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Assessment of Effectiveness of Geologic Isolation Systems

GEOLOGIC FACTORS IN THE ISOLATION OF NUCLEAR WASTE: EVALUATION OF LONG-TERM GEOMORPHIC PROCESSES AND CATASTROPHIC EVENTS

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PREFACE

Associated with commercial nuclear power production in the United States is the generation of potentially hazardous radioactive waste products. The Department of Energy (DOE), through the National Waste Terminal Storage (NWTS) Program and the Office of Nuclear Waste Isolation (ONWI), is seeking to develop nuclear waste isolation systems in geologic formations. These underground waste isolation systems will preclude contact with the biosphere of waste radionuclides in concentrations which are sufficient to cause deleterious impact on humans or their environments. Comprehensive analyses of specific isolation systems are needed to assess the post-closure expectations of the systems. The Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program has been established for developing the capability of making those analyses.

Among the analyses required for the system evaluation is the detailed assessment of the post-closure performance of nuclear waste repositories in geologic formations. This assessment is concerned with aspects of the nuclear program which previously have not been addressed. The nature of the isolation systems (e.g., involving breach scenarios and transport through the geosphere) and the great length of time for which the wastes must be controlled dictate the development, demonstration, and application of novel assessment capabilities. The assessment methodology must be thorough, flexible, objective, and scientifically defensible. Furthermore, the data utilized must be accurate, documented, reproducible, and based on sound scientific principles.

The current scope of AEGIS is limited to long-term, post-closure analyses. It excludes the consideration of processes that are induced by the presence of the wastes, and it excludes the consideration of nuclear waste isolation in media other than geologic formations. The near-field/near-term aspects of geologic repositories are being considered by ONWI/DOE under separate programs. They will be integrated with the AEGIS methodology for the actual site-specific repository safety analyses.

The assessment of repository post-closure safety has two basic components:

- identification and analyses of breach scenarios and the pattern of events and processes causing each breach;
- identification and analyses of the environmental consequences of radionuclides transport and interactions subsequent to a repository breach.

The Release Scenario task is charged with identifying and analyzing breach scenarios and their associated patterns of events and processes.

The Release Scenario task is concerned with evaluating the geologic system surrounding an underground repository and describing the phenomena which alone or in concert could perturb the system and possibly cause a loss of repository integrity. Output from the Release Scenario task will establish the boundary conditions of the geology and hydrology surrounding the repository at the time of an identified breach. These bounding conditions will be used as input for the consequence analysis task, which will employ sophisticated hydrological transport models to evaluate the movement of radionuclides through the groundwater system to the biosphere.

The Release Scenario task has contracted with a number of consultants to obtain expert scientific opinion about the geologic processes which could affect an underground repository. The consultants were asked to specify processes and events which might affect potential repository sites and, if possible, to give rates and probabilities for those phenomena. The consultants have also been involved with the description of the system interactions and synergisms.

This report contains information obtained by one of the AEGIS consultants during the FY-1978 research effort. The research described in this document is being continued during FY-1979 and FY-1980. Because of the ongoing nature of the Release Scenario methodology development effort, many of the results and conclusions outlined in this report are subject to change upon completion of additional research and analyses. The information contained in this report is based upon the expert opinion of an individual consultant and should be treated as such.

SUMMARY

SRI International has projected the rate, duration, and magnitude of geomorphic processes and events in the Southwest and Gulf Coast over the next million years. This information will be used by the Department of Energy's Pacific Northwest Laboratory (PNL) as input to a computer model, which will be used to simulate possible release scenarios and the consequences of the release of nuclear waste from geologic containment. The estimates in this report, although based on best scientific judgment, are subject to considerable uncertainty.

An evaluation of the Quaternary history of the two study areas revealed that each had undergone geomorphic change in the last one million years. The Lower Mississippi River Valley, in particular, was periodically trenched and then aggraded as a result of the advance and retreat of glaciers to the north. The Southwest experienced continued tectonic and volcanic activity in the Quaternary, with lakes forming in many of the closed tectonic basins during the Pleistocene. The Grand Canyon went through a period of rapid downcutting during middle to late Pliocene, with estimated rates as fast as 0.33 $m/10^3$ year.

The long-term geomorphic processes evaluated in this study were denudation, entrenchment, and aggradation. Denudation was found to be an important mechanism of overall basin lowering, and estimates of probable future denudation rates were derived. Entrenchment will occur in the major river basins of the Southwest and Gulf Coast. The rate of entrenchment in the Southwest is closely tied to the projected rate of tectonic uplift in the region. Aggradation will occur in the Gulf Coast during the waning stages of glaciation. The volume deposited by aggradation of the river bed should be assumed to equal the volume removed through entrenchment. A summary of this information is presented in Table 1.

