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California's Ground-Moving Weather

We have often heard the expression "earthquake weather," and ordinarily have discounted its implications in favor of alternative factors more fundamentally related to shaking of the ground. But other kinds of ground movement that also are important to California's residents have led to more realistic expressions of unhappy implication, among which are "flood weather" and "landslide weather." Rarely benign in their behavior or effects, these recurring elements of normal geologic activity are figurative mud in the public eye, and they have been especially troublesome in areas of concentrated population.

The climatic norm in California implies a pleasantness that is consonant with reality for much of the time; yet large departures from this norm are not infrequent. In terms of rainfall, for example, the long-time average of about 15 inches per year for several populous areas represents ranges of 30 inches or more between annual extremes. Much of this precipitation results from individual storms that occur chiefly during the period December through March, or from series of storms that tend to be scattered irregularly through this wintertime wet season. The heaviest rainfall also is irregularly distributed in a geographic sense, owing mainly to variations in storm tracks and to marked contrasts in topography. The effects of topography can be very important, as reflected by large local differences in precipitation during numerous regional storms.

WATER ON THE GROUND

In considering relationships between weather and undesirable movements of the ground, we can focus primarily upon two kinds of features—uncontrolled runoff of exceptionally large amounts of water over short periods of time, and the penetration of additional large amounts into the subsurface over longer periods. Here rainfall is the prime factor in most parts of California, although the significance of other kinds of climatic contributions cannot be denied. For example, more than 600 inches of winter snow and an appropriate pattern of temperatures in the Sierra Nevada can lead to disastrous spring flooding in the Sacramento and San Joaquin Valleys, as occurred at least four times between 1880 and 1907. Or combinations of storm waves and extremely high tides can result in accelerated erosion and local collapse of coastal cliffs, even when no heavy precipitation is involved. But such events either are limited in scope or involve inundation more than movement of the ground.

How much water may the ground be required to deal with during periods of extraordinary precipitation? And what kinds of things can happen? The historic record provides some eyebrow-raising data. In the winter of 1861-62, a most uncharacteristic season within a long sequence of near-average to very dry years, repeated storms doused San Francisco with nearly 50 inches of rain, and in Los Angeles the skies leaked without stopping for a full month. Adobe structures seemed to dissolve under the downpours, while on most valley floors buildings became islands in huge lakes and then were heavily pounded by wind-driven waves. Large parts of the Sacramento and San Joaquin Valleys were converted into an enormous inland sea, and the entire state appeared to be drowning as every river, creek, and dry wash became a torrent of muddy, debris-laden water. According to contemporary accounts, mud as much as five feet deep was deposited in the parlors of some Sacramento homes. This must have been a new sad note for those residents of

By RICHARD H. JAHNS

more than a century ago, but it has an all-too-familiar ring for many persons now living in the state.

