-3:

<u>Young Earthflow</u>

3 Arrays of horizontal drains, 400 ft long

<u>Qlsiy on steep slope band (poly 21)</u>

Array of horizontal drains, 330 ft long

<u>Polygon 17 (Qlsh);</u> Array of horizontal drains, 280 ft long

<u>Polygon 24 (Qlsy);</u> Array of horizontal drains, 360 ft long

Details and cost estimates are given in Table 9-1. However, before these drains are installed, computations need to be made as to their predicted water yield based on length, spacing, gradient, and diameter. After these calculations are made, they need to be confirmed in 2 ways. First, by measuring the yields of the first as-built drain array, to compare the actual performance with the predictions. If yields are less than predicted, the array design will have to be altered to increase yields. Second, to monitor the lowering of water table elevations in those piezometers within the influence zone of the horizontal drains. This lowering can also be compared to that predicted by steady-state flow models for drains.

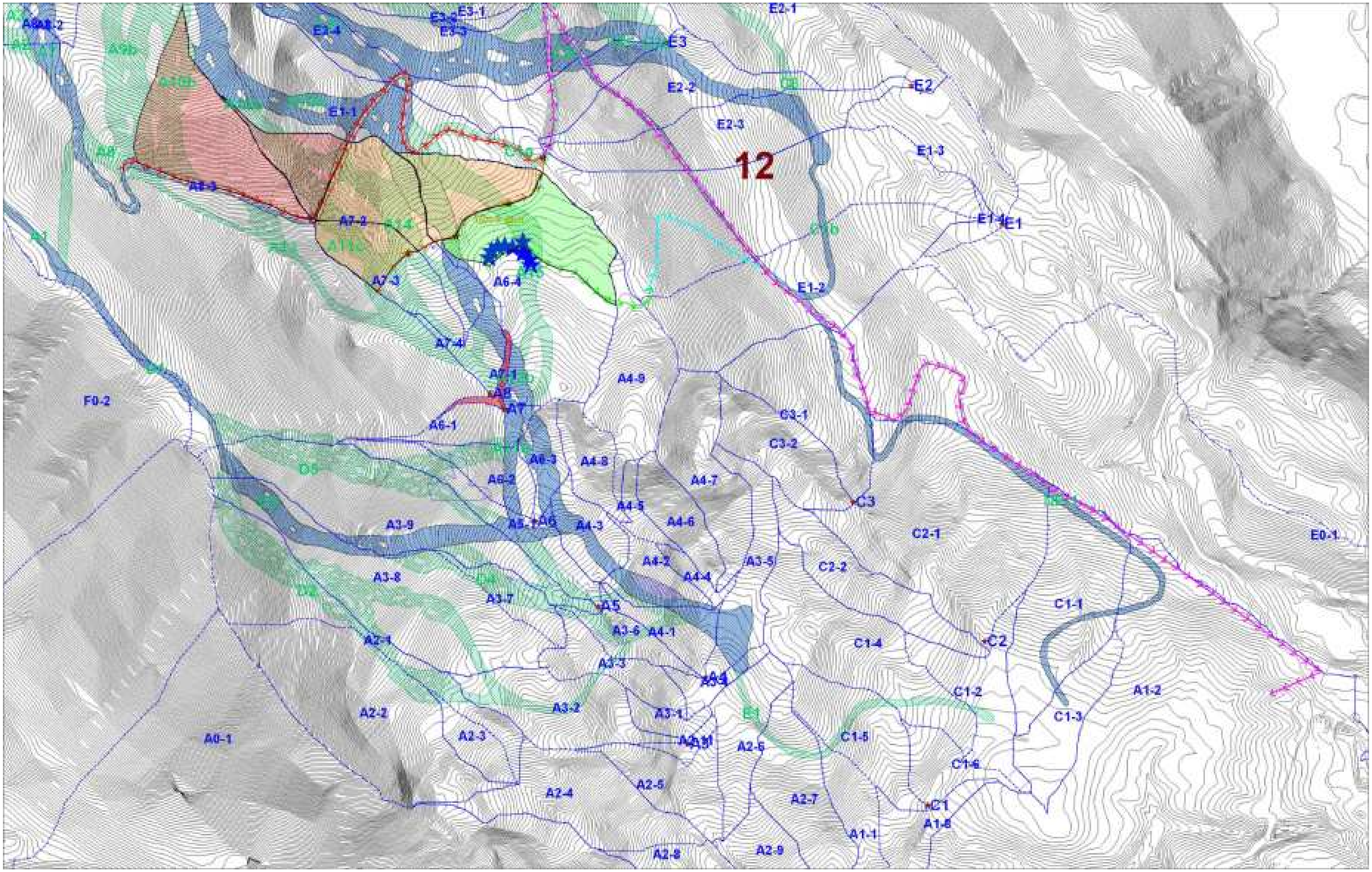

Fig. 9-1. Network of proposed water bars/ditches on Chicken Bone (upper left) that would divert runoff into a roadside ditch along Snodgrass Road (purple). Colored regions show watershed areas drained by the upper Snodgrass Roadside Ditch (red), Chicken Bone Ditch (orange), and lower ChickBone Ditch (green, then light blue along old road).