Catastrophic events were evaluated in order to determine their significance to the simulation model. Given available data, catastrophic floods are not expected to occur in the two study areas. Catastrophic landslides may occur in the Southwest, but because the duration of the event is brief and

TABLE 1. Summary of Projected Rates for Geomorphic Processes

	Rate		Total Erosion after 10^6 yr	
	Average ($m/10^3$ yr)	Maximum ($m/10^3$ yr)	Average (m)	Maximum (m)
Denudation				
Gulf Coast	0.05	0.15	50	150
Southwest	0.10	0.30	100	300
Entrenchment				
Gulf Coast				
Mississippi River near mouth	50[a]	75[b]	100[c]	150[c]
200 km upstream	6[a]	20[b]	30[c]	40[c]
Southwest[d]	0.20	1.0	200	1,000
Ashfalls[e]				
Gulf Coast[f]	$X10^1$	$X10^2$	Unknown	Unknown
Southwest[f]	$X10^2$	$X10^3$	Unknown	Unknown

(a) Assumes 5,000 years for entrenchment period.
(b) Assumes 2,000 years for entrenchment period.
(c) Erosion occurring during each full glacial period. A period of aggradation follows entrenchment and tends to replace the removed sediment.
(d) Assumes uplift comparable to Late Mesozoic.
(e) Other catastrophic events considered were landslides and floods.
(f) These figures represent the order-of-magnitude increases in denudation expected.

Source: SRI

the amount of material moved is small in comparison to regional denudation, such events need not be included in the simulation model. Ashfalls, however, could result in removal of vegetation from the landscape, thereby causing significant increases in erosion rates (see Table 1). The probability of ashfalls occurring in the two study areas is being investigated by another geologic consultant to PNL.

Because the estimates developed during this study may not be applicable to specific sites, general equations were presented as a first step in refining the analysis. These equations identify the general relationships among the important variables and suggest those areas of concern for which further data are required. If the current model indicates that geomorphic processes (taken together with other geologic changes) may ultimately affect the geologic containment of nuclear waste, further research may be necessary to refine this analysis for application to specific sites.

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ACKNOWLEDGEMENT

This research was supported by the Waste Isolation Safety Assessment Program (WISAP) conducted by Pacific Northwest Laboratory. The program was sponsored by the Office of Nuclear Waste Isolation, managed by Battelle Memorial Institute for the Department of Energy under Contract EY-76-C-06-1830. On 1 October 1979, WISAP became the Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program and the Waste/Rock Interactions Technology (WRIT) Program. This report was issued by AEGIS.

INTRODUCTION

BACKGROUND

The federal government is planning to construct repositories for the terminal storage of radioactive wastes. The radioactive wastes to be stored include unreprocessed fuel rods and low-level wastes from components of the nuclear fuel cycle. Waste containers will be placed in an underground repository in a selected lithologic unit. Present investigations for suitable geologic containments are primarily focusing on the bedded salt of the Southwest, the Columbia River Plateau basalts in Washington, and the Gulf Coast salt domes.

Radioactive wastes may endanger life if they are prematurely released into the biosphere, so the potential effects of possible disruptive events or processes on the integrity of the waste repositories must be evaluated. Pacific Northwest Laboratory (PNL) has undertaken such a study for the Department of Energy through the office of Nuclear Waste Isolation. The Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) program is developing a computer-assisted methodology to simulate possible release scenarios and the consequences of the release. Geological consultants were employed to establish the boundary conditions for the release scenarios. PNL contracted with SRI International to provide preliminary geomorphologic data for the Southwest and the Gulf Coast for input to the methodology.

APPROACH

We have projected the rate and duration of geomorphic processes and events in the Southwest and the Gulf Coast over the next million years. We have also projected the magnitude of changes from these processes and events.

To do so we have reviewed the pertinent literature; evaluated the geomorphic history of each region, especially during the Quaternary Period; identified the geomorphic processes and events likely to be significant in the two regions of interest; and finally estimated the average and worst-case conditions expected over the next million years. Given funding and time limitations, this research is considered an initial analysis.

DESCRIPTION OF THE STUDY AREAS

EXISTING GEOMORPHIC ENVIRONMENT

Figure 1 indicates the locations of the two study areas. The landforms, climate, and geomorphic processes common to each differ substantially.