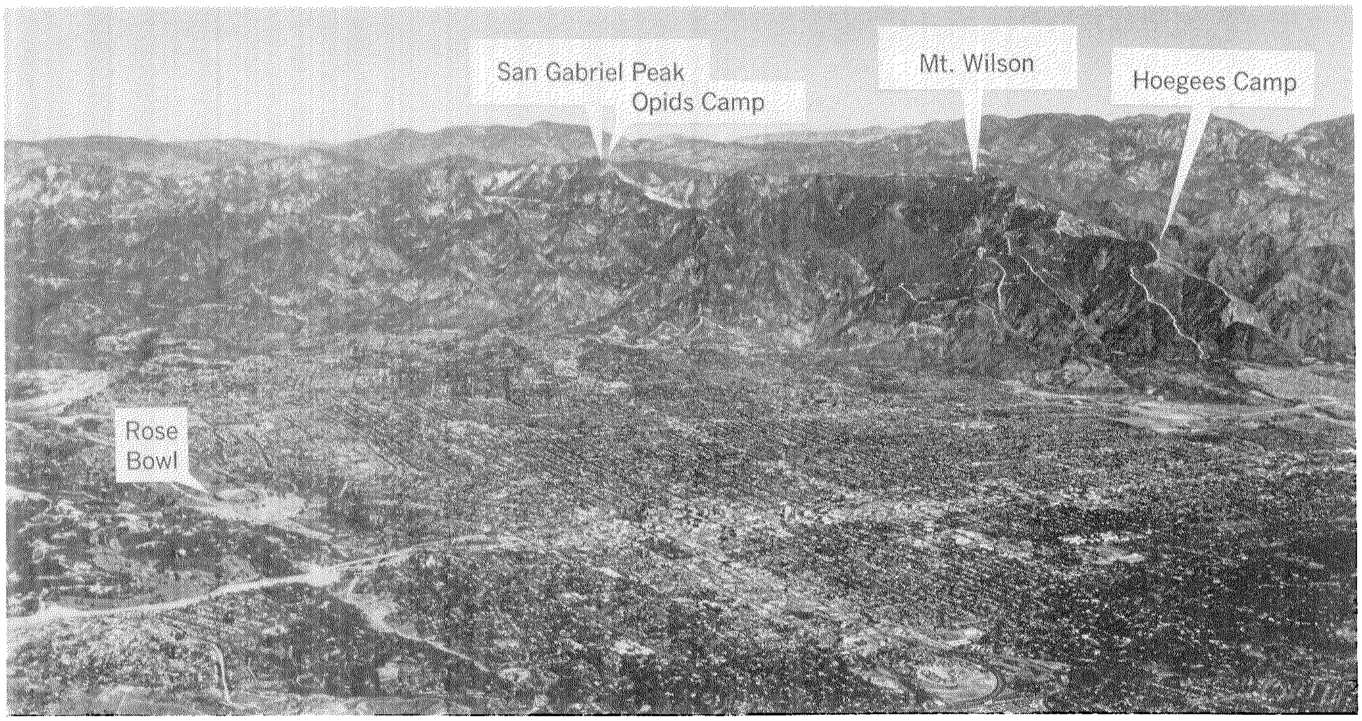
In southern California the shallow Lake Elsinore, which had been essentially dry during the preceding year, filled to a depth of at least 50 feet and overflowed in 1862, all within a period of little more than three months. Since that time the lake has gone through numerous cycles of evaporative shrinkage and rainfall-nourished expansion, with at least eight separate episodes of overflow. Some periods of expansion reflected relatively long wet seasons or successions of such seasons, and all of them marked the occurrence of brief storms characterized by high intensities of precipitation.

The mountain ranges fringing the broad lowland area that includes Los Angeles are in a semi-arid region; yet they have received some remarkable contributions of moisture from time to time. During January 1916, for example, 50 to 60 inches of rain fell over much of the San Gabriel and San Bernardino Mountains, with considerable parts of the total coming from one three-day storm. Adjacent lowland areas received 32 to 40 inches during that same month. The western San Gabriel Mountains are particularly noted for short-term precipitation of great intensity, especially on ridges and canyon walls only short distances from Pasadena and other cities along the southerly base of the range. Gauges at Opids Camp, Mt. Wilson, and Hoegees Camp recorded 21 to nearly 26 inches of rain during the three-day period February 28—March 2, 1938—a moisture dosage that only slightly exceeded one from a similar storm during the period February 14-16, 1927. And on January 22, 1943, a 24-hour record of 26.12 inches was established at Hoegees Camp; during that same day 22.32 inches of rain fell at Opids Camp, where the winter season's ac-

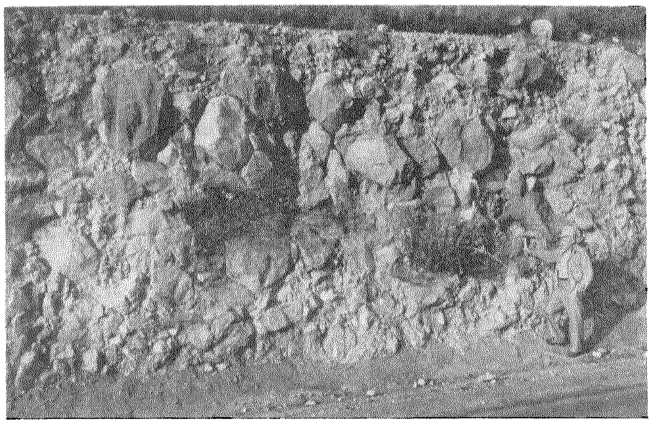
"California's Ground-Moving Weather" has been adapted from the first John P. Buwalda Memorial Lecture, "How Firm is Terra Firma," delivered in Beckman Auditorium on November 18, 1968, by Richard H. Jahns, dean of Stanford University's school of earth sciences. Jahns was a particularly appropriate person to give this lecture. He was a student of John Buwalda's at Caltech, then his colleague on the geology faculty, and he shared many of Dr. Buwalda's professional interests—including the subject of the lecture.

