GEOGRAPHIA POLONICA 23, 1972

SOME RATES OF GEOMORPHOLOGICAL PROCESSES

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This brief report summarizes three sets of measurement data on certain processes.

The first concerns the rate of movement of soil on hillslopes, especially by mass movement or slow gravitational creep. The results are abstracted from an unpublished manuscript by the junior author who reports on the measurements which Leopold began 10 or more years ago and to which in more recent years Emmett has added new sites and has carried on the annual remeasurement. The results are those from "mass-movement lines", which consist of a series of pins or iron rods, 10 inches (25 cm) long driven vertically into the ground along a straight line-of-sight, secured at each end with stiff iron posts. The Survey consists of setting a theodolite over one of the end bench marks and orienting on the other. The distance of each individual pin from the line of sight is recorded. Resurveys are usually made annually.

These lines of pins have been established at sites mostly in the western United States at different altitudes, precipitation, and vegetation. The characteristics of the sites and the results of measurements are summarized in Table 1.

An interesting aspect of these data is the progression of downhill motion with time as can be seen in the successive resurvey data, especially in the sites for which 6 to 9 years of data are available. The cumulative downslope motion at the ground surface is shown for several sites in Figures 1 and 2. The cumulative curves show that the amount of motion in successive years was about equal.

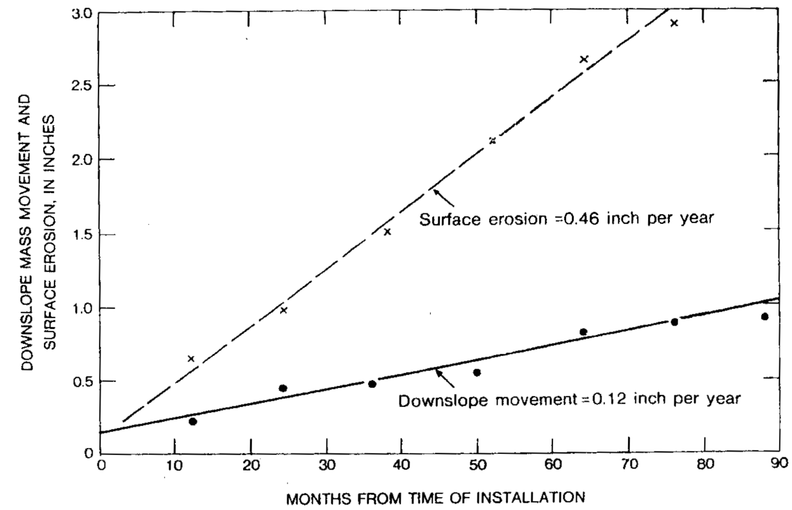
Because various individual pins on a given mass-movement line are on somewhat different local hillslope gradients, the downhill motion and the surface erosion at different pins can be plotted against the local gradient as in Figure 3. This graph shows that downhill motion increases slightly with gradient but is less sensitive to gradient than is surface erosion. Emmett concluded that of the sites studied where local gradient is less than 15° the hillslopes studied do not experience either surface erosion or downslope mass movement.

The next set of data concern downslope creep measured in modified Young Pits. The measurement procedure is that described in the review of field methods for hillslope studies, published in Revue de Geomorphologie Dynamique, p. 157, 1967. In brief, a pit is dug in the soil and into one face of the exposed undisturbed profile a narrow slot is dug into which is placed a vertical plate consisting of small rectangles of aluminum. This column of discrete plates is placed in a plane parallel to the contours. The location

TABLE 1. Downslope movement of iron pins on mass movement lines (from Emmett)

	Average local gradient (degrees)	Rock type	Soil depth	Vegetation	Elevation (ft)	Annual precipitation (in)	No. of years of observation	Average[1] downslope movement (in/y.)	Surface erosion (in/y.)
Coyote Arroyo, nr. Santa Fe, N.M.	25	Alluvium	3 ft	Pinon woodland	7,000	14	7	0.12	0.46
Slopewash Tributary, Santa Fe, N.M.	35	,,	,,	,,	,,	,,	9	.20	.40
Ski Basin Site, nr. Santa Fe N.M.	23	Granite	1–3 ft	Spruce	9,000	25	4	.30	0
Big View Site, Dickerson Park, Wyo.	21	Limestone	3–6 ft	Alpine grass	9,500	20	3	.14	.02
Twin Cabins Site, nr. Pinedale, Wyo.	18	Bouldery till	—	Sage, aspen	8,000	15±	2	.12	0
Forsaken Gully Site, nr. Moneta, Wyo.	35	Shale	3–5 ft	Sage	4,000	14	6	.34	.30
Last Day Gully Site, nr. Hudson, Wyo.	16	Shale	3–6 ft	Sage	4,000	12	5	0	.05
Aching Shoulder Site, Midden Rock, nr. Four Corners, Ariz.	31	Igneous rubble	—	Semidesert grass	4,000	8	5	0	.10

[1] Corrected to ground surface, and data are best graphical fit.



