STATUS OF THE EMERALD CREEK LANDSLIDE, REDWOOD NATIONAL PARK

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ABSTRACT

A landslide in Redwood National Park was monitored during 1981-82 after an attempt at stabilization. Heavy equipment removed 7,000 yd^3 of log landing material, and constructed a 17-ft-deep trench designed to intercept surface and groundwater from upslope areas. Stage recorders showed that of the total 105 in of rainfall, about 40% was intercepted as surface runoff and and 6% was removed as groundwater. A network of piezometers showed areas of positive pore pressure. Some inadvertently acted as inclinometers, showing a shear plane at 12 ft depth. Resolution from time lapse movies was insufficient to show ground movement. Repeated surveys and mapping of scarp development indicated inactivity of the original headscarp and the right lateral scarp, and the formation of a new headscarp downslope of the excavated area. Maximum surface movement of individual blocks in the active area was 21.2 ft horizontal and 10.6 ft vertical. Magnitude of movement appears correlated with periodic rainfall.

INTRODUCTION

One of the main goals of Redwood National Park's (RNP) Rehabilitation Program is to reduce hillslope erosion caused by previous logging activities, in an effort to mitigate impacts on Redwood Creek and its tributaries. Mass movement features (landslides) related to land use are an important sediment source to the stream system of Redwood Creek (Janda et al. 1975, Nolan and Janda 1981). Although less numerous than other erosional features, each landslide may deliver a volume of sediment that is larger by up to three orders of magnitude than other single sources. Often material redistributed on the natural slope by man (i.e., cutting and sidecasting during road building) has re-activated movement on older landslides or initiated movement of marginally stable ground. Disruption of natural drainage can often cause increased saturation of material and eventual failure. Several land-use related landslides have been treated and monitored since the RNP expansion in 1978. Common treatments include removal of a portion of sidecast material and/or construction of surface drains to divert water away from the slide mass. The benefits of these treatments include reduction in: 1) surface runoff and shallow interflow reaching the slide; 2) loading of the natural slope (slope surcharge; and 3) the amount of debris that would eventually enter the stream system. Observation of other work at RNP shows that reduction of slope surcharge and water content appear to decrease the rate of movement and/or redistribute the portion of hillslope failing or moving. Landslide monitoring observes the patterns and rates of movement following treatment. It usually includes repeated photography from permanent locations and a limited theodolite survey of the slide mass before and after treatment, and yearly after winter rains. The Emerald Creek landslide seasonally delivers clay, silt, gravel, and organic debris to a third-order stream which enters Redwood Creek immediately upstream of the Tall Trees Grove (Fig. 1). Potential impact of the slide to the Tall Trees Grove are greater and more immediate than many erosional features treated at other rehabilitation sites. For description of sedimentation impacts on Redwood Creek basin, see Best et al. (1983).

Study Area

The Emerald Creek landslide is located on a steep, wet, lower slope adjacent to Emerald Creek which supports an old growth redwood forest. The landslide extends upslope to a landing on the C-90 road, a logging haul road built in 1975. The hillslope above the road was clearcut logged and tractor-yarded in 1976. A major structural feature, the Grogan Fault, trends north-northwest and passes within

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Redwood National Park, P.O. Box 36, Orick, CA 95555

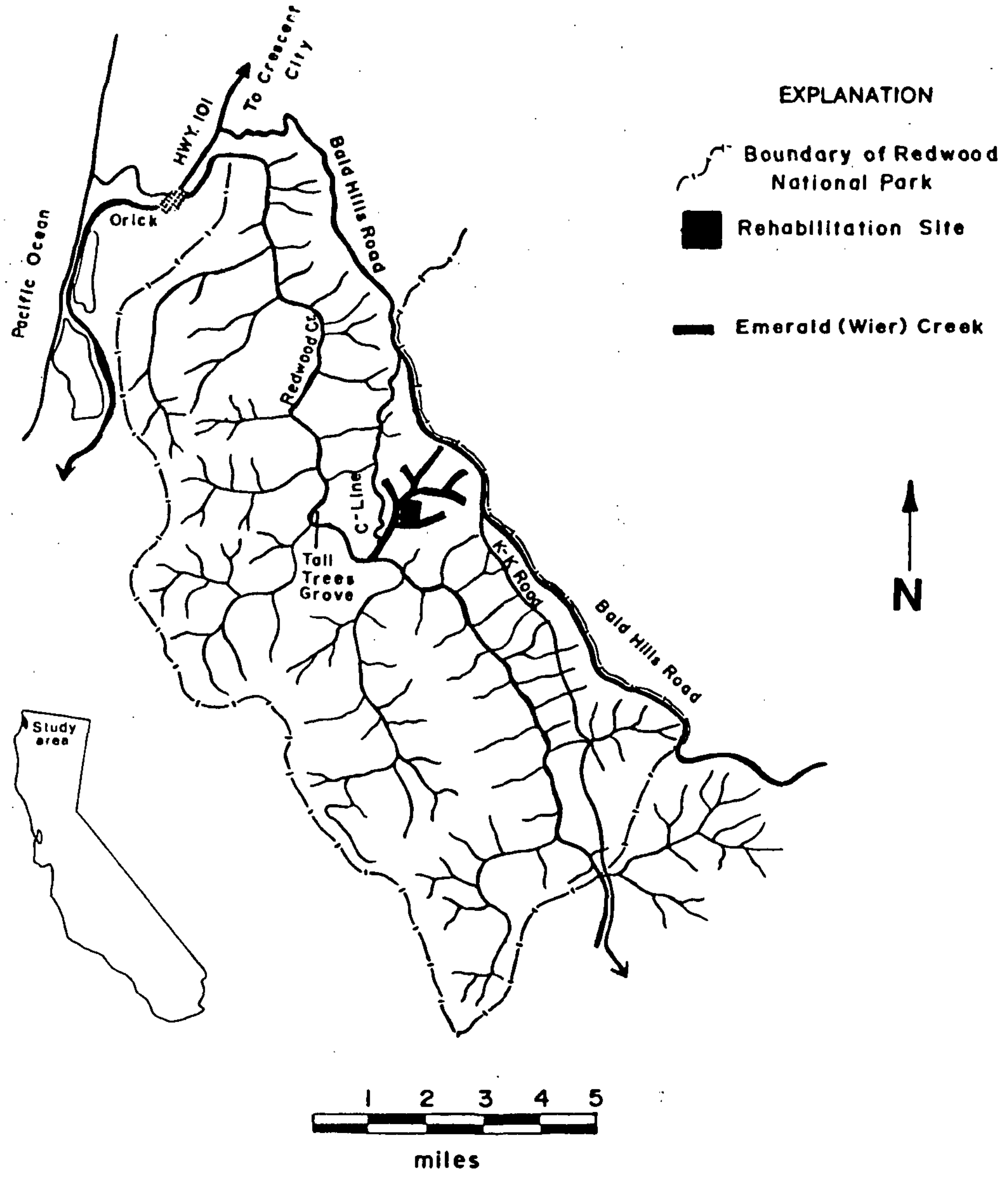

Figure 1

Location Map of Emerald Creek Landslide, Redwood National Park (from Madej, et al., 1980)

1,000 ft west of the landslide. Bedrock is highly sheared Franciscan unmetamorphosed sandstone and siltstone and sheared Franciscan schist. The combination of a lower slope, wet locality and the sheared bedrock results in severe slope stability problems.