Richard Jahns came to Caltech as a freshman in 1931 and earned two degrees (BS '35, PhD '43) in geology under Buwalda's tutelage. In 1946 he joined Buwalda's staff as assistant professor of geology. In 1960 he left Caltech to become chairman of the department of earth sciences at Penn State.

John Buwalda founded Caltech's division of geology in 1926 and served as its chairman until 1947, when he returned to his "first love," field work on California's faults and earthquakes. He died in 1954. The memorial lectures in his honor, sponsored by the division of geological sciences and made possible largely through the gifts of friends and colleagues, were launched last fall with the Jahns talk. Since that time southern California's weather has provided some interesting punctuation for the author's remarks.



The western San Gabriel Mountains, bordering Pasadena (center) and heavily settled parts of the San Gabriel Valley, are particularly noted for short-term rainfall of great intensity. Hoegees and Opids Camps (out of sight at the bottoms of deep canyons) register record rainfall—26.12 inches during one 24-hour period in January 1943, and a winter season's total of 80 inches that same year.



This fossil debris flow, revealed in cross section by a roadcut near Pala in San Diego County, is a chaotic accumulation of blocks, boulders, tree fragments, and stony rubble —a coarse slurry that debouched from the mouth of a nearby canyon at least 10,000 years ago.

cumulation ultimately reached 80 inches.

Such overly generous contributions of water are potent reshapers of the landscape. They form temporary torrents that carve deeply into the steep mountain slopes and pick up enormous charges of debris en route to adjacent valley and basin areas. There uncontrolled parts of the runoff deposit various assemblages of mud, rubble, boulders, and trash, commonly in places where they are not welcome. Parts of the San Fernando, San Gabriel, and San Bernardino Valleys were thus devastated by the great March Flood of 1938, and four years earlier the La Cañada-La Crescenta Valley was invaded by rushing waters and bouldery slurries during the New Year's Day Flood of 1934. The slurries, much heavier and more slow moving than ordinary flood runoff, filled normal channels of drainage and then thrust across settled areas as great tongues that engulfed all objects in their paths. They resulted from cloudburst precipitation—13 inches or more in 24 hours—on adjacent steep mountainsides that had been denuded of protective vegetation by a forest fire during the previous fall season. Large debris flows of this kind have an impressive capacity for incorporating and transporting boulders, automobiles, buildings, and other heavy objects. Though infrequent and spotty in their occurrence, they have visited many parts of the state during the recent geologic past.

What may have been the most spectacular cloudburst in California's historic record seems to have attracted relatively little attention at the time, even though it occurred only a few miles from Pasadena. In the spring of 1926 a week-long storm brought 25 inches of rain to the area centering about San Gabriel Peak, with half of the total falling during a ten-hour period on April 4. At 3:30 a.m. on that day, a gauge at Opids Camp registered 1.02 inches of rain in a single minute and another inch during the following two minutes! One result of this extraordinary downpour was the detachment and removal of everything that was loose or could be loosened from the precipitous northerly slopes of the peak. An unusually coarse debris flow moved downward to the mouth of a gulch at Opids Camp, where it came to rest as a rampart-like slug of granitic boulders and blocks, trees, and finer-grained detritus—250 feet long, 50 to 75 feet wide, and about 40 feet in maximum thickness.

WATER IN THE GROUND

The surface effects of precipitation and runoff are invariably accompanied by less obvious penetration of water into the ground. Much of this water replenishes any existing deficiencies in the soil, most significantly in the root zone of the plant cover, and during extended wet periods substantial amounts may gradually move to deeper levels. But the orderly processes of infiltration are too slow to handle more than a small fraction of the precipitation from heavy storms. When such precipitation is especially intense, the destructive behavior of runoff can be worsened, rather than eased, by contributions of water augmenting the moisture already present in the shallow subsurface.

Here the recipe for prompt and widespread disaster in populated areas calls for steep slopes, an underlying few feet of soil or other relatively loose and uncompacted materials, and a minimum of surface stabilization from deeply rooted plants. Add very large amounts of water in very short periods of time, and the real action begins. Some of the water soaks into the mantling materials of the slope, where it both reduces their cohesiveness and increases their gross weight. Meanwhile, vigorous surface runoff cuts small gullies into the slope, especially where provisions for drainage have failed to prevent undesirable concentrations of flow. Soon parts of the scored slope are progressively loosened and detached as irregular patches, a few square feet to several acres in extent, that then move downhill. Typically they are broken and internally stirred during this descent, arriving at the foot of the slope as mobile slurries or accumulating there as thick masses of incoherent debris.