Gulf Coast

The Gulf Coast, which is within the Coastal Plains physiographic province, is characterized by rolling uplands with young to mature coastal plains. The flood plain and delta of the Mississippi River are the major geomorphic features of the area.

The humid subtropical climate of the region is characterized by relatively mild and humid winters and uniformly hot and humid summers. Cold, dry, polar or arctic air masses occasionally reach the Gulf in winter, bringing frost and sometimes snow. The Gulf is also subject to Atlantic hurricanes that cause storm surges, strong winds, heavy rains, and coastal flooding. Average annual precipitation ranges from 81 cm in east Texas to 163 cm at the mouth of the Mississippi River.

The soils in the region have developed from marine sands and clays, and are predominately sandy, acidic, and low in fertility. Approximately 20% of the soils are considered to be subject to moderate to severe erosion (Pearson and Ensminger 1957). The lush vegetation is primarily mixed southern hardwood forest.

Southwest

The Southwest is diverse in both physiography and climate. The area extends over four physiographic provinces: Basin and Range, Colorado Plateau, Southern Rocky Mountains, and the Great Plains. The Basin and Range province (Nevada, western Utah, southern Arizona, and New Mexico) is characterized by dissected fault-block mountains with associated large alluvial fans and bajadas. Depending on the elevation, the climate is arid to semiarid. The Colorado Plateau (eastern Utah, northern Arizona, northwestern New Mexico) ranges from 900 to more than 3,000 m in elevation. It is generally a well-dissected structural plateau and includes the Uinta Mountains and Canyonlands

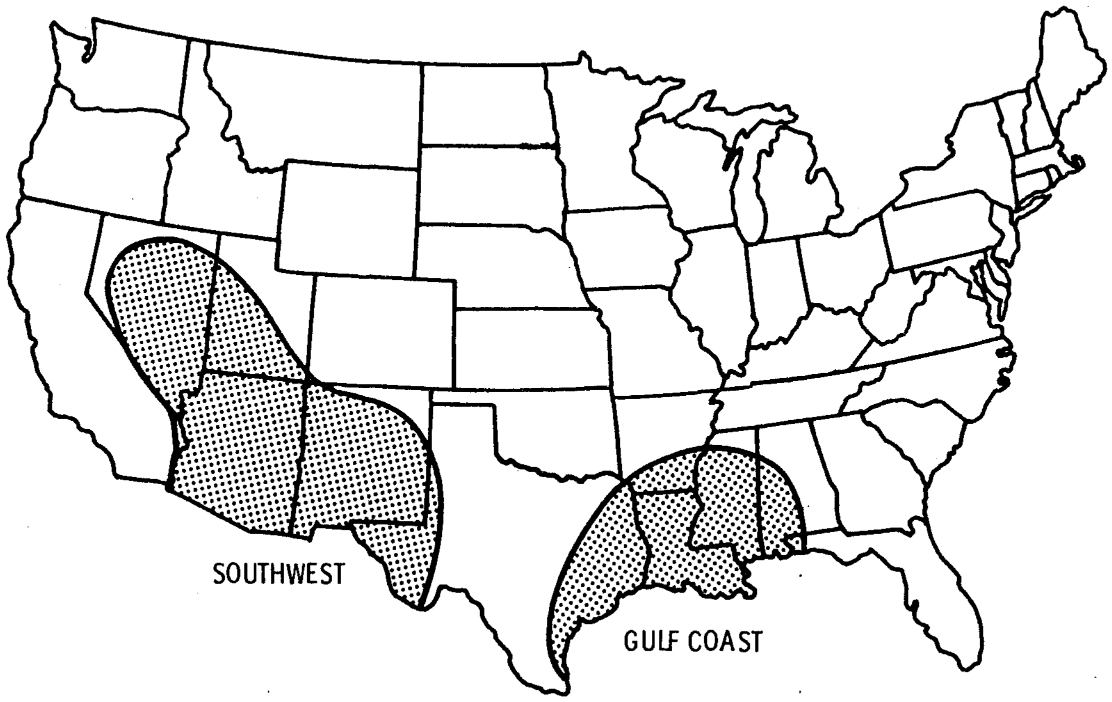


FIGURE 1. Location of Study Areas

in Utah and lava flows in New Mexico. The climate is semiarid, except above 3,000 m where it is mountain or alpine. The Southern Rocky Mountain province in north central New Mexico has steep, precipitous mountains (Sangre de Cristo range) and open, grassy valleys (San Luis Valley). Depending on the elevation, the climate ranges from semiarid to alpine. The Great Plains in eastern New Mexico are comprised of rolling hills and high plateaus with some entrenched streams. Climate in this province is generally semiarid.