The log landing at the head of the landslide was built in a wet area between two minor ridges. The topographic drainage area upslope of the landslide is approximately 3 ac. The landing was constructed with fill (soil) and slash (logs, branches, and bark), and perched on a 26° to 36° slope uphill of Emerald Creek (Fig. 2, 3).

Slide History

Soon after logging occurred in 1976, the landslide became noticeably active. By 1978, at the time of park expansion, a 2-ft scarp had appeared in the road. The outboard edge of the landing had dropped 8 ft. The years between 1978 and 1981 experienced average to below average rainfall, yet the landslide continued to be active.

By 1981 (Fig. 2) the headscarp was 5 to 8 ft high, and the landing edge had dropped a total of 17 ft since construction. Downslope of the road several old growth redwoods had fallen and the soil mantle was further destabilized by root upheaval. The north lateral scarp was continuous with the headscarp and showed evidence of recent activity. From the headscarp down to the 100-ft-wide mudflow, the south lateral scarp was discontinuous and defined by enechelon ground tears. From the top of the mudflow the creek, the south margin was a well-defined 3-ft lateral scarp.

Assessment and Treatment

Preliminary examination of the arcuate headscarp and apparent back rotation of the slump blocks below the headscarp suggested that the feature was a rotational slump. The toe location was not readily apparent. At first the toe appeared to be at the break in slope coinciding with the top of the mudflow area, but it was suggested later that unless underlying lithology caused the shear surface to emerge midslope, the toe should be at the creek (Seidelman, pers. comm.).

Average length and width of the site were 375 ft and 200 ft, respectively. The depth of failure for slides with arcuate headscarps was calculated using the following formula: $D = S \tan(\theta - \phi)$, where D = depth of slip surface; S = slope distance from top of crown to chord (the line connecting extremities of the curve of the crown which lies in the plane of the original ground; θ = angle of headscarp from horizontal; and ϕ = angle of original ground slope (Collins and Hicks 1971). The depth was calculated to be about 60 ft and a volume of from 40,000 to 70,000 yd^3 was used for management decisions. Interpreted slip surface locations are plotted on Fig. 3. At least 10,000 to 20,000 yd^3 of the landslide was expected to enter the stream system (Seidelman, pers. comm.). Road reaches and hillslopes adjacent to the landslide showed signs of instability. Continued failure of the landslide could remove lateral and downslope support from adjacent areas and possibly increase their movement rates.

Treatment was desirable as both a corrective and preventive measure. In order to reduce the weight of the hillslope, the largest possible volume of landing material was removed while keeping within monetary and time limits. Fig. 3 shows the hillslope profile before and after the excavation of 7,000 yd^3 (between 1/10 and 1/6 of the total landslide volume).

A 10% chance to stop the landsliding was postulated, if a set of dewatering drains were excavated to divert water away from the slide. Suggested drain depths were 1.5 to 4 ft to intercept surface water and shallow interflow, and 15 to 20 ft for groundwater (Seidelman, *in littera)*. A trench of 17-ft average depth was excavated and back-filled with sand and gravel at the inboard edge of the road immediately upslope of the landslide (Fig. 3, 6). Plastic sheeting was placed in the trench at the 4-ft depth in order to confine and entrain the surface water. After diversion for measurement, water from both drains was routed downhill to Emerald Creek (Fig. 7). At worst, the prescribed treatments were expected to improve chances that the slide would fail slowly (Seidelman, *in littera)*.

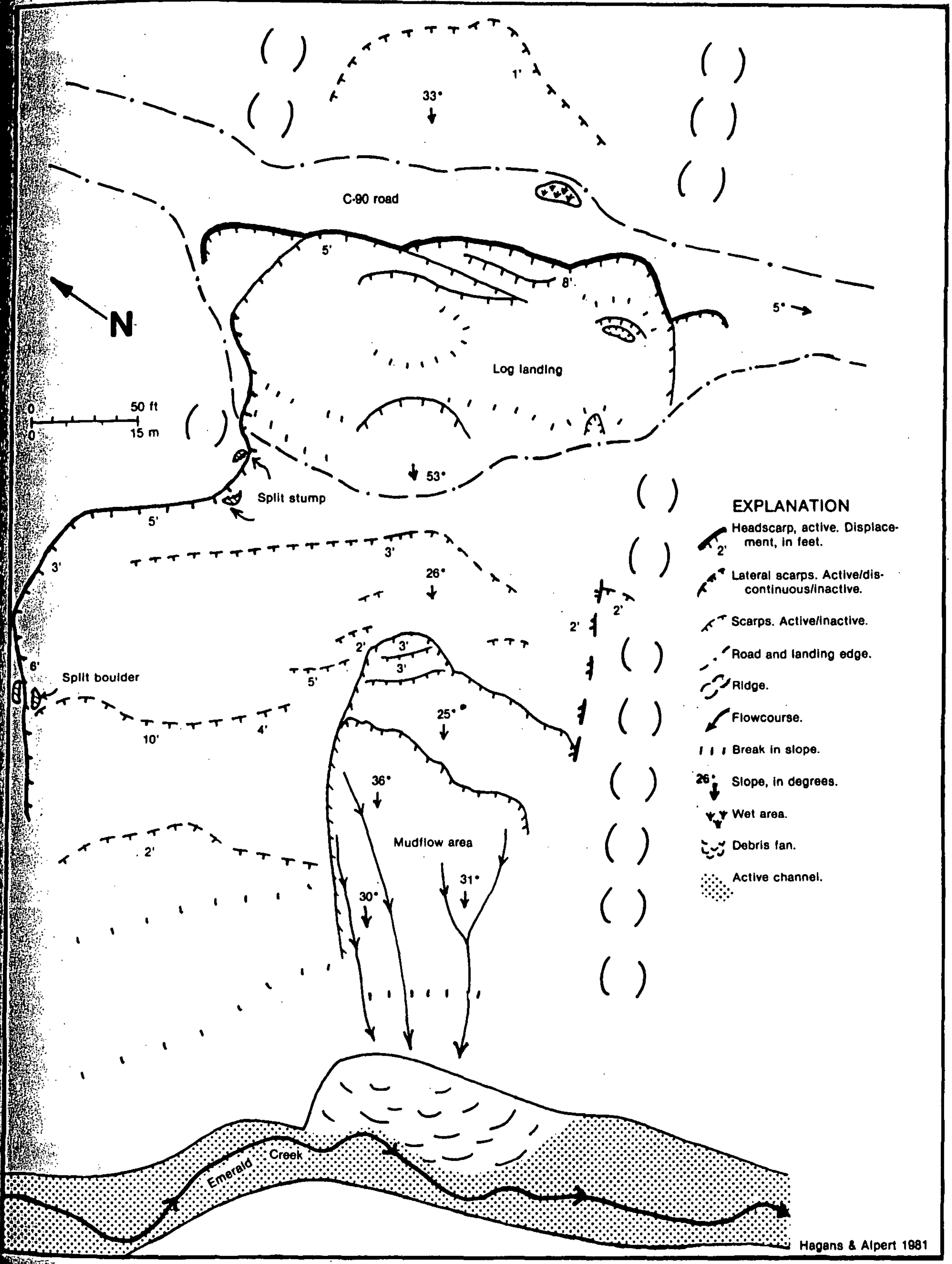

Figure 2

Plan Map Before Treatment, Summer 1981, Emerald Creek Landslide, R.N.P.