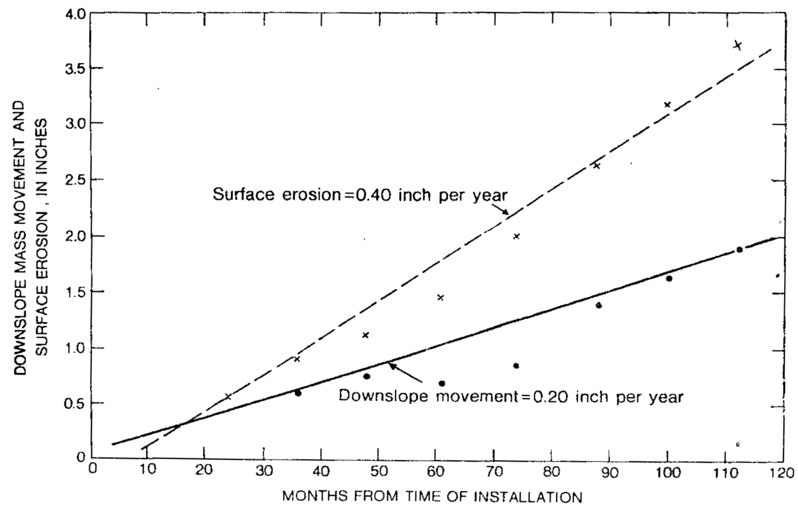
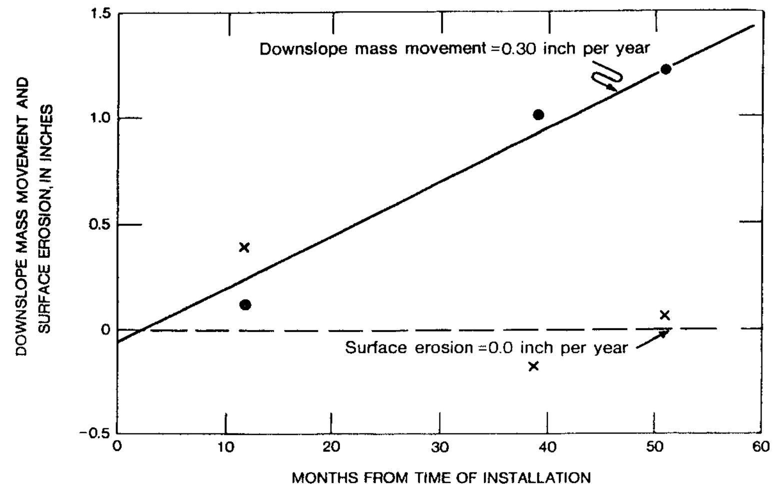


Fig. 1. Cumulative downhill creep and surface erosion measured by mass movement pins
upper — Coyote Arroyo; lower — Slopewash Tributary, both near Santa Fe, New Mexico, U.S.A. (from Emmett, 1971)

of each plate in the vertical column is determined by theodolite sighting between iron rods driven deeply in the ground to serve as bench marks. After installation and recording, the pit is filled.

Preferably two years later, the pit is re-excavated and the location of the plates resurveyed.



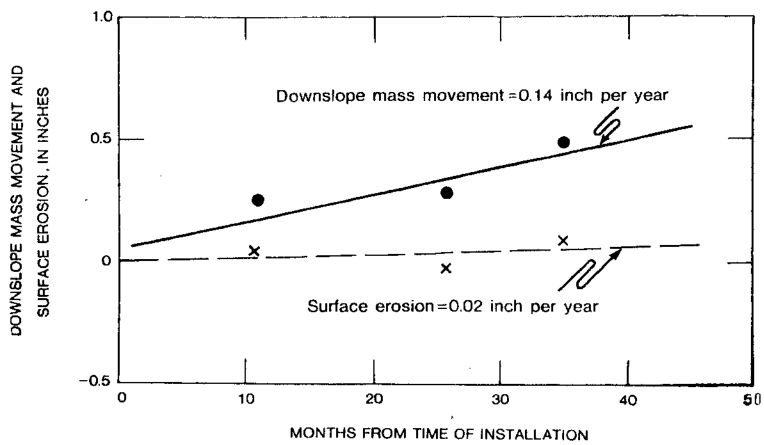


Fig. 2. Cumulative downhill creep and surface erosion measured by mass movement pins
upper — Ski Basin Slope near Santa Fe, New Mexico; lower — Big View Slope, Dickerson Park, Wyoming U.S.A. (from Emmett, 1971)

