Sediment movement in disequilibrium gully-fan systems

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Abstract. Evolution of gully-fan systems on reclaimed spoil piles permit analysis of sediment movement in fluvial systems dominated by ephemeral flow. Sediment budget investigations indicate sediment yield fluctuates temporally and spatially depending upon sediment availability and size; local channel slopes; and storm timing and intensity. Generally, gullies display cyclic sediment production and erosion. Along fans, channels either simultaneously cut or fill during individual storms from fall through spring or they cut or fill along the length of the fan during intense summer storms.

INTRODUCTION

In humid central Pennsylvania, surface coal mining often takes place along upper hillslope segments due to minimum overburden thickness. Following mining, strip mine operators backfill and restore slope forms to their approximate original pre-mined contour as required by law (Surface Mining Conservation and Reclamation Act, 1971). Operators then replace topsoil, re-seed, and install water and sediment control structures, such as water diversions and ponds, to check sediment movement within reclaimed areas and to prevent off-site erosion and sedimentation. Once reclaimed, hillslopes are left to stabilize with additional remedial surface reclamation measures taken only where needed.

During the years that follow reclamation, hillslope erosion proceeds rapidly. Unlike the pre-mined, creep-dominated slope, reclaimed surfaces have sparse vegetation, impermeable soils, and long, uninterrupted drainage basins. Consequently, fluvial processes prevail, dominated by short-duration storm discharge with high peak flow rates. Infiltration capacities are quickly exceeded during high intensity, short-duration rainfall, producing runoff that integrates rapidly and flows quickly down gradient along any slope declivity. In many cases, excess runoff cannot be diverted from spilling over the oversteepened, abrupt outslopes that typify the reclaimed hillslopes studied in Pennsylvania and, consequently, severe erosion occurs as gullies develop, eroding concave fluvial profiles over outward convex slope forms.

Gullies predominate along the reclaimed surfaces studied in central Pennsylvania, many of which drain small areas. All gullies studied are morphologically similar to the valley-side gully type, discussed in Harvey, M.D. *et al.* (1985).

Gullies that drain larger areas have proven to be unstable, yielding large volumes of sediment that are transported for relatively short distances within short periods of time. The larger gully types contain well-developed alluvial fans, channel slopes and widths of which affect flow and control sediment yields from the gullies.

Because of their hydrological interdependency, the gullies and related fans are referred to here as gully-fan systems.

This research focuses upon sediment movement within and yield from disequilibrium drainage systems dominated by ephemeral flow and how sediment transport is controlled by basin morphology; sediment availability; storm character and timing; and stream power magnitude. Fifteen gully-fan systems, located along reclaimed hillslopes in central Pennsylvania, were studied. Only those basins that contain well-developed drainage basin limits and one primary convex outslope element were selected. Areas were mined during the early 1970's and were subject to contemporary reclamation laws. Reclamation within these areas continued through 1979. Gully-fan systems found at each site were initially surveyed during 1982 to determine sediment yields, and to describe overall drainage basin morphology. These areas were similarly studied during 1983-84 to determine which gully-fans have stabilized. For those that continued to evolve, detailed plane table maps, cross channel and logitudinal channel surveys, and grain size analyses were completed. In addition, rain gauges and flume stream-gauges were installed. Maps, channel surveys, and grain size analyses were conducted at intervals determined by episodes of sediment movement and, in all, ten episodes over a one-and-one-half annual cycle were studied. Additional rainfall and freeze-thaw data were obtained from the nearest recording station.

RESULTS

Table 1 contains drainage basin and channel dimension data, collected during the summer of 1982, for fifteen separate gully-fan systems. Data are arranged in increasing order of drainage basin size. Regression analysis of the data indicate that gully volume and, hence, sediment yield due to gullying is not only correlated (equations provided in Table 1) to drainage basin length and drainage basin width but also to the maximum relief of the convex outslope of the reclaimed spoil pile itself. Gully volume is also correlated (r squared = 0.85) to channel length, which, in addition to maximum outslope angle is also dependent upon drainage basin length. Follow-up field surveys reveal that most gullies have stabilized. The larger, more unstable gullies, however, were still active. The most unstable gully (Number 12) yielded 3777 cubic metres of sediment over 3 years.