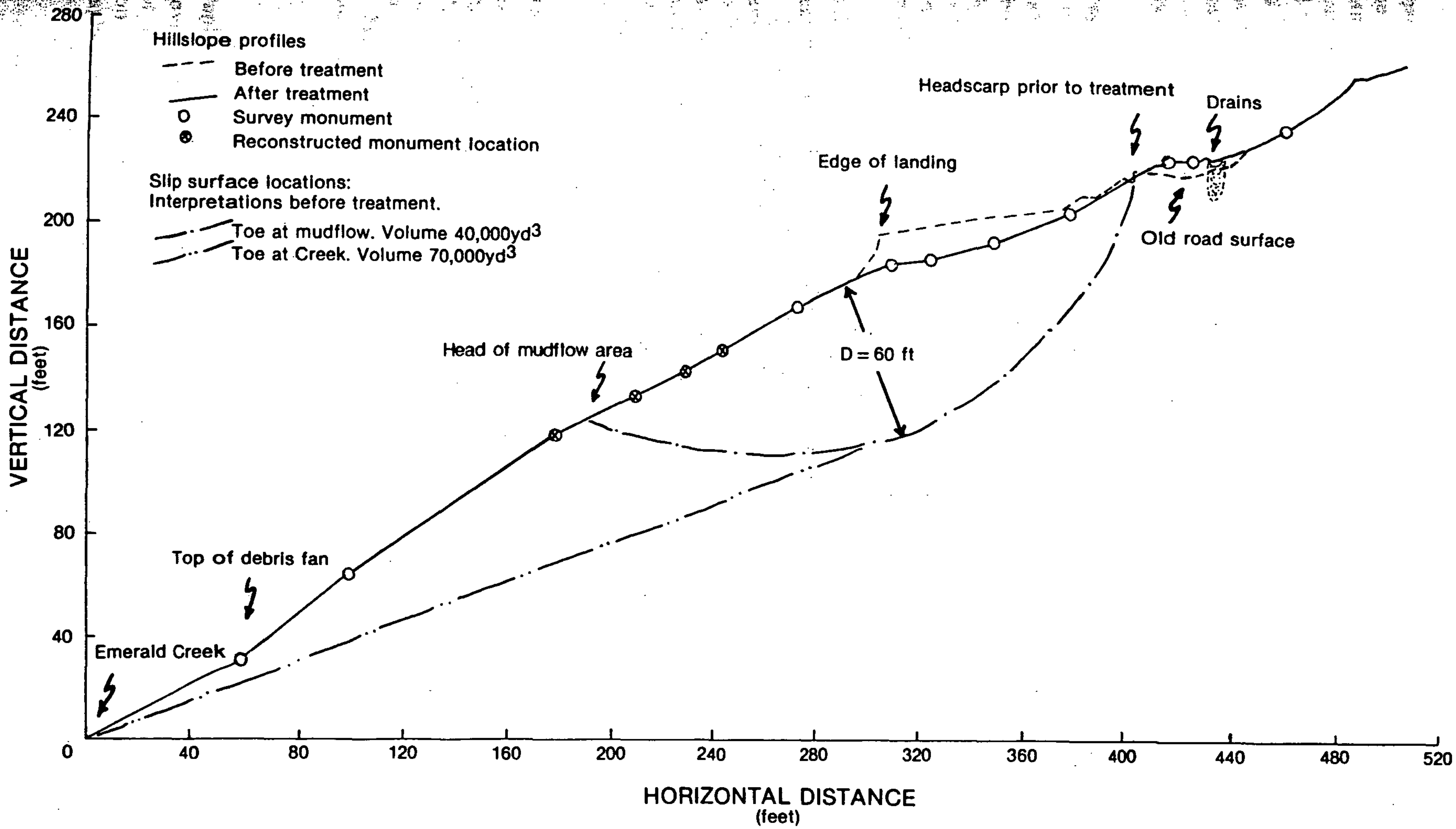

Figure 3

Profile Before and After Treatment, Summer 1981, Emerald Creek Landslide, R.N.P.

METHODS

Observation of the development of this large scale landslide, even if no treatment had been performed, should help to evaluate and target for management decisions other landslides in the park. Information desired included but was not limited to: causes of landslide occurrence; identification and quantification of controls affecting movement; volumes of material in the landslide mass; volumes of material which will enter the stream system; rates of slide movement and sediment delivery; and short- and long-term impact on the stream system.

Several monitoring techniques were used to study the hydrology and nature of movement of the slide mass, and will be continued with improvements in the future. Photographic, hydrologic, survey, and scarp mapping procedures were established, and data were collected throughout the winter of 1981-1982.

Photographic

A Super-8 movie camera was set up on the opposite side of Emerald Creek to observe rate and morphology of mass movement. A light-sensitive timer exposed one frame/2 min during daylight hours, however thick fog and rain often obscured the image. Some frames were blurred because of condensation on the outside of the waterproof plexiglass camera case. In addition, photographs were taken from permanent locations (photo points) established in 1978 and 1981 as part of rehabilitation documentation. Sequential 35 mm photographs show development of erosional features and vegetation regrowth through time, and aid in evaluating treatment effectiveness.

Hydrologic

Basic hydrologic data were gathered for rainfall, drain discharge, and water levels in piezometers. Storage (10-in. Clear-vue) and recording (Stevens Type A) gauges were installed to measure amount and intensity of rainfall and evaluate its relationship to slide movement. Continuous stage recorders (Stevens Type F) were used to quantify the volumes of water discharged by the drains. Piezometers were installed on and around the excavated landing area to observe changes in pore pressure which is a major contributing factor to landslide movement (Sowers and Royster 1978). Drilling showed clayey and rocky lithologies which contained varying amounts of moisture. Only seven piezometers were installed due to difficulty of drilling, though more had been planned. Depths of drill holes ranged from 11.7 to 17.7 ft. Water levels and stored rainfall were measured weekly.

Movement

Exact magnitude and direction of the slide mass movement during the winter were measured by surveying individual monuments using a theodolite with electronic distance meter. New monuments were established throughout the winter. A grid array of 89 stakes were resurveyed from one to four times during the winter, usually after each major storm period. Thirty-two natural features (trees, boulders) and 16 other monitoring features (piezometers, rain gauges) were surveyed for ground control. Scarps and cracks were mapped several times throughout the winter. Survey data provided good ground control for repeated mapping of scarps and moving blocks of material.

RESULTS

Photographic

Movie film resolution did not show movement because of distance from the slide, small film size, and poor visibility. Super-8 movies taken at 300 to 400 ft from a landslide do not show sufficient resolution to differentiate scarp migration and block movement of less than 20 ft. Sequential 35 mm photographs from permanent locations were effective in documenting changes within the slide mass. Problems exist in densely forested areas because views are obscured by standing and/or downed trees. Also, it is difficult to predict locations of scarp development and block movement. Overviews ameliorate this problem, but detail is lost.

Hydrologic

Total rainfall of 1982 was 105 in, whereas the average rainfall for the basin was 80 in (Janda et al. 1975). Daily totals, periodic totals, and daily cumulative totals of rainfall are plotted in Fig. 4, 5, and 10, respectively. The greatest 24-hr storm total was 5.7 in or .24 in/hr on 19 December (Fig. 4). That storm lasted 80 hrs at an average intensity of 0.12 in/hr. Fig. 10 shows rainfall was distributed in three distinct periods: 11 November 1981 to 4 January 1982, it rained nearly constantly, averaging 0.91 in/day; 4 January to 13 April, a longer period with the same amount of rain but with three dry periods of two to three weeks in length, averaged 0.44 in/day; and 14 April to 26 August no significant rain fell.