The Colorado is the major river basin in the Southwest. It drains eastern Nevada, all of Utah, all of Arizona, and portions of northern and western New Mexico. The remainder of New Mexico falls within the Rio Grande River Basin. Much of southern and central Nevada has internal drainage.

The major geomorphic feature of the Southwest, and perhaps of the world, is the Grand Canyon. The canyon resulted from downcutting by the Colorado River as the surrounding land was being uplifted, and it is more than 1 mile (1.6 km) deep in some places.

QUATERNARY GEOMORPHIC HISTORY

The Quaternary Period (1,800,000 years B.P. to present) wrought significant geomorphic changes on the face of the earth. Because this period coincides with the most recent million years of the earth's history, its geomorphic changes have been reviewed to provide a basis for predicting future conditions.

Gulf Coast

Widespread Pleistocene glaciation was accompanied by a eustatic fall in sea level that led to entrenchment and deepening of the Mississippi River Valley near the Gulf of Mexico. The maximum depth of entrenchment probably was equivalent to the minimum level of the ocean, or approximately 120 m (Seyfert and Sirkin 1973). At the same time, the upper part of the Lower Mississippi Valley was being widened and deepened. Braided streams were common. Major tributaries to the Mississippi, such as the Missouri and the Tennessee, increased their discharges, thereby causing valley degradation and terrace formation. Maxwell (1971) estimates that river entrenchment in Alabama increased by a factor of three during the Pleistocene (see Table 2).

Maximum aggradation of the Lower Mississippi Valley occurred in the waning stages of the last Wisconsin glaciation and lasted no more than a few thousand years (Saucier 1974). The Mississippi River altered from braided to meandering when the ratio of sediment to water decreased sufficiently to begin degradation. This change occurred approximately 12,000 years B.P. at Baton Rouge and 6,000 years B.P. north of Memphis. During the most rapid phase of deglaciation, from about 10,000 to 7,000 years B.P., sea level may have risen at a rate of 1 cm/yr (Bloom 1978).

The deltaic plain of the Mississippi River was structurally active during the Quaternary. Estimates of movement are shown in Table 2.

During the Holocene (10,000 years B.P. to present), little change has occurred in the Lower Mississippi Valley. Deltaic deposition in Louisiana occurred as the sea level rose. In the last few thousand years, the Mississippi River has continued slowly to aggrade its flood plain and to build its delta across the continental shelf.

TABLE 2. Quaternary Changes in the Mississippi River Basin

Entrenchment in Alabama (Maxwell 1971)	
Pre-Pleistocene	2.5 $cm/10^3$ yr
Pleistocene	7.0 $cm/10^3$ yr
Maximum Entrenchment (Seyfert and Sirkin 1973)	
Lower Mississippi Valley	120 m
Deltaic Plain (Saucier 1974)	
Subsidence near Gulf	12 $cm/10^2$ yr to 3 $m/10^2$ yr
Five Islands Salt Dome Region	45 m vertical displacement
Rates of Uplift (Maxwell 1971)	
Adjacent to Gulf Coastal Plain	1.2 $cm/10^3$ yr

Southwest

Tectonism and volcanism, which began in the Tertiary as a result of movements of crustal and oceanic plates, continued into the Quaternary. The Colorado Plateau was uplifted nearly 1,500 m during the late Tertiary and early Quaternary (Seyfert and Sirkin 1973). In the Basin and Range province, normal faulting and volcanism, which began in the Tertiary, continued into the Quaternary. However, volcanism in the western United States appears to have been less intense in the late Pleistocene than during the late Tertiary and early Pleistocene.

The Basin and Range province has about 140 closed tectonic basins. Most of these basins contained lakes during the last glaciation. The lakes ranged in size from shallow playas to large lakes such as Lake Bonneville, which is more than 330 m deep at its maximum. Researchers suggest that most of these lakes developed because of a more favorable precipitation/evaporation ratio than now exists. Flint (1971) hypothesizes that the pluvial lakes resulted from precipitation about 80 percent greater than now, evaporation about 30 percent less, and mean annual temperature 5 to 8°C cooler.