This scenario repeatedly has been translated into reality, especially at localities where man has modified the natural topography without sufficient note of possible consequences. Unhappy endings have occurred most often in the San Francisco, Los Angeles, and San Diego regions during the past 25 years of increasingly intensive settlement in hillside areas. It does not follow that catastrophes must attend grading of the land on any scale, but certainly the development of raw cuts in weak ground, emplacement of fill without proper compaction, and loading of soft slope materials with heavy, shallow-rooted plants will not contribute to long-term safety. Though widespread in their occurrence during periods of exceptionally intense rainfall, slope failures of the shallow or "skin" type are rarely large. Yet a home clogged with debris representing a fresh scar on an adjoining slope is nothing less than tragedy for the owner.

Equally wide ranging are many kinds of surficial failures in the hills and mountains beyond centers of population. These are nonetheless of real significance to the public, as they can add enormous amounts of debris to storm runoff that gathers in canyons and invades settled valley areas below. This lesson was offered rather violently to southern California residents in 1811, 1825, 1884, 1890, 1914, 1916, 1934, 1938, and 1943—each succeeding time to increased numbers of them. Indeed, it is recognition of the potential impact of future catastrophic floods on a burgeoning population and on correspondingly expanded areas of valuable property that has numerous geologists, engineers, and public stewards glancing uneasily back over their shoulders. To keep pace with growing requirements is a formidable challenge for an already sophisticated program of flood-control installations.

In contrast to the effects of uncontrolled runoff and shallow soaking of the ground are numerous larger slumps and landslides that have plagued Californians again and again. Most of these failures have involved masses of relatively weak or easily detached bedrock that have moved outward and downward on slopes in response to gravity. Triggering of displacement from positions of equilibrium, whether occurring once or many times at a given locality, can be variously ascribed to several factors, acting either singly or in some combination. Among these are earthquake shaking, selective overloading of the ground, removal of support from downslope areas, and increases in amount of subsurface water. Here man often has revealed himself as a disagreeably effective imitator and competitor of nature, for he has triggered many slides through his own reshaping of the terrain and his introduction of water into the ground as local concentrations.

The historic record clearly indicates that naturally introduced water can be the most important prompter of large-scale ground failure. Such failure may closely follow single storms, especially where attendant, severe runoff removes the toes from existing landslide masses that occupy steep canyon walls. The Eel and Russian Rivers in northern California, for example, have thus triggered numerous large slides at times when they were at very high flood stages. More often, however, landslide movements are delayed by days, weeks, or even months following episodes of unusually heavy precipitation, and a few have followed series of successively wet years. Such irregularities in lag times can be ascribed mainly to differences in the patterns of precipitation, the rates at which water infiltrates the subsurface and raises groundwater levels, and the various interactions between water and the subsurface materials. Detailed relationships among these factors are well understood for relatively few of the known landslides in California.

The extraordinary storm of 1938 immediately activated many earthflows in the Ventura area, and with only a little delay quickened the movements of large landslides that had been causing extensive damage to wells and other installations in the Ventura Avenue Oilfield for more than a decade. The weight of the added water must have been an important factor in this early response, but more than two months later a much greater movement was triggered in one of the slides by a fairly small excavation at its base. A similarly delicate state of near-equilibrium evidently now exists in the large Portuguese Bend landslide near Los Angeles, where slow movement has been continuous during the past 12 years. Here strain-gauge readings have shown that a few inches of rain from a single storm is sufficient immediately to double the rate of movement, evidently from the added increment of weight.

An interesting contrast in timing is provided by a large compound landslide mass in Portola Valley, south of San Francisco, that was originally formed in 1890. Precipitation during the winter of 1889-90 was exceptionally heavy, but it came late in a ten-year period of excess rainfall and hence probably augmented a subsurface accumulation that already was near-critical for massive ground failure at this locality. Various parts of the slide complex have been reactivated in subsequent years, most recently in 1967 (right). Additional examples of large bedrock landslides whose initial movements followed series of severe rainstorms or series of unusually wet years are known elsewhere in the San Francisco Bay region, in the Palos Verdes, San Joaquin, and Puente Hills of the Los Angeles region, and in other coastal parts of the state.