All surface water which would have entered the slide from upslope was intercepted. Surface water removed by the drains between 12 November and 14 April was approximately 406,000 ft^3 (3x10^6 or 9.3 ac/ft) or 40% of the rain that fell with the 3 ac contributing watershed uphill of the landslide during that period (Fig. 4). The drainage area effectively contributing runoff is difficult to determine due to a dense network of tractor trails which may divert some surface flow. The runoff/rainfall ratio seems to be somewhat low compared to published data for nearby large streams (Nolan and Janda 1981) and Redwood Creek (Lee et al. 1975). The slide area itself generated an unmeasured amount of runoff which was observed to flow into and along internal and lateral scarps.

The groundwater drain removed 56,000 ft^3 of water, an unexpectedly low 6% of the total rainfall. Since mapping showed predominantly sandstone bedrock upslope, permeabilities were presumed to be fairly high.

Many peak water levels in the piezometers were missed due to the periodic measurements (Fig. 4, 5). Continuous data would have allowed some correlation with rainfall and mass movement rates. Most piezometers were dry except during periods of high rainfall. Only two showed measurable water throughout the winter. P-6, located in a wet clayey area on the excavated landing area (Fig. 6), was artesian with water levels 2 - 4 ft above ground most of the winter and responded strongly to rainfall (Fig. 5). P-1 is in a clayey seep on the road cut bank 50 ft higher in elevation than P-6 (Fig. 6), and responded more to the overall wet season than specific storms. P-1 may tap an unconfined aquifer and reflect the groundwater table, whereas P-6 is in a confined aquifer which is probably a perched water zone.

Movement

Two piezometers acted inadvertently as inclinometers. On 12 November, after 12.9 in of rain to date, the 717.7-ft deep hole of P-5 (Fig. 6) was pinched at 12 ft deep. Four days later it was 6 ft deep. At this time an 8 to 10 ft headscarp formed at the edge of the excavated area, downhill of the original headscarp and uphill of the "inclinometers" (Fig. 6). The south lateral scarp had extended uphill to the new headscarp. By 16 December, after 27.6 of rain, P-4, the 15-ft deep piezometer 77 ft uphill of P-5 (Fig. 6), was pinched at 6 ft deep.

By February, 1982, after 75 in of rain, blocks of material downslope of the new headscarp and above the mudflow area moved 13 ft or more according to surveyed monuments. The final scarp map (Fig. 7) and the map of monument movement after the winter (Fig. 8) illustrate overall slide changes. No measurable displacement occurred at the old headscarp. A new headscarp had formed and migrated slightly uphill. The south lateral scarp became continuous and well-defined up to the new headscarp. No change occurred on the north lateral scarp. The major movement was translational, downhill sliding of blocks (Fig. 9) in part defined by pre-existing scarps (Fig. 2). Maximum total movement was 21.2 ft horizontally and 10.6 ft vertically. The magnitude of distance moved was probably influenced by the relatively wet winter (25 in above the basinwide average). The mudflow area was altered by fluvial processes, but showed no mass movement. In 1981, the slide mass seems to include a smaller area than before treatment.

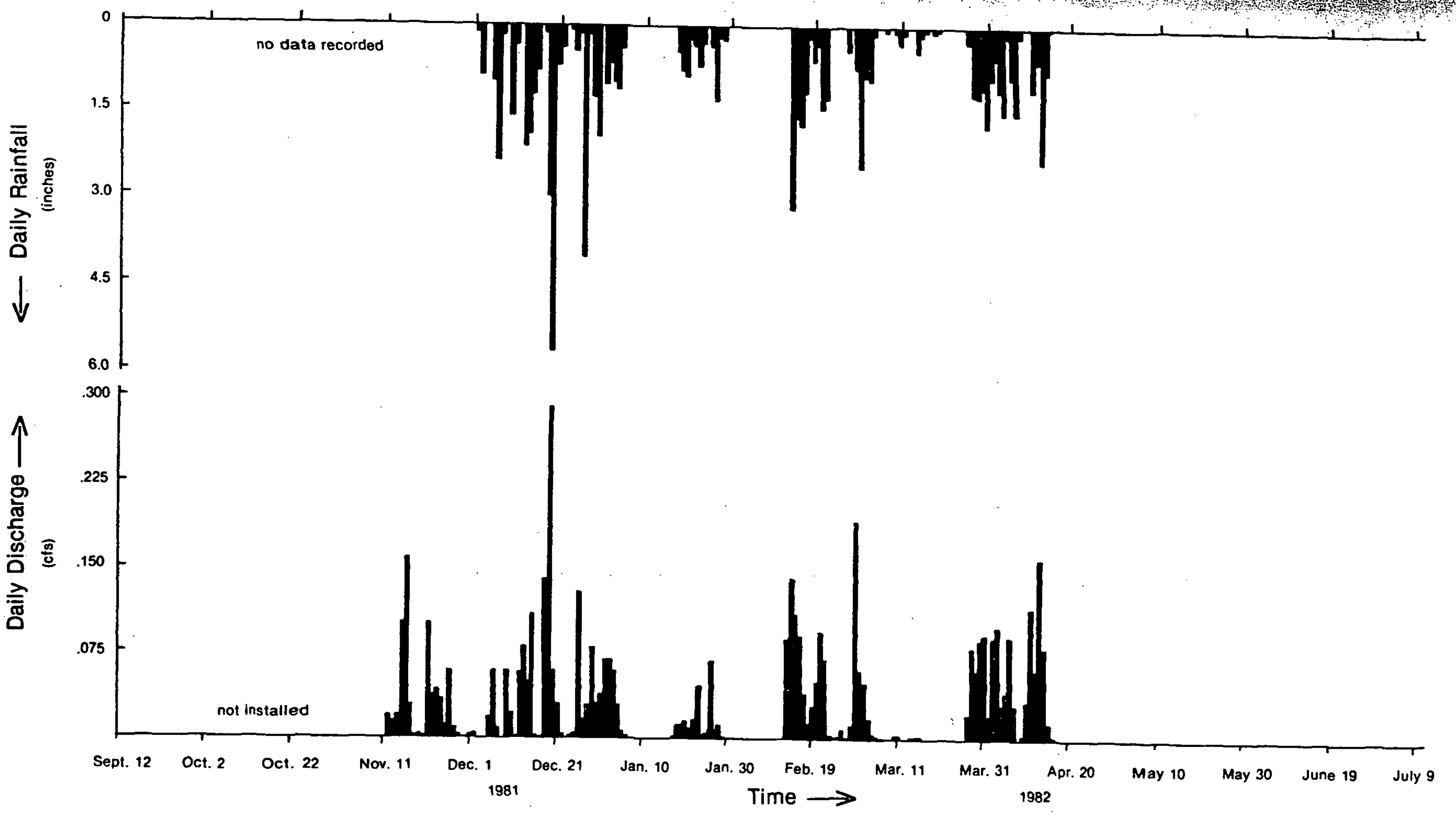

Figure 4

Daily Rainfall Totals and Average Daily Discharge of Surface Water Drain During Winter 1981-82, Emerald Creek Landslide, R.N.P.