The major geomorphic feature in the Southwest is the Grand Canyon. The Canyon has had a complex history of uplift, downcutting, and volcanism that began sometime in the Tertiary. The Colorado River, of course, has been evolving since the uplift of the Rocky Mountains began (or was resumed) at the end of the Cretaceous Period (65,000,000 years B.P.). Hunt (1969) postulated that the Grand Canyon at the Kaibab Plateau was first incised in early Miocene time (20,000,000 years B.P.) by the ancestral San Juan River as a result of superposition during the last 450 m of uplift at the Kaibab Plateau. West of the Kaibab upwarp, the San Juan River joined the ancestral Little Colorado River. At that time these streams had a discharge only about one-fifth of the present capacity of the entire river basin. Assuming present rates of discharge, the combined San Juan/Little Colorado Rivers had a discharge of from 2 to 3 million acre-feet (maf) (2.5×10^9 to 5×10^9 m^3) annually.

Hunt (1969) believes that drainage from the northern part of the present Colorado River Basin did not discharge southward beyond the Henry Mountains or the Kaiparowits Plateau until the end of Miocene time (7,000,000 years B.P.). Until then, discharge to the south was probably small, because much of the drainage from the Southern Rocky Mountains was repeatedly ponded within the mountains, and the Green River was contained somewhere north of the Uinta Mountains.

According to Hunt's interpretation, the early drainage left the Colorado Plateau by way of the dry canyon at Peach Springs. By middle Miocene time (13,000,000 yr B.P.), the Grand Canyon was more than 300 m deep and extended from the east side of the Kaibab Plateau to somewhere southwest of Peach Springs. Deepening of the canyon was repeatedly interrupted by uplifts of the fault blocks crossing it. In Hunt's words (1969, p. 116):

> By late Miocene time, the drainage was blocked from discharging at Peach Springs by uplift of the now dry canyon and by volcanic materials which came into it from the Basin and Range province. The ponded drainage began escaping along fissures in the limestone at the position of the lower Granite Gorge. When the drainage was joined by the Green and Colorado Rivers, the increased discharge could have opened the lower end of the Grand Canyon through the limestone. By my interpretation, the Colorado River did not discharge as surface water through the whole length of the lower Granite Gorge until after the limestone was deposited.

The foot of the Grand Canyon provides good evidence that no large river discharged there until middle or late Pliocene time (3 to 4,000,000 years B.P.). However, downcutting during the last half of the Pleistocene (1,000,000 years B.P.) is believed to have been minimal (Hunt 1969). At the mouth of Toroweap Valley, lava flows extended into the canyon from the north when the river was within 15 m of its present position. Therefore, the entrenchment at the foot must have occurred during a 2 to 3 million year period.

Estimates of probable downcutting rates for the Grand Canyon during various periods in the geologic history are shown in Table 3. Note that maximum downcutting rates for short periods of time (1,000 years and less) might have been two to three times higher than those shown.

Some uplift of the Colorado Plateau is still occurring, as indicated by precise leveling in the Lake Mead area. Subsidence of Lake Mead has been measured at a rate of 12 $m/10^3$ yr, but with a total expected subsidence of only 0.25 m (Gould 1960, cited in Schumm 1963). This sinking is apparently caused by the load of the water in the reservoir and by a southwest tilting of the lake basin, which is linked to the possible continuing uplift of the southwest rim of the Colorado Plateau (Hunt 1969).

TABLE 3. Downcutting Estimates for the Grand Canyon[a]

Downcutting (m)	Geologic Time Scale	Time Period (10^6 yr)	Rate ($m/10^3$ yr)
300	Pre-Middle to Middle Miocene	3 to 5	0.10 to 0.06
1,000	Middle to Late Pliocene	3 to 4	0.33 to 0.25
140	Early Pleistocene	0.8	0.18
15	Middle Pleistocene to present	1.2	0.01

(a) Estimates based on Hunt (1969).