Figure 1a is an oblique aerial photograph of a typical, large, unstable gully-fan system (Number 15, Table 1) that has been evolving along a reclaimed hillslope since 1976. The gully and fan segments are indicated as G and F, respectively. Figure 1b is a photograph of the backfilled spoil as exposed along a section of sidewall, an exposure revealing the coarse grained and poorly sorted character of backfilled spoil in the area. Figure 1c shows fan head incision, whereas Figure 1b shows fill located distally down the fan channel. A plane table map outlining the gully-fan is presented in Figure 1e; also presented are the cross section profile locations that were surveyed to produce estimates of gully erosion and fan deposition. Between 1976 and 1982, 1838 cubic metres of spoil were eroded from the gully and allocated to various storage sites. Shown also in Figure 1e are grain size and sediment volume distributions allocated to the knickpoint, gully channel, fan, and fan channel sediment storage sites. The upper curve of each is the total volume distribution, in hundreds of cubic metres of grain sizes eroded from the gully. Areas darkened in each distribution show volumes of various grain sizes

TABLE 1 Summary of drainage basin and gully dimensions

NO	B	BL	BW	BR	A	MR	CHL	CHLM	L	W	D	VOL
1	.4	228	24	23	.6	8	160	61	25	6	3	102
2	1	268	73	52	.3	17	161	147	59	6	3	182
3	1	288	54	23	.4	15	205	153	50	5	3	148
4	1	244	46	35	.5	2	230	61	49	2	2	51
5	2	213	91	23	.6	10	449	284	55	9	5	480
6	2	213	122	13	.1	7	129	96	70	2	2	139
7	5	456	175	17	.1	4	379	275	43	5	3	137
8	5	292	219	21	.2	5	230	61	54	8	4	290
9	5	320	213	15	.2	4	119	174	35	3	1	43
10	5	286	274	12	.1	4	570	458	33	4	1	44
11	6	512	480	52	.3	17	956	387	63	9	5	346
*12	11	634	268	52	.2	15	3009	377	94	18	7	3777
13	11	532	266	34	.1	6	1612	1751	120	5	3	410
14	18	560	488	31	.4	9	1847	1139	85	7	4	518
*15	21	640	292	47	.2	5	1668	1277	96	12	6	1838

No = Drainage basin and gully-fan system number

Independent variables:

B = Drainage basin area (hectares)
BL = Drainage basin length (metres)
BW = Drainage basin width (metres)
BR = Drainage basin relief (metres)
A = Outslope angle (degrees)
MR = Maximum outslope relief (metres)

Independent variables:

CHL = Sum of rill and minor gully channel lengths above main gully (metres)
CHLM = Sum of inter-channel lengths in drainage basin (metres)
L = Maximum gully length (metres)
W = Maximum gully width (metres)
D = Maximum gully depth (metres)
VOL = Gully volume (cubic metres)

* active gully

Stepwise regression equations:

VOL = -1492 + 6.39 BL -3.46 BW + 46.33MR
CHL = -1509.8 + 5.2 BL + 1140A

Multiple R	R squared	Adjusted R squared
0.80	0.63	0.53
0.89	0.79	0.76

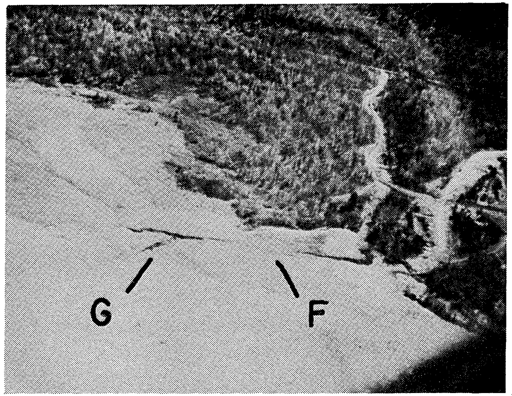


Figure 1 a.

Figure 1 b.

Figure 1 c.

Figure 1 d.