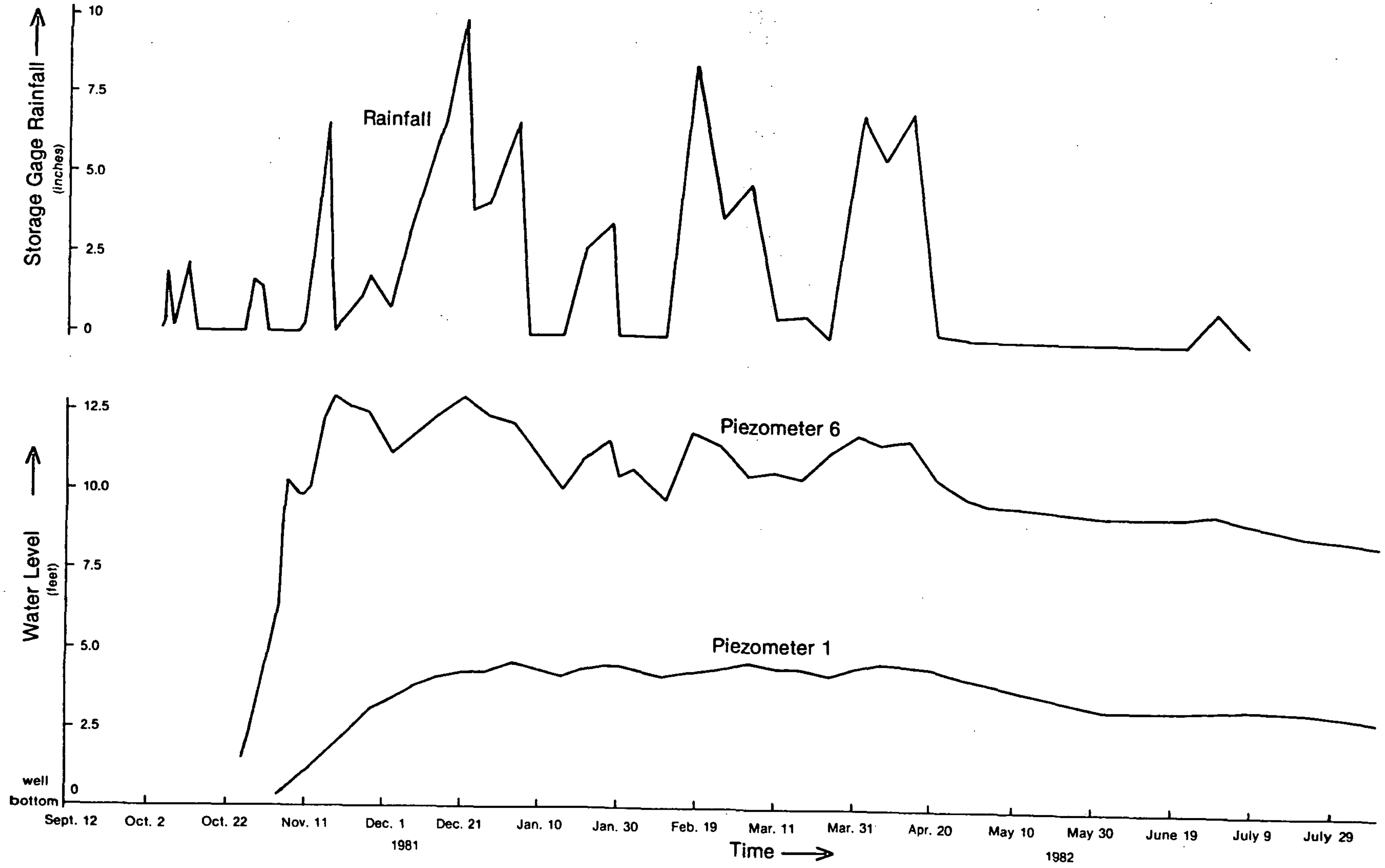

Figure 5

Periodic Measurements of Rainfall and Water Levels During Winter 1981-1982, Emerald Creek Landslide, R.N.P.

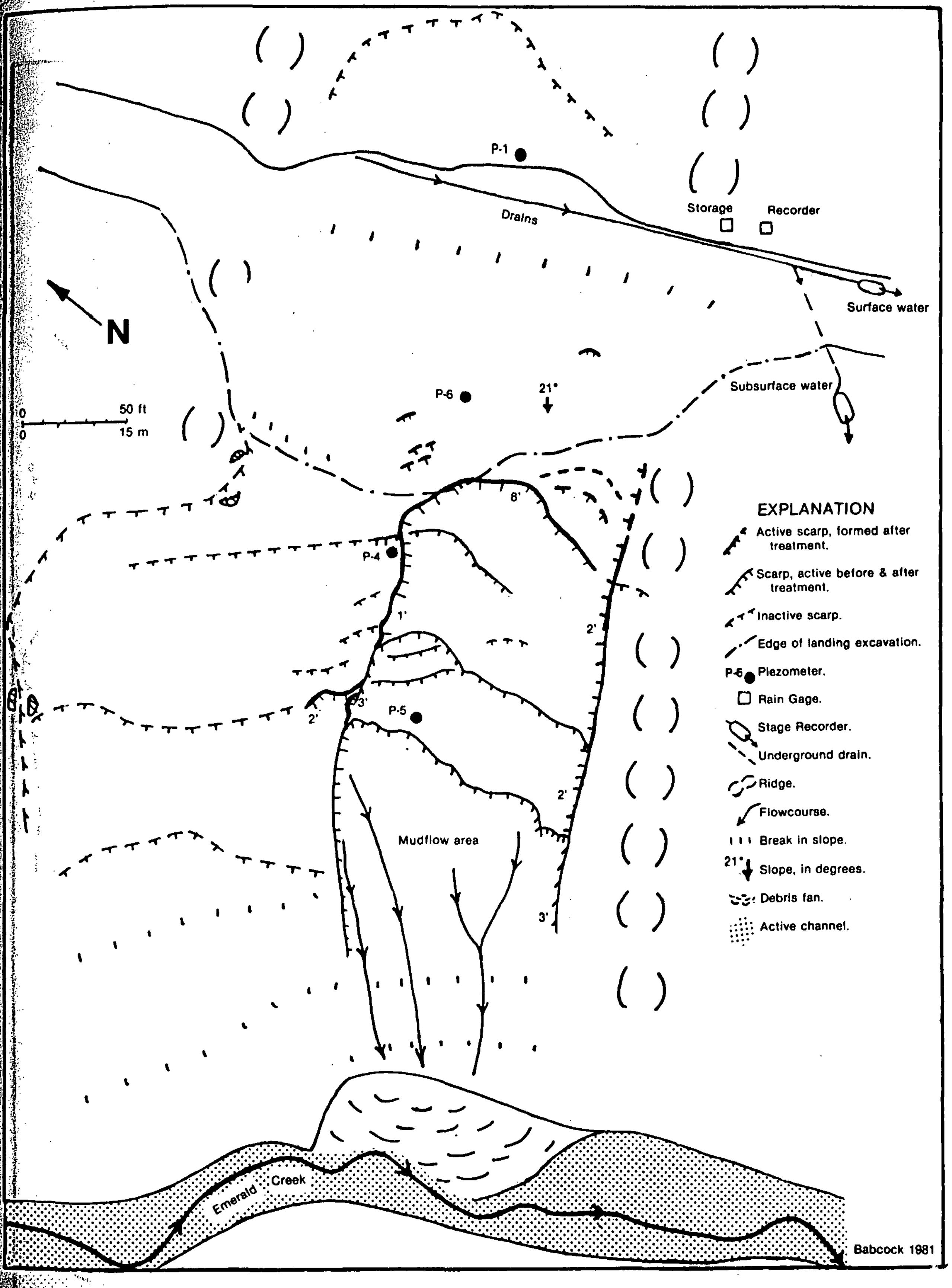

Figure 6

Plan Map Showing Change of Scarps, November 1981, Emerald Creek Landslide, R.N.P.
Rain-to-date 22 in. Average Movement 3.5 ft.