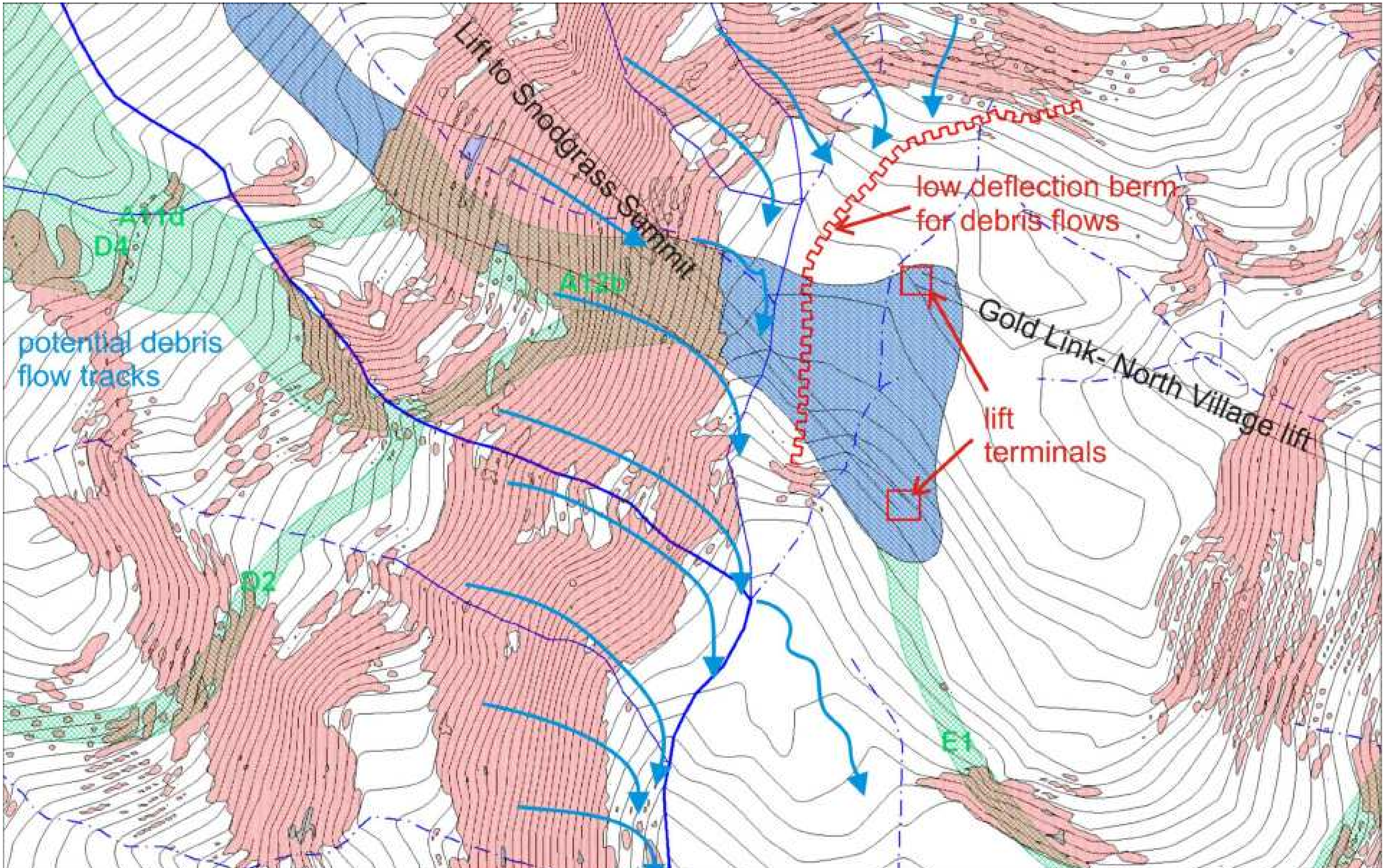

Fig. 9-2. Proposed low debris deflection berm (red zig-zag) to protect two lift terminals (red squares) at the base of the steep slope band (pink; slopes steeper than 17°). Blue lines show hypothetical debris-flow tracks from the steep slope band.

Table 9-1. Horizontal drain arrays and approximate cost to install.

Section	Polygon	No. of drains	Drain length (ft)	Total Length	Cost/ft	Total Cost
West	9	6	350	2100	$10	$21,000
Central	1*	18	400	7200	$10	$72,000
Central	21	6	330	1980	$10	$19,800
Central	17**	6	280	1680	$10	$16,800
Central	24	6	360	2160	$10	$21,600
East	36	12	400	4800	$10	$48,000
			Total	19,920		$199,200

* best site to test system efficacy for a strongly confined (artesian) aquifer, because PZ-6A and -6B lie just upslope of the middle array

** alternative site, to test system efficacy for a weakly confined aquifer, because PZ-11 lies within the array. In PZ-11, water was encountered at -52 feet upon drilling, but had risen to -44 ft within a few weeks after drilling

9.3 Eastern Cross-Section (the East Slide)

MITIGATION: Surface Water

No surface water mitigation is proposed for the East Slide itself, since it is a non-disturbance zone. The ditches proposed for Chicken Bone meadow will have an indirect impact on the East Slide, since they will be diverting overland flow that may have infiltrated water that would travel into the East Slide.

MITIGATION: Groundwater

We recommend two arrays of horizontal drains, 400 ft long (Fig. 9-3), to be drilled northward from the base of the steep slope separating polygons 36 and 34. This slope was the site of our Upper Trench, which exposed thrust faults and folds related to overriding of polygon 36 over polygon 34.