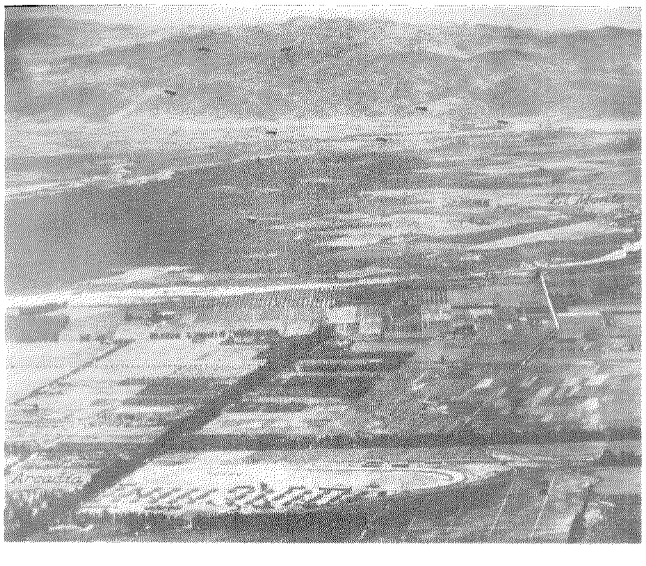
YESTERDAY AND TOMORROW

That ground-moving weather has been a recurring and highly important element of life in California is a matter of historic record, and there is every reason to believe that it will revisit us from time to time in the future. But when, and how often? Granting that our period of direct observation has been all too short and that rainfall records during this period seemingly were made only to be broken later on, what trends or patterns can be reasonably projected into the next few decades? Here it is useful to look again at the past.

During Late Pleistocene times, dating back from about 10,000 years ago, California's climate was considerably wetter than it has been since. Doubtless it was no accident that these were times of vigorous and widespread flooding and landsliding in the state, and tens of thousands of shallow topographic benches in the hills and mountains mark sites of ancient ground failure. Many of these benches are now occupied by dwellings, and it is fortunate that relatively few of the landslides have been reactivated during post-Pleistocene time. Quite apart from trends in the frequency of strong earthquakes, it can be suggested that the ground surface has been somewhat less mobile during the past few millenia than it was earlier. But these mere fragments of geologic time are still much too long to be useful for our present purposes.

Detailed climatic records extending back a little more than a century plainly reveal a cyclic pattern in the temporal distribution of California's rainfall. Sequences of relatively wet years have alternated with sequences of much drier ones, and the trends of accumulating rainfall surplus or deficiency have been interrupted only now and then by individual years of countering dryness or wetness. Moreover, this pattern of recurring wet and dry

This small landslide, which occurred in Portola Valley in San Mateo County in the spring of 1967, was a reactivated portion of a much larger landslide complex that originally developed in 1890 following several years of exceptionally heavy rainfall.



The San Gabriel Valley and Puente Hills as they appeared in 1918 through a telephoto lens from Mt. Wilson. Many parts of these hills are underlain by soft, shaly rocks, and portions of their somewhat dimpled topography reflect the presence of numerous natural landslides—a situation that reveals a challenge for the time when residential and business developments thrust further south and up into the hills. (The old Balloon School in Arcadia is in the foreground, and its students seem to be involved in field work nearby.)

periods evidently has characterized the climate of the state for a period of time far longer than that embraced by our measurements of precipitation.

The late Edmund Schulman and his colleagues at the University of Arizona's Laboratory of Tree-Ring Research devoted years of careful study toward determining a centuries-long chronology of climatic changes in southwestern United States.

Some results of their work on moisture-sensitive conifers in the lower forest zones of California show some impressive similarities among growth patterns for different species of trees from widely separated localities. Particularly striking are correlations of growth patterns that are thought to reflect major shifts in trends of precipitation.