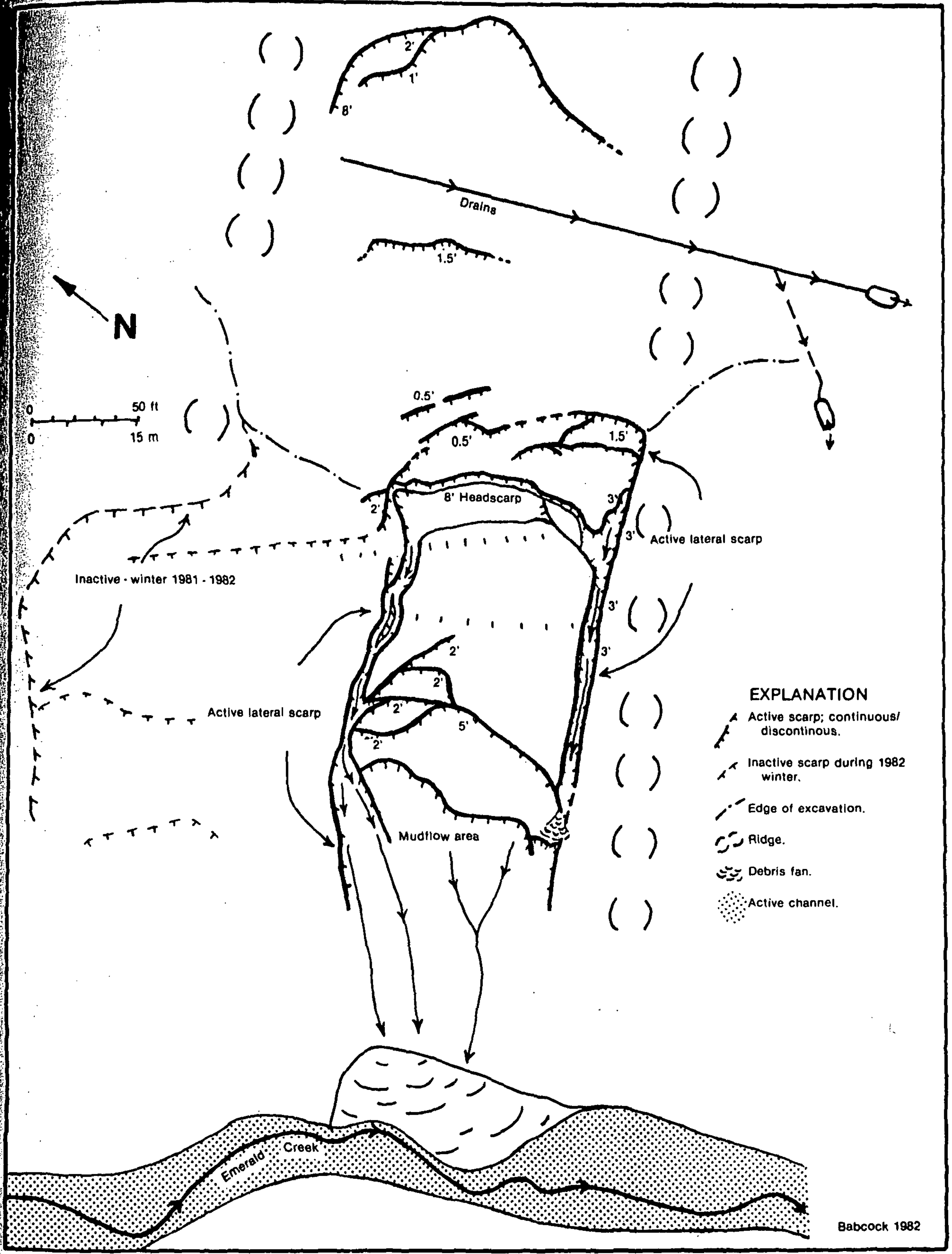

Figure 7

Plan Map Showing Scarps After Winter 1981-1982, Emeral Creek Landslide, R.N.P.
Total Rain 105 in. Average Movement 18 ft.