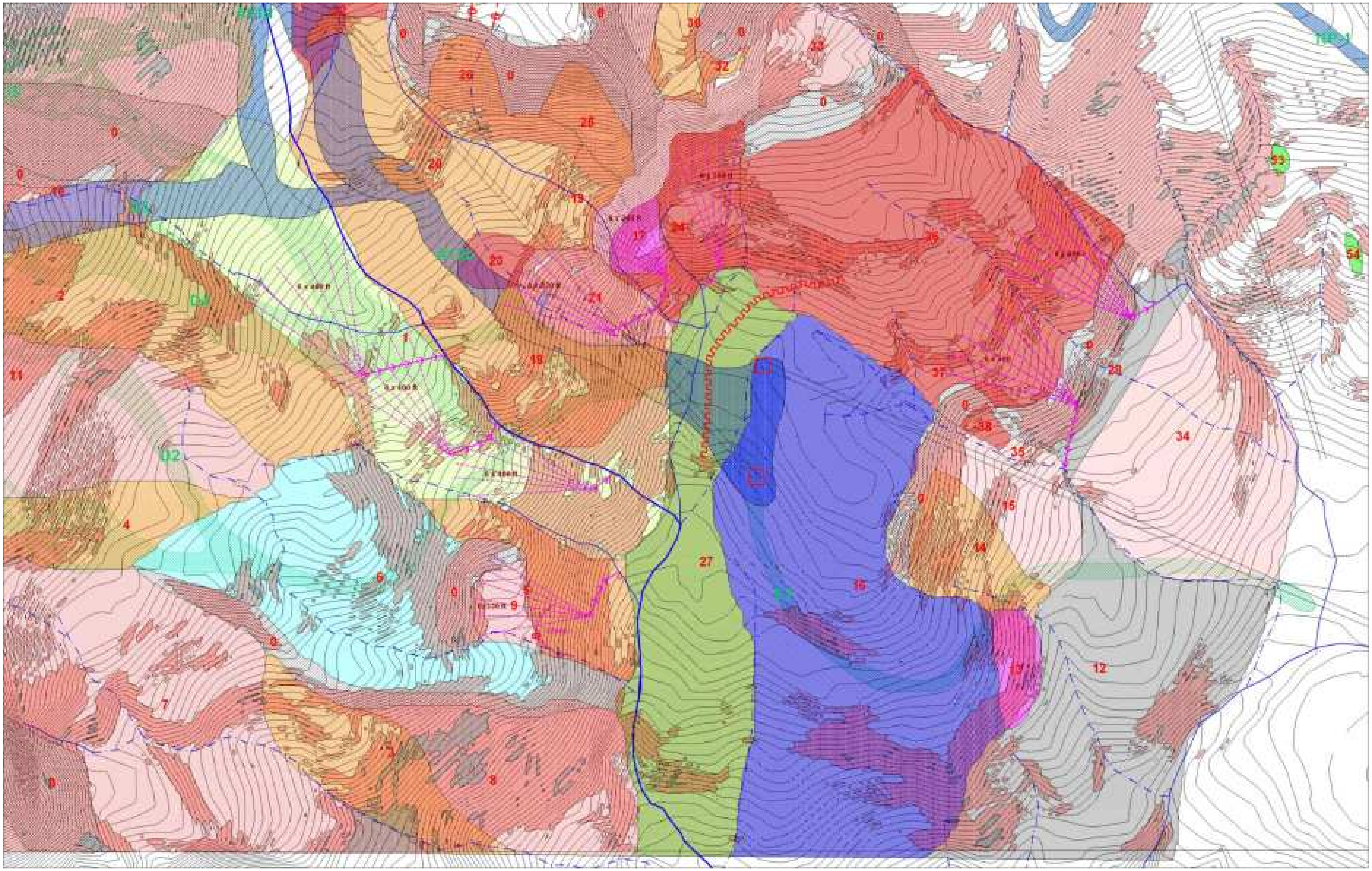

Fig. 9-3. Proposed horizontal drains (purple lines in fan-shaped arrays) to be drilled into the base of the steep slope band and toescarp of polygon 36 on the East Slide. From south to north, 1 array in polygon 9; 3 arrays in polygon 1; 1 array each in polygons 21, 17, 26; 2 arrays in polygon 36. Purple lines with arrows show pipelines that convey water from the drain manifold to the nearest natural drainage.

9.4 Philosophy of Mitigation

The mitigation proposed herein is targeted to reducing pore water pressures, because that is (in our opinion) the most cost-effective water to increase slope stability in the steep slope band areas. The mitigation actions are localized to affect those limited areas where calculated Factors of Safety of pre-existing deep landslides are 1.11 and below. The proposed mitigation ditches and horizontal drains will not be visible to the causal observer from a distance.

Alternative approaches such as toe buttresses and shear keys could also be considered if these hydrologic measures do not achieve the desired results. However, those more “brute-force” engineered structures, due to their required volume of earth moving and earth shaping, are more intrusive and visible. They would be more appropriate for developed areas such as residential and commercial subdivisions, rather than for a ski area on public lands.