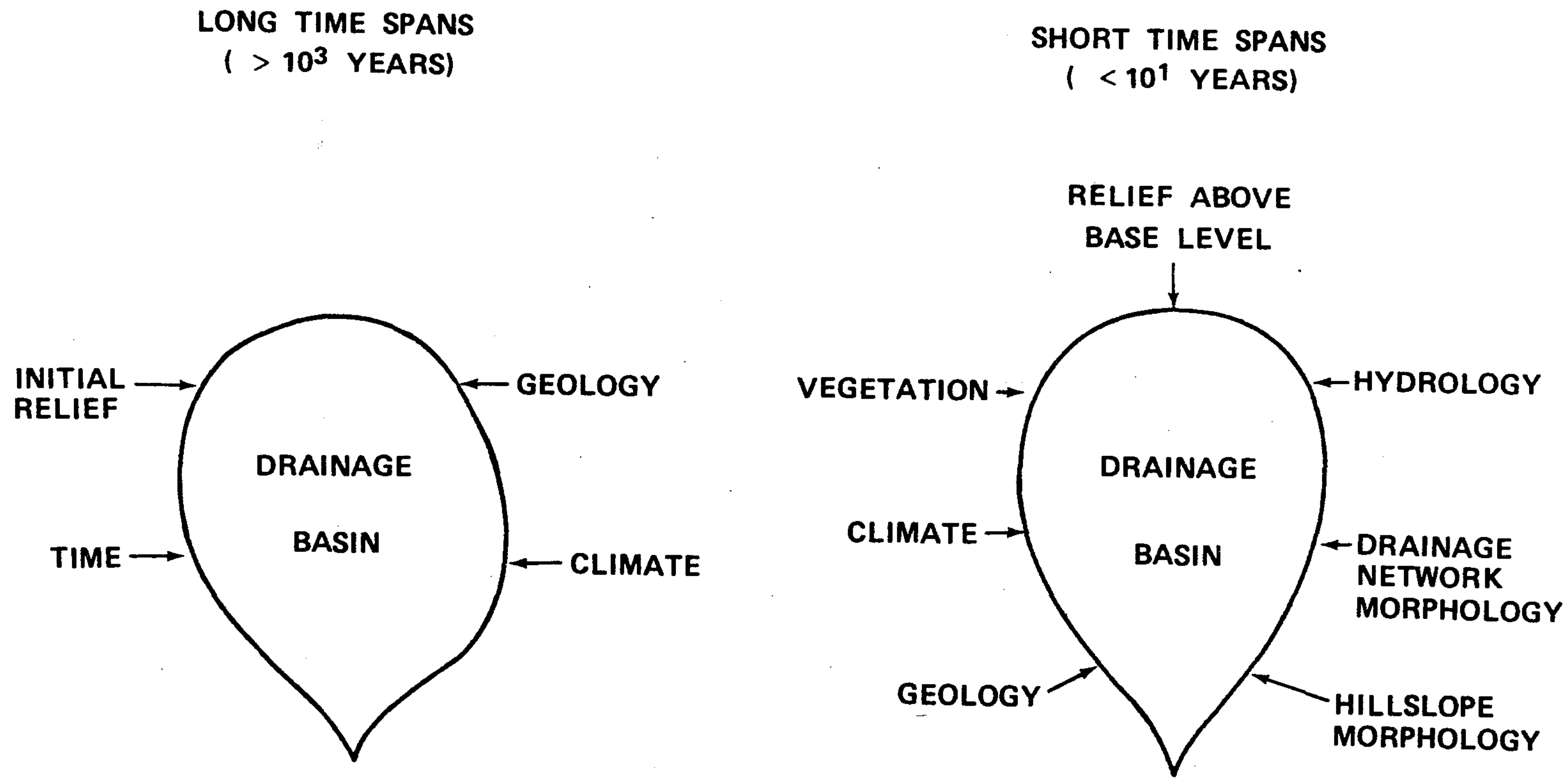
PROBLEM FORMULATION

Geomorphic processes are influenced by many variables. Geomorphologists tend to evaluate these processes and variables over periods that are generally less than 100 years. In fact, recent advances in the field have centered around mathematical modeling and quantitative analysis of variables affecting landscape formation over periods as brief as one year. On the other hand, little research has addressed the problems associated with estimating long-term erosion and landform development.

Given the number of variables contributing to the development of landforms over time, the paucity of the research is not surprising. However, the key element to remember is time. As Schumm and Lichty (1965) aptly stated: "The distinction between cause and effect in the development of landforms is a function of time and space..." As an extension of this thought, one finds that when the time frame is expanded, the number of independent variables is reduced. Figure 2 illustrates this finding: When the time is expanded from 10 years to 1,000 years, the number of independent variables is reduced from seven to four.

Because the number of independent variables is reduced as the time frame expands, somewhat cruder measures can be used in place of specific analytical measurements to represent long-term, basin-wide changes in morphology. Denudation rates are one such measure. Commonly presented as the number of meters a basin is lowered in a one thousand year period, denudation rates afford a reasonable long-term estimate that tends to smooth out pulses in the system. In other words, denudation rates can be thought to represent watersheds in a steady-state condition (Langbein and Schumm 1958, Menard 1961).