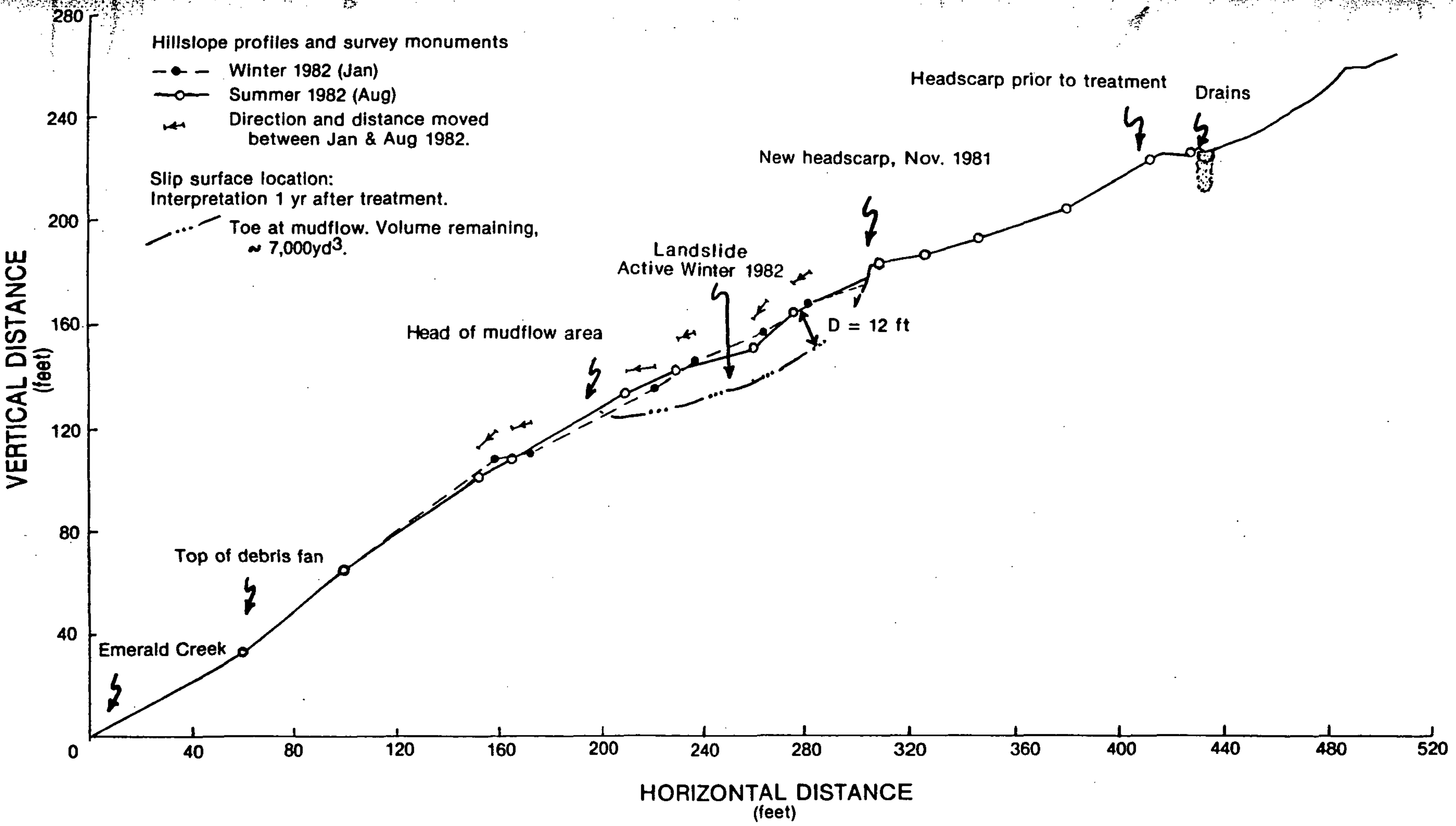

Figure 8

Monument Movement and Slope Profiles in January and August, 1982, Emerald Creek Landslide, R.N.P., With Present Interpretation of Failure Plane

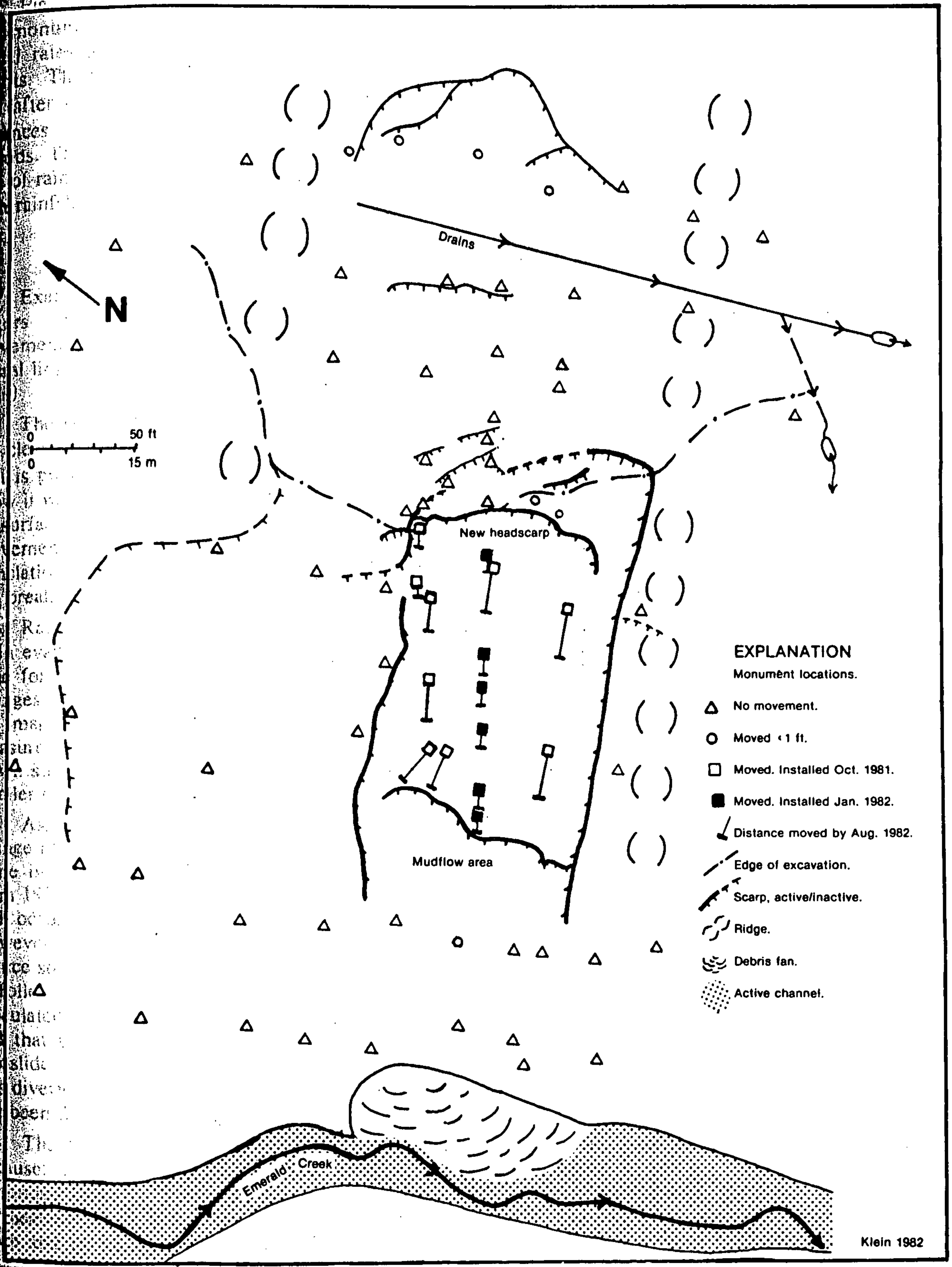

Figure 9

Plan Map Showing Total Monument Movement After Winter 1981-1982, Emerald Creek Landslide, R.N.P.

Fig. 10 shows time plotted against cumulative rainfall and the cumulative horizontal movement of two monuments. The slopes of the line segments drawn between monument distances do not indicate actual rates of movement, since movement was observed to be dependent upon individual rainfall events. The slopes of the line segments are partly dependent on when measurements occurred before and after a major storm. The slopes could be called "averaged movement rates". Representative distances of monument movement were 12.8 ft, 2.5 ft, and 0.5 ft, respectively, for the three rainfall periods. The "averaged movement rates" mimic the seasonal rainfall distribution (e.g., the averaged rate of rainfall within a period of time). Although surveyed infrequently, movement correlates strongly with rainfall. The effect of antecedent soil moisture on slide movement has not been evaluated.

DISCUSSION AND CONCLUSIONS

Exact causes of the formation of the landslide and the identification and quantification of the factors controlling its further development have been difficult to determine. The alteration of movement patterns 1 yr following treatment, however, is striking. The areal extent of the head and lateral limits was markedly smaller in 1982 (150 ft long, 100 ft wide) than in 1981 (375 ft long, 200 ft wide).

The depth of failure appears to be shallower than previous interpretation suggested. Evidence is not clear whether a deep-seated slip surface ever existed (Fig. 3) or what its downslope extent may be. If it is present, the lack of measurable movement on the mudflow and old headscarp system (Fig. 2) show it was inactive in 1981-82. The shallow failures observed possibly could represent the adjustment of surface blocks on a deeper failure. Evidence of a shallow slip surface include the initiation of movement early in the wet season, the observed depth of the bent piezometers, and the observed translational gliding of blocks which Fig. 9 also illustrates. The toe of this failure plane is probably at the break in slope at the top of the mudflow.

Rates of sediment delivery to Emerald Creek can be estimated by survey data. These have not been evaluated at this time. Determination of impacts on the stream system by the landslide requires time for observation. Eight cross-sections established on Emerald Creek have not shown significant changes in 1 yr. Input of material from the landslide seems to coincide with high streamflow. Since the majority of material may be transported downstream at that time, it is difficult to accurately measure the volume of sediment contributed by the landslide. If changes are recorded in future years it will still be difficult to attribute them solely to landsliding. Upstream of the landslide occur several smaller sources actively delivering sediment to Emerald Creek.