The data presented are for 6 such pits installed in 1964 or earlier and for which the latest resurvey was in 1971. The movement, therefore, represents that taking place over 7 years. The location is on wooded hillslopes in the headwaters of Cabin John Creek, a tributary to the Potomac River near Washington, D. C. The annual precipitation is 45 inches, most of which occurs in non-summer periods but there are heavy thunderstorms in summer which wet the soil for short periods. The soil is frozen for at least two winter months

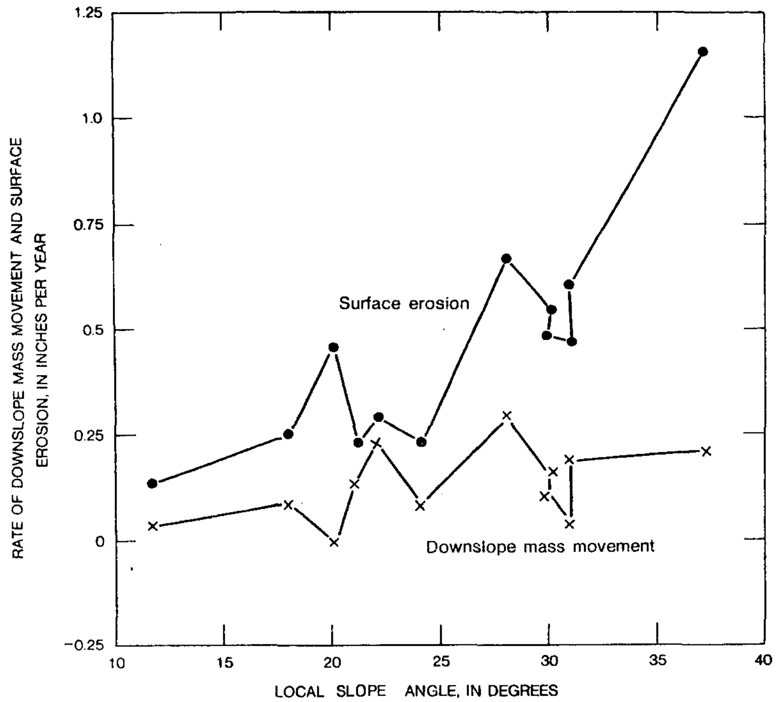


Fig. 3. Erosion and mass-movement rates as a function of local slope angle for mass movement pins, Coyote Arroyo near Santa Fe, New Mexico, U.S.A. (from Emmett, 1971)

and may remain moist for as long as four months during winter. It is presumed that downhill creep is concentrated in late winter and spring.

The soil material is deep, representing the Piedmont, which experienced long periods of weathering in pre-Pleistocene as well as Pleistocene time. Solid bedrock crops out in places within the study area but generally a weathered regolith at least 10 feet deep covers most of the hillslopes. The bedrock is gneiss containing veins of quartz which provide hard cobbles to the local streambeds. The forest is second growth, tulip-oak-hickory association.

In all except the earliest installations we drove an iron rod deep in the soil with the upper end at the level of the bottom of the excavated pit. This was to be a check on whether the bench marks (iron rods) exposed at the ground surface had been moved downhill as a result of soil creep. This procedure turned out to be most fortunate. When the 1971 surveys were compared with data at the time of installation, the buried bench marks appeared to have moved uphill in every pit where a buried rod was used. All pits for which buried bench marks were not used have been eliminated from the tabulation. These amounts of apparent uphill movement are shown at the bottom of Table 2 under the heading "Measured relative movement" and opposite "Buried Bench Mark".