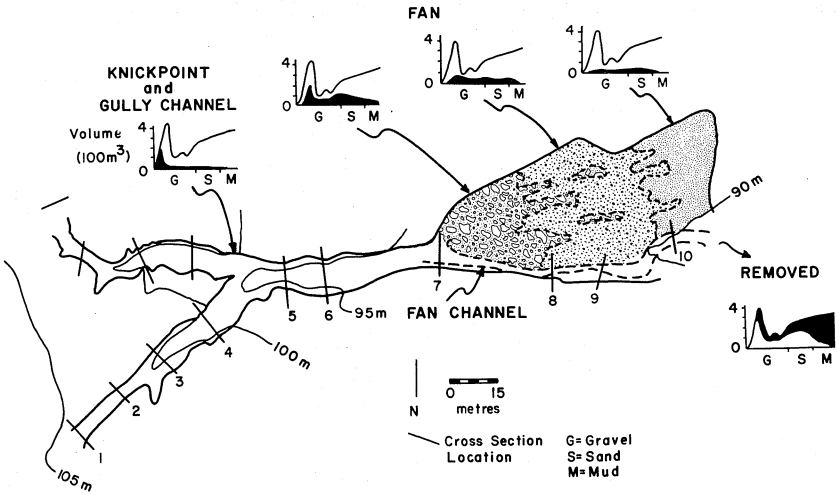


Figure 1 e.

Fig. 1 Gully-fan located at Snow Shoe, Pennsylvania. (a) Oblique aerial photograph; (b) backfilled spoil, scale in tenths of a metre; (c) a one metre fan head incision; (d) distal fan channel fill, large clast is 5 cm; (e) plane table map.

from 0.14 to 0.42 degrees; widths, although generally narrower during the winter, ranged from 0.7 to 3.3 m. No seasonal trend to slopes and widths for either the gully or the fan channel were noted. Gully channel slopes and widths ranged from 0.09 to 0.14 degrees and from 1.5 to 6.0 m, respectively. Fan channel slopes ranged from 0.05 to 0.07 degrees, while widths ranged from 2.5 to 8.0 m. accessed from the total volume mobilized and allocated to the various storage sites. Material removed from the system is also darkened on Figure 1e (Lower right). At the time of measurement, the fan channel storage site was empty, having recently been swept clean of fill.

Figure 2 contains longitudinal and cross channel surveys collected at Snow Shoe during 1982-83. Ten profiles, (Figure 1e) corresponding to those found along the more active portion of the system, were surveyed. Vertical tick marks indicate cross channel profile locations. Darkened areas denote sites of sediment fill, while areas enclosed in dashes denote sediment removal or cut. Spatial transfers of sediment from the knickpoint, to the gully and, ultimately, to the fan can be traced from left to right within each sample interval. Temporal changes through the ten sample intervals can be traced from top to bottom.

Sediment budgets over a one-and-one-half annual cycle for both the gully and fan segments at Snow Shoe are shown in Figure 3. Along the upper diagram in Figure 3 are rainfall and freeze-thaw data obtained on-site and from a recording station at Philipsburg, located approximately 27 km to the southwest. Data plotted in the lower diagram represent net sediment volumes stored during each of the ten sample intervals. By comparison, these two diagrams indicate that gullies store sediment in the winter and produce sediment during all other times. On the other hand, fans can either erode or store sediment throughout the year.

Additional sediment budget relationships for sample intervals 3 to 10 are provided in Table 2. This table also compares volume yields to flow, rainfall, and stream power conditions. Similar to Figure 2, spatial yields of sediment from the knickpoint, to the gully and, ultimately, from the fan, can be traced across the columns along each sample interval. Listed also are rainfall character and peak flow discharge data corresponding to the erosive rainfall event. Stream power values are also provided and were calculated from peak flow rates, found in the table, and from pre-flow slope and width conditions. Knickpoint slopes, steepest during the summer, ranged

DISCUSSION

During the years following reclamation, hillslope erosion proceeds rapidly. In cases where excess surface runoff is allowed to spill over convex slope forms, gullies develop. The larger, the better-integrated, and the higher the outslopes of the reclaimed drainage basin, the further the gully-fan system will be from equilibrium. Gullies draining smaller areas quickly stabilize within several years. Larger gullies, however, require longer periods of time to stabilize and yield larger volumes of sediment through gully expansion.