Assessment of the landslide treatments is tentatively based on one year's data. It is expected to change as the landslide develops. Review of the rainfall and movement history of the landslide allows some inferences to be made. Displacement at the headscarp was observed to progressively increase from 1978 to 1981, relatively dry years. If rainfall had again been average in 1982, and if no treatment had occurred, the headscarp would have been expected to enlarge a similar or greater amount. However, the rainfall was 30% greater than average. Greater rainfall should increase soil saturation, reduce soil strength, and promote failure (Varnes 1978) but the areal extent of active sliding decreased. It follows that the treatment was probably responsible for the reduction in landslide size. It is speculated that removal of the head portion of the slide mass (7,000 yd^3) essentially stabilized that area and that below the right lateral scarp. The specific role of surface water in stability of the Emerald landslide is now known. Nevertheless, 40% of surface water otherwise introduced onto the slide mass was diverted. It is speculated that more movement would have occurred if the 406,000 ft^3 of water had not been diverted.

The subsurface drain did not divert much groundwater. The small groundwater discharge may be because: 1) untested gravel material used in the drain may have a low permeability, and water continued downhill into the landslide mass; 2) areas of high groundwater discharge (increased permeability along shear planes) were not intercepted by the ditch; or 3) groundwater flow lines are steep and the drain is not sufficiently deep to intercept water. The subsurface hydrology is not well

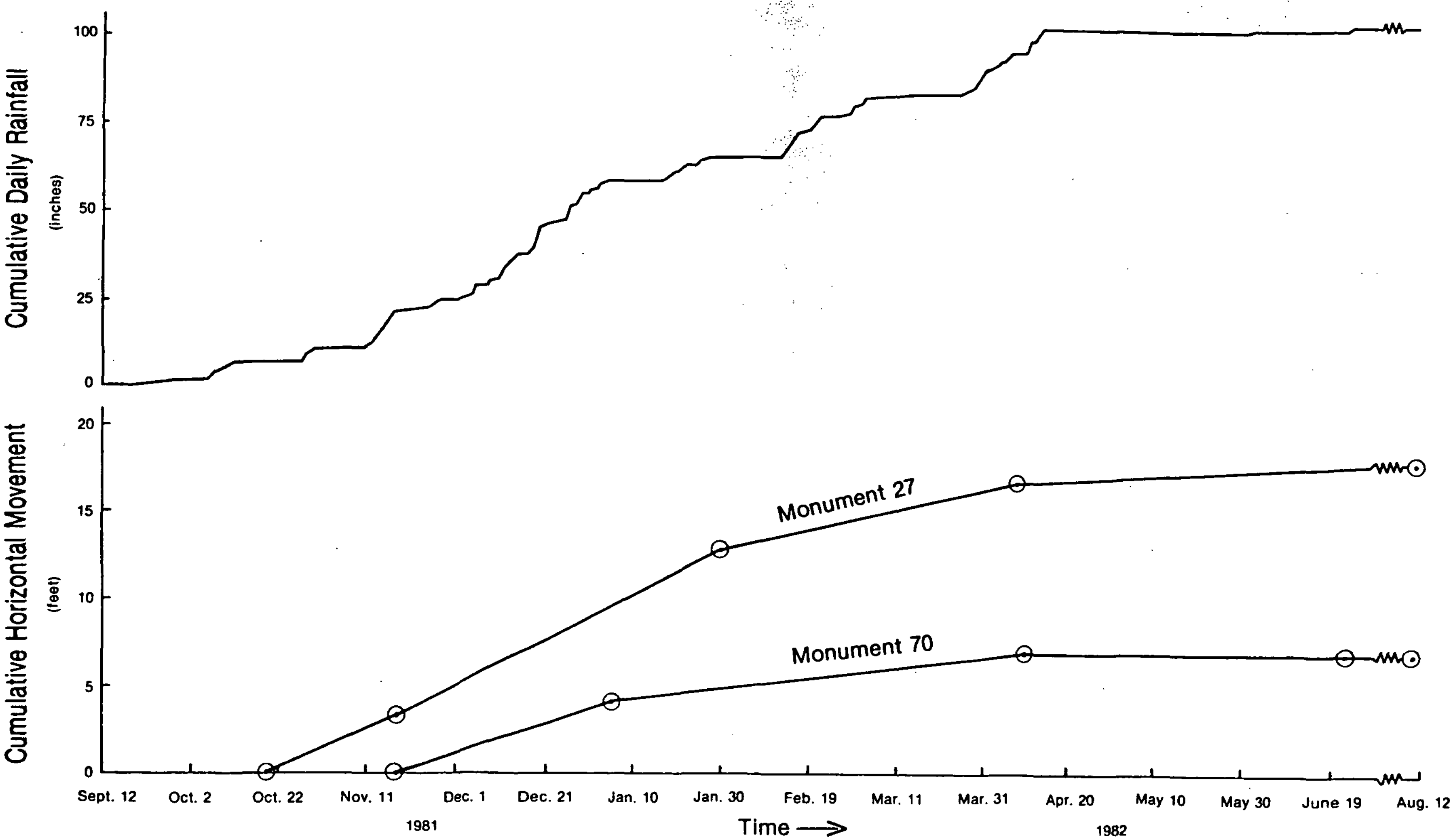

Figure 10

Cumulative Rainfall and Horizontal Movement of Two Monuments During Winter 1981-1982, Emerald Creek Landslide, R.N.P.

stood due to the lack of groundwater monitoring before treatment and the small data base after treatment. The hydrology is complicated by the large degree of bedrock shearing and the complexity of the lithologies.

MANAGEMENT RECOMMENDATIONS

Analysis: In hindsight it would have been beneficial to do a slope stability analysis either by Park or by specialized consultant. At the least, this should include a landslide hazard rating, standard engineering tests, and simple calculation of failure plane depth.

Treatment: Dependent on the factors controlling landsliding (analysis phase), determine if the can be slowed by economical treatment. For example: If decreased amounts of groundwater reduce landsliding, are the soils sufficiently permeable to provide significant discharge to a surface drain? Subsurface drain construction is expensive. Slightly less expensive is the common treatment of removing weight from the head of a landslide. But if the weight is not the controlling factor or if the landslide is too far developed to be stabilized, money is wasted. Surface drain construction is least expensive of the three treatments but its usefulness should be evaluated.

Monitoring: Monitoring a landslide after treatment is beneficial if other landslides may be treated. Photographs from permanent locations, scarp development maps, and especially monument surveys provide visual and accurate numerical documentation and are relatively inexpensive.

At Emerald Creek landslide, physical scientists made the evaluations and treatment plans, supervised treatment, and carried out the monitoring activities. Physical scientists need to be involved in this type of evaluation and management decision.

ACKNOWLEDGEMENTS

Thanks go to Mary Ann Madej, John Sacklin, and Ken Utley for their review of the paper, and Marquette for graphics. Danny Hagans and Mark Alpert took on the expensive, logistical nightmare of an experimental treatment promising a very uncertain outcome. Bill Weaver devised the general monitoring scheme and ensured the equipment was available. Ron Sonnevil managed to coordinate the personnel and logistics for installing the monitoring devices as well as keep the rest of the monitoring program alive. Paul Seidelman shared his valuable experience specific to landslide stability. Special acknowledgement is due Randy Klein and Rock LaHusen whose hard work and ingenuity were largely responsible for the data generated from this study.