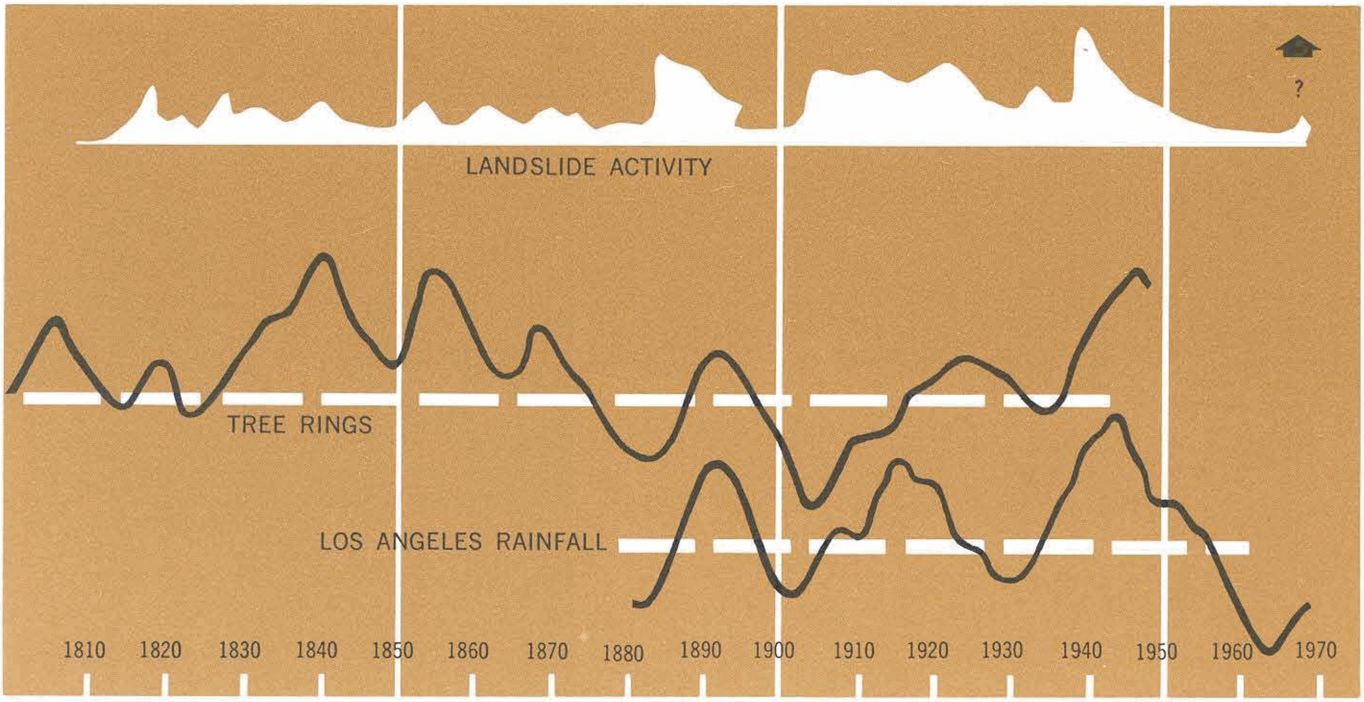
Schulman also turned his attention to some exceptionally long-lived conifers of upper timberline areas, and, since his death in 1958, this work has been continued by C. W. Ferguson and others at the University of Arizona. A 7,100-year tree-ring chronology has been developed for the Bristlecone pine in the White Mountains of east-central California, where a 4,600-year record from living trees has been extended back in time through the addition of data from long-dead ones. Interpretation of this composite record can be expected to indicate the pattern of moisture variations during much of post-Pleistocene time.

Trends in ring growth of carefully selected trees, and their close correlation with available climatic records certainly fortify the notion that California's rainfall has been markedly cyclic in its distribution over many past centuries. During the most recent five and one-half centuries, the average length of dry periods has been 16 years and that of wet periods 13 years. Respective averages of 15 and 12 years apply to the last three and one-half centuries, when the cycles appear to have been somewhat more regular. The latest dry sequence, which began in 1945, was a relatively long one interrupted by a few years of above-average moisture. Yet the record of preceding climatic cycles foretold a shift to a sequence of wet years. This shift appears to have occurred nearly four years ago, but early stages of the new sequence have been partly masked by one very dry year (1968) and by another of about average precipitation. At present we can anticipate a generally wet period that probably will last at least into the mid-seventies. It may well include exceptional storms and ground-moving phenomena reminiscent of those in 1938 and 1943.