Recent controversy (Trimble 1975, Schumm et al. 1976) has arisen in regard to whether denudation rates that are based on current stream sediment loads are applicable. Since the time when European settlement of the United States began, accelerated erosion has overloaded streams with sediment; the eroded material not transported from the basins has been deposited as colluvium and alluvium. The implication is that denudation rates derived from



SOURCE: After Schumm and Lichty, 1965

FIGURE 2. Independent Variables that Influence the Cycle of Erosion During Different Time Spans

analysis of present conditions grossly overestimate past rates. As Schumm et al. (1976) point out, at any one time during the evolution of a drainage basin, either storage or flushing of sediment will predominate. In fact, field studies of Quaternary sediments and experimental studies (Schumm and Parker 1973) have confirmed that episodes of storage and flushing occur throughout the normal developmental history of a drainage basin. Remobilization of sediment will occur (or has occurred) when the slope of the valley-fill deposits increases with time and approaches a geomorphic threshold of instability (Schumm 1974). In addition, some investigators have attempted to minimize the influence of man's activity on the erosion data by selecting areas where little agricultural activity is recorded (Langbein and Schumm 1958). Therefore, denudation rates do provide useful estimates of past rates of regional erosion, although it is apparent that modern rates may be several times those of the past (Douglas 1967).

Thus, man's extensive influence on sediment yield is obvious. In addition, a time lag must be accounted for in considering the removal of Quaternary sediments from the valley slopes and river beds. Nevertheless, two basic assumptions underlying this research are that mankind will continue and that glaciations will continue as predicted by the Milankovitch theory (cyclic, with a 100,000-year recurrence interval). Therefore, it is not unreasonable to assume that recent rates will continue into the future, in particular when the objective is to estimate possible maximum rates.

LONG-TERM ESTIMATES OF CONTINUOUS GEOMORPHIC PROCESSES

To predict possible maximum rates for the next million years, this chapter evaluates three continuous geomorphic processes--denudation, entrenchment, and aggradation--for the Southwest and the Gulf Coast.

DENUDATION

As discussed in the section entitled Problem Formulation, at any given time a basin is undergoing net storage or flushing of sediment. For example, sediment will be stored until a geomorphic threshold is passed; at that time erosion (or flushing) begins. Consequently, erosion rates represent a normal, yet unstable, period in the history of a basin. Denudation, on the other hand, occurs over longer periods, and this lengthy duration tends to even out short-term anomalies. Therefore, although in some cases man has increased rates of erosion by seven or eight times since European settlement, denudation rates that are based on data gathered in the last 100 years should provide a reasonable compromise between short-term (<100 yr) erosion in localized areas and long-term (>1,000 yr) evaluation of a drainage basin.

The first calculations of denudation rates were made by Dole and Stabler (1909) (see Table 4) and were based on data obtained from the dissolved and suspended sediment load of streams. Judson and Ritter (1964) and later Judson (1968) conducted a similar analysis with much better data, especially for dissolved load, and arrived at remarkably similar results. Post-1950 estimates of regional denudation are shown in Table 5. Note that climate and tectonic environment have a significant influence on the estimated rates; for example, the Kosi River Basin, which receives sediment eroded from Mt. Everest, has an estimated denudation rate 20 times higher than that estimated for the Gulf Coast.

Corbel (1959, cited in Thornes and Brunsden 1977) documented rates of denudation in regions of different climatic and physiographic characteristics. Although he attributed more denudation to chemical solution than most other authorities accept, his rates are comparable to those estimated by many others (see Table 6).

TABLE 4. Rates of Denudation for Major River Systems

River	Drainage Area (10^3 km^2)	Denudation Rate (cm/10^3 yr)
Mississippi	3,250	5
Missouri	1,370	4
Colorado	600	6
Ohio	550	5
Potomac	40	3
Susquehanna	70	3

Source: Dole and Stabler (1909)

TABLE 5. Recent Estimates of Denudation

Location	Rate (cm/10^3 yr)	Source of Data
Mississippi River Basin	5	Judson and Ritter 1964, Judson 1968
Colorado River Basin	17	Judson and Ritter 1964, Judson 1968
Western Gulf	5	Judson and Ritter 1964, Judson 1968
South Atlantic and Eastern Gulf	4	Judson and Ritter 1964, Judson 1968
North Atlantic	5	Judson and Ritter 1964, Judson 1968
Colorado River Basin	18	Wolman and Miller 1960
White Mountains, California	24	Lamarche 1968
Large basins in semiarid regions	7	Schumm 1963
Small basins in semiarid regions	15	Schumm 1963
Northern Alps	61	Wegman 1957[a]
Kosi River Basin, Nepal and India	98	Khosla 1953[a]
Rocky Mountains, Late Cretaceous	12-20	Menard, 1961

(a) Cited in Schumm (1963); these rates were thought to represent maximum values by the author.