Most of the sediment introduced into these unstable gully-fan systems occurs through erosion of the gully itself, either from freeze-thaw or mass movement processes active along the sidewalls during colder months or from channel sidewall and bottom scour generated during warmer months (a process also noted by Howard and

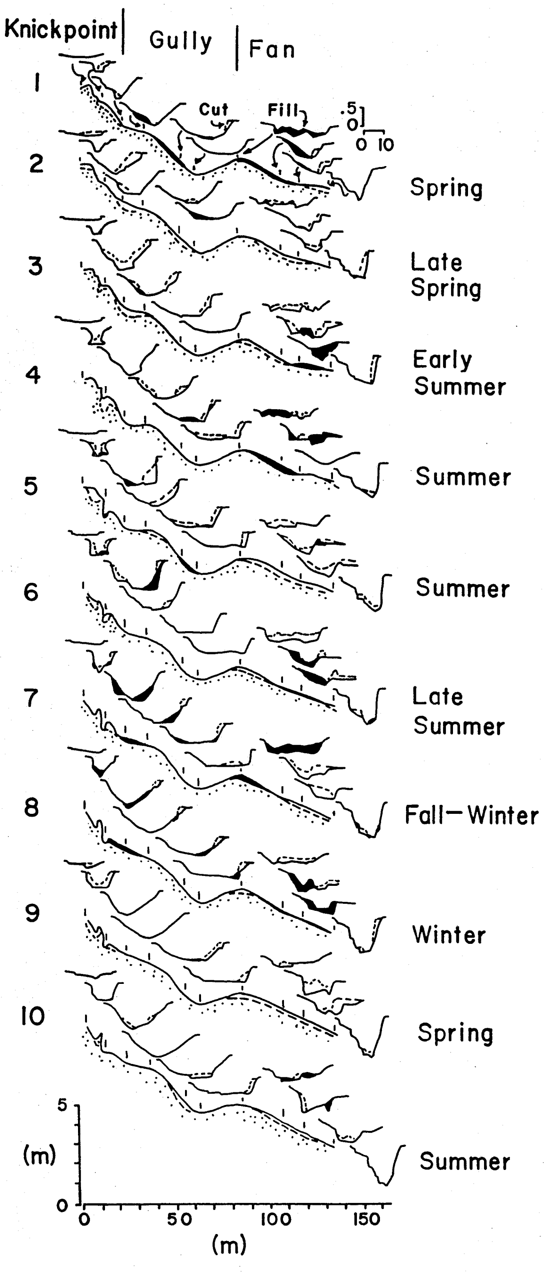
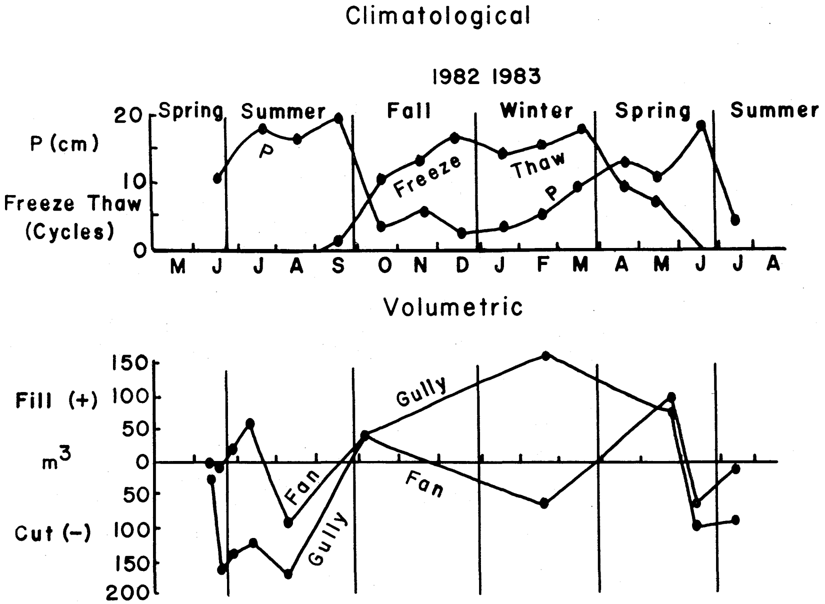


Fig. 2. Spatial and temporal cut and fill changes for a gully-fan located at Snow Shoe, Pennsylvania. Profile numbers also correspond to sample interval.



Climatological

Volumetric

Fig. 3. Sediment budget relationships for the gully and fan portions of the Snow Shoe gully-fan system.

Kerby, in 1983, for fluvial channels rapidly evolving after vegetation removal in the coastal plain of Virginia. During the first few years of gully expansion, much of the coarse sediment eroded from the gullies remain stored in adjacent alluvial fans. As gully and fan channels integrate, the suspension load as well as much of the coarse-

TABLE 2 Summary of sediment volume yields, rainfall, and flow character.