Correlations between rainfall and landslide activity in California already have been noted, and the frequency plot (opposite page) reveals the sensitivity to heavy precipitation that has been shown by parts of the ground on which we live. This plot is based upon occurrences of more than a thousand natural landslides in coastal parts of the state between the Eel River and San Diego, as noted in newspapers, journals, and the scientific literature. It is no more than approximate because neither the record nor the survey of the record is complete, but the correlations are nonetheless unmistakable. There also is some indication that ground failure has been most vigorous and widespread during early parts of most wet periods, and that it has tended to taper off during their later parts. The frequency plot dates from 1810 because available reports on older landsliding are too scattered to be of statistical value, and it has not been carried much beyond 1950 because of difficulties in distinguishing wholly natural slides from those prompted in part by the hand of man.

As a sort of final touch, we can recognize yet another correlation that carries interesting implications for our immediate future. Two significant trends were started almost simultaneously a quarter of a century ago—one by nature and the other by man. Just as a long run of wet years gave way to a period of prevailing deficient moisture that was to last for two decades, the end of World War II ushered in a time of tremendous growth in California's population and hillside development. Having mastered powerful new techniques for reshaping the natural terrain, man now applied them on larger and larger scales to provide ever increasing numbers of building sites above the flatlands. The combined effectiveness of bulldozers, backhoes, scrapers, carryalls, and other heavy earth-moving equipment led to substantial changes in the face of the land—as work went forward during year after year of relatively low rainfall. Only with a few heavy wintertime storms did nature give warnings that the existing set of climatic ground rules might be greatly altered for some future series of years.

It is fortunate that these occasional warnings did not go unheeded by everybody. Rainstorms during the 1951-52 season inflicted such grave local damage, especially to newly developed properties in parts of southern California, that the city of Los Angeles instituted its own set of ground rules for hillside development. Through the Grading Ordinance of 1952, specific requirements that included input of geologic data were established for certain kinds of terrain. Partly in response to observed effects of heavy rains in later years, these requirements were subsequently modified and strengthened, especially in the important fields of supervision and inspection. Other cities and several counties have followed the good example of Los Angeles



THE RELATIONSHIP OF NATURAL LANDSLIDE ACTIVITY TO RAINFALL TRENDS IN PARTS OF CALIFORNIA. *The computer-smoothed curve for Los Angeles rainfall, as plotted by students at Stanford University, shows cumulative departures from the long-term annual mean of about 15 inches. Wet and dry periods are indicated independently by the smoothed curve representing cumulative departures of annual tree-ring growth (Bigcone spruce) from a 550-year average. The frequency plot of landslide activity is based on historical data for more than 1,000 episodes of natural sliding in coastal areas of the state.*

in formulating and enforcing new grading codes, and it can be hoped that similar regulatory measures will soon spread with reasonable coordination to all populous areas in the state.

An upward swing in the cyclic moisture curve inescapably promotes higher mobility of the terrain. In some contrast to events of the past two decades, increased flood erosion and deposition, further visitations by flowing masses of debris, the appearance of many new landslides, and some reactivation of existing ones now can be expected during the next decade or so. Ground failures are certain to occur in areas where the hills have been reshaped without proper attention to topographic and geologic relationships, and stern tests will be applied to the effectiveness of grading codes developed during recent years. New scarring of slopes by gullies and slumps will reflect the delivery of mud and other debris to thousands of residential properties, hopefully on a relatively small scale for most of them.

Existing works for flood control will be severely challenged, and immediate needs for additional installations will become rather apparent. As the levels of groundwater gradually rise, a host of more subtle effects may well make an appearance. The lower parts of some cuts will begin to weep, long-dry springs will become active again, and clear streams will grace many canyons that for a long time have been occupied by no more than occasional muddy floodwaters. Where large bodies of relatively impervious fill have been placed in canyons without adequate provision for underdrainage, water may begin to surface at unlikely places above the original canyon bottoms. Seeps beneath homes and in backyards will be among the less pleasant expressions of modified circuits in movement of the augmented groundwater supply.

Thus we can look forward to some interesting and even exciting times. In appraising those happenings that will strike us as most objectionable, we should appreciate the fact that a great number of more serious problems undoubtedly will have been forestalled by established flood-control measures and grading regulations—elements of regimentation that too often have elicited grumblings and resentment from land developers, builders, and the general public. Further, we should have excellent opportunities for improving our understanding of the natural environment, as our attention is perforce drawn to the message repeatedly communicated by Caltech's late John P. Buwalda—"We must never take for granted this ground on which we live."