A careful study was made of sources of error-instrumental, reading, and computing errors. We conclude that none of these sources could account for the apparent uphill movement of the buried rods. The best explanation is

TABLE 2. Measured and adjusted measurements of downhill creep in modified Young Pits Sisters area near Bethesda, Maryland, U.S.A., 1964–71 (7 years)

	Measured relative movement (cm)						Movement corrected by reference at depth (cm)						Probable actual movement (cm)					
Depth (cm)	Pit 1 plates	Pit 2 pins	Pit 4 plates	Pit 5 plates	Pit 7 plates	Pit 8 plates	Pit 1 plates	Pit 2 pins	Pit 4	Pit 5	Pit 7	Pit 8	Pit 1 plates	Pit 2	Pit 4	Pit 5	Pit 7	Pit 8
0	+0.08	.....	+0.28	+(2.26)	+3.52	(+1.33)	+0.18	.....	+0.56	(+1.96)	+0.652	+(1.51)	0±.2	.....	+.6±.2	(+2.0±.2)	+0.7±.2	(+1.5±.2)
3	+.13	.....	+.04	+.43	+3.91	+.07	+.23	.....	+.13	+.32	−.091	+.25		.....	+.3±.2	0±.2	0±.2	+.3±.2
6	+.12	+0.15	−.56	−.80	−.16	−.07	+.22	+0.88	−.28	−.50	+.14	+.11		+.9±.2	0±.2		0±.2	0±.2
9	+.17	.....	+.36	−.36	−.11	−.34	+.27	.....	−.08	−.06	+.19	−.16		.....				
12	−.08	−.30	−.30	−.44	−.08	−.23	+.02	+.37	−.02	−.14	+.22	−.05		+.4±.2				
15	+.15	−.47	−.28	−.42	−.22	−.66	+.25	+.26	0	−.12	+.07	−.48		0±.2		0±.2		
18	−.01	.....	−.03	−.50	−.23	−.24	+.09	.....	+.25	−.20	+.07	−.06						
21	−.06	−.44	−.33	−.54	−.23	−.32	+.04	+.29	−.05	−.24	+.07	−.14						
24	+.08	.....	−.59	−.48	−.16	−.14	+.18	.....	−.31	−.18	+.14	+.04						
27	+.03	−.40	−.28	−.48	−.23	−.12	+.13	+.33	0	−.18	+.07	+.06						
30	−.03	.....	−.30	−.58	−.16	−.07	+.07	.....	−.02	−.28	+.14	+.11						
34	+.01	−.50	−.30	−.62	−.16	.....	+.11	+.23	−.02	−.32	+.14	.....			0±.2		0±.2	0 ± 2
37	−.05	.....	.....	.....	.....	.....	+.05	.....	.....	.....	.....	.....						
40	+.03	.....	.....	.....	.....	.....	+.13	.....	.....	.....	.....	.....						
43	+.12	−.44	.....	.....	.....	.....	+.22	+.29	.....	.....	.....	.....						
46	−.16	−.60	.....	.....	.....	.....	−.06	+.13	.....	.....	....	.....		0±.2				
49	−.12	.....	.....	.....	.....	.....	−.02	.....	.....	.....	.....	.....						
52	−.20	.....	.....	.....	.....	.....	−.10	.....	.....	.....	.....	.....						
55	−.14	.....	.....	.....	.....	.....	−.04	.....	.....	.....	.....	.....						
58	−.23	.....	.....	.....	.....	.....	−.13	.....	.....	.....	.....	.....						
61	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0±.2					
Buried bench mark	−.10	−.73	−.28	−.30	−.30	−.18	.....	.....	.....	.....	.....	.....						

+ is downhill motion; — is uphill.
( ) indicates possible disturbance and thus doubtful record.
"Plates" refer to pits where flat aluminium plates were the markers moving downslope.
"Pins" refer to pits where markers are horizontal rods rather than flat plates.
Ground surface gradient at each pit: Pit 1, 34%; Pit 2, 35%; Pit 4, 54%; Pit 5, 40%; Pit 6, 25%; Pit 8, 30%.

that the iron rods extending from the surface downward and marking the line of sight from which the movement of installed plates is measured have also moved downhill. Therefore, the observed movement of plates at various depths below the surface have been corrected by adding to observed relative movement that of the buried bench mark. These corrected values appear in the center section of Table 2.

In the right hand section of the table the final results are presented as probable amounts of downhill motion, with a confidence limit for each. The

TABLE 3. Erosion and deposition in channel of Watts Branch near Rockville, Maryland, U.S.A., determined by annual remeasurement of monumented cross-sections (Drainage area, 3.7 sq. mi.)