	Knickpoint		Gully		Fan					
NO	Qs	SP	Qs	SP	Qs	SP	Qm	T	Dur	Mxint
3	141	74	164	10	151	3	.26	1.4	1.6	3.9
4	30	60	130	57	75	12	.60	3.9	1.1	7.7
5	78	128	184	21	275	8	.46	4.2	1.9	3.8
6	14	39	31	10	71	4	.48	3.8	4.5	4.5
7	20	48	30	9	66	4	.24	2.3	17.8	0.3
8	00	23	00	12	00	3	.27	2.4	22.9	0.2
9	75	15	109	8	192	44	.18	2.0	11.0	0.3
10	47	62	91	17	94	7	.49	5.5	17.5	0.9

NO = Sample interval number
Qs = Sediment volume yields (cubic metres)
SP = Maximum stream power (kg/sec/m)
Qm = Peak discharge flow (cubic metres per second)
T = Rainfall total (cm)
Dur = Duration of rainfall (hrs)
Mxint = Maximum rainfall intensity (cm/hr)

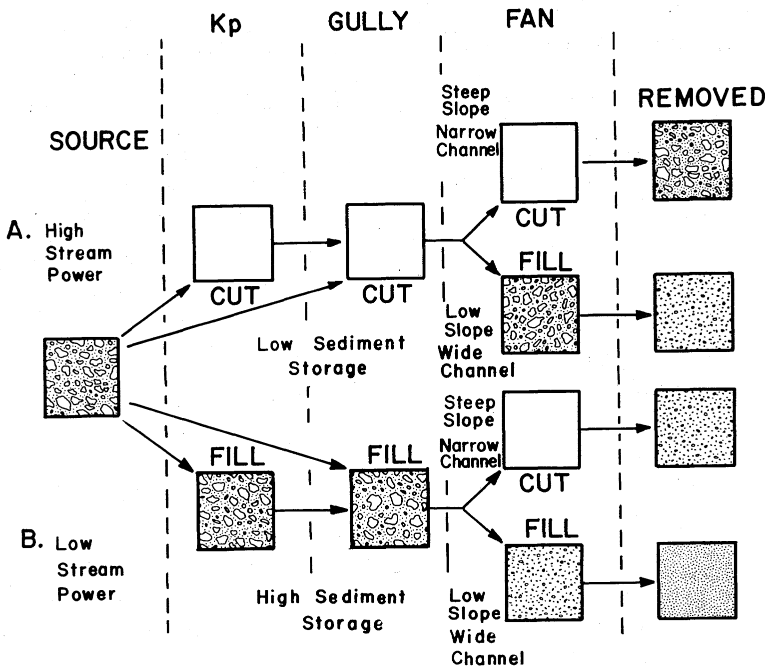


Fig. 4. Seasonal cut-and-fill paths for the disequilibrium gully-fans: located in central Pennsylvania. A is a summer cut-and-fill path, while B is a fall through spring path. Kp refers to knickpoint.

grained material transported as traction and saltation loads migrate from the system entirely. Total sediment yields fluctuate annually and spatially depending upon sediment availability and size; storm intensity and timing; and stream power.

Figure 4 illustrates the manner in which these disequilibrium gully-fan systems transfer sediment mobilized from a coarse-grained, poorly-sorted source. From the source, two paths can be taken: (1) an upper, summer-cut-and-fill path (A in Figure 4) influenced by high stream power generated during short duration, high intensity, storms; and (2) a lower fall through spring cut-and-fill-path (B in Figure 4) influenced by lower stream powers developed during longer duration lower intensity rainfall events.

Along the upper path, all grain sizes are mobilized through knickpoint and gully cutting. If the gully flow has high stream powers and if local antecedent slopes along the fan are steep and channels narrow, much of the sediment can be entirely removed from the system producing coarse-grained, distal floodplain fills. However, if local antecedent slopes are low and channels wide, coarse fan head fills are likely to occur. Along the lower path all grain sizes again are mobilized; however, lower stream powers move grains finer than that moved during the summer or upper path now producing finer-grained floodplain fills. As these gully-fan systems equilibrate by eroding convex outward slopes, sediment moves in pulses within annual cyclic time scales and in storm-by-storm time scales. Moreover, various grain sizes are allocated to different storage sites responding to local stream power conditions generated during storm events.

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