Cross-section name	Channel area original (sq.ft)	Channel area 1970[1] (sq.ft)	Number of years	Ratio: 1970 area / original area	Percent change channel area per year %	Bed elevation change (ft)
1–2	73.1	56.5	17	0.77	−1.3	+0.4
1–4	106.8	53.5	17	.50	−2.9	+.8
1–5	74.8	52.7	17	.70	−1.7	−.1
44A–45	49.6	28.0	9	.56	−4.8	−.4
48–10	29.5	38.6	8	1.31	+3.9	−.5
40–41	31.7	31.8	8	1.00	0	−.2
15–17	133.0	74.3	17	.56	−2.6	+1.3
42–43	100.0	64.5	8	.64	−4.5	+.6
15–18A	85.0	59.0	17	.69	−1.8	+.3
35–34A	37.8	38.8	12	1.02	0	+.3
32–33	52.1	58.9	14	1.13	+.9	+.6
46–47	50.1	30.9	11	.62	−3.4	0
22A–47	60.2	41.7	17	.69	−1.8	−.5
25A–23A	72.8	59.0	17	.81	−1.1	+.7
22–24	58.2	41.6	17	.71	−2.4	+.4
Average all data	67.2	48.6		.78		
Average for 17-year data only	83.0	54.9	17	.66	1.7	+.4

[1] Includes some deposition on flood plain which is not within the channel as usually defined.

confidence, usually 2 mm, represented the average of the uphill or downhill corrected movement values at a depth where it may be assumed no movement is occurring.

The results indicate that despite the thick layer of regolith, downhill creep was measurable by our methods only in the upper 3 to 6 cm. The amount of this motion — even in the upper layers — was less than the measurement error in two out of six pits. The amount of movement varied from 0 to 9 mm in 7 years.

Our conclusion is that in this area of 45 inches (114 cm) of annual precipitation, a locality of deep soil material, and in an open hardwood forest, soil creep occurs only in the topmost 6 cm and at a rate of about $^1/_2$ mm/year.

For such small rates of movement, measurement methods deserve careful consideration and care in their use.

The third set of data summarized here concerns changes in the channel of a small perennial stream, Watts Branch, a tributary to the Potomac River, which drains westward about 15 miles north of Washington, D. C. The measurements were made in an alluvial valley through which this stream meanders at a place where its drainage area is 3.7 square miles (9.6 km^2). Land use is principally for agricultural crops. The average annual discharge is 3.22 cfs (.091 m^3/s). In the study area, along a river distance of 700 feet (213 m), the width of water surface at low flow is 13 feet (4 m) and at bankfull, 19 feet (5.8 m). The river slope is .00397.

In 1953, Leopold established a series of channel cross sections, the ends of which were secured with iron posts driven below the ground surface so that they could be relocated by measurement but would not be disturbed by surface use. These cross sections have been resurveyed every year. Some had to be abandoned due to lateral movement of the channel and other new ones were installed. As of 1970, there were annual resurvey data available for 17 years for 8 cross sections and a minimum of 8 years of record for the others.

The changes in the cross sectional area of channel are summarized in Table 3. The land use in the surveyed zone has been pasture. During the 17 years urbanization has encroached on portions of the headwaters. The progressive decrease of channel area can at least in part be attributed to the increased loads of suspended sediment attributed to land opened for construction. The construction of houses has decreased the amount of drainage area devoted to farming, but even in 1970 the majority of the area is still farmland.

In the 17 years the channel has decreased in cross-sectional area an average of 1.7% per year. For those cross sections measured during the full 17 years, the 1970 channel is 0.66 that existing in 1953, a loss of 28 square feet out of an original 83 square feet. Most of this is due to narrowing by the plastering of silt on channel banks. The width-depth ratio has decreased. The streambed elevation has risen 0.4 foot but the channel slope has not changed significantly.

There has been deposition overbank, near the channel but outside the usual high water channel. This, however, is not uniform, but only in some locations. The importance of this overbank or out-of-channel deposition has not yet been analyzed.

The channel has moved laterally in some places a large amount, but in some sections no lateral change of position has occurred. The largest lateral movement on any cross section was 20 feet or about one channel width.

More details worthy of note are contained in the data but omitted here for brevity. Photographs of the channel, a description of the bank erosion process, and a map of portions of the study area have been published (Leopold, et al., p. 87, 88, 325, 468).

United States Geological Survey, Washington, D. C.

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