TABLE 6. Denudation Rates for River Basins in Various Climates

Region	Denudation Rates (cm/10^3 yr)
Lowlands	
Climate with cold winter	2.9
Intermediate maritime climate	2.7
Hot-dry climate (New Mexico)	1.2
Hot-moist climate with dry season	3.2
Equatorial climate (dense rainforest)	2.2
Mountains	
Semihumid periglacial climate	60.4
Extreme nival climate (SE Alaska)	80.0
Climate of Mediterranean high mountain chains	44.9
Hot-dry climate (SW United States)	17.7
Hot-moist climate (Mexico)	9.2

Source: Corbel (1959) as cited in Bloom (1978)

Schumm (1963) evaluated the variation in denudation rates caused by effective precipitation; that is, the amount of precipitation required to produce the known amount of runoff (Langbein and Schumm 1958). As shown in Table 7, the maximum denudation rates occur when effective precipitation ranges from 25-38 cm. High denudation rates can be expected in the Southwest, where effective precipitation ranges from 20-30 cm. However, the Gulf Coast's effective precipitation ranges from 63-127 cm, indicating that estimated denudation rates should be lower there.

Schumm (1963) and Carson and Kirkby (1972), both cited in Thornes and Brunsden (1977), assembled data on rates of uplift and denudation and compared the two to determine whether Penck's (1953) assertion that denudation may keep pace with the rate of uplift is valid. When comparing Table 8 with the estimates of denudation shown previously, it is obvious that uplift rates are significantly higher by as much as three orders of magnitude. This fact tends

TABLE 7. Drainage Basin Denudation Rates, Based on Effective Precipitation

	Effective Precipitation (cm)	Mean Sediment Yield (10^3 kg/km^2)	Mean Denudation Rate (cm/10^3 yr)
Gaging station data[a]	25	240	9
	25-38	280	10
	38-51	200	7
	51-76	200	7
	76-102	140	5
	102-152	80	3
Reservoir data[b]	20-23	500	19
	25	420	16
	28	530	20
	36-64	400	15
	64-76	510	19
	76-97	280	10
	97-102	200	7
	102-140	170	6
	140-254	160	6

(a) Average drainage area of 3,800 km^2
(b) Average drainage area of 75 km^2

Source: Schumm (1963)

TABLE 8. Rates of Uplift for Orogenic and Isostatic Conditions

Type of Uplift	Area	Rate (cm/10^3 yr)	Source
Orogenic	Japan	79-7,500	Tsuboi 1933
	California	480-1,260	Gilluly 1949
	Persian Gulf	300-990	Lees 1955
	Southern California	390-600	Stone 1961
Isostatic	Fennoscandia	1,000	Gutenberg 1941
	Southern Ontario	3,500	Gutenberg 1941

Source: Cited in Thornes and Brunsden (1977) to support Davis (1925), who theorized that rapid tectonic uplift of a region was followed by a long period of quiescence while the land was worn down by denudation. Schumm (1963) later expanded this theory by hypothesizing that brief periods of rapid isostatic readjustment occurred as a result of continuing denudation.

Although the Southwest and the Gulf Coast have some tectonically active areas, the associated rates of uplift and subsidence are very slow (refer to Description of the Study Areas). From the data available, it appears clear that uplift and isostasy are much faster than denudation. Therefore, to evaluate a worst case, denudation could be assumed to equal uplift (or subsidence). (Information concerning rates of uplift and subsidence in the two areas of study are being supplied by other consultants to PNL.)

Given the data previously presented on regional geomorphic characteristics and the data presented thus far in this chapter, estimates of maximum and average denudation rates were made (see Table 9). These estimates assume that any uplift or subsidence which occurs will be quite slow. If information being generated by other consultants indicates that this is not the case, the estimates shown in Table 9 should be adjusted upward.

TABLE 9. Estimates of Future Denudation Rates

	Average Rate ($cm/10^3$ yr)	Maximum Rate ($cm/10^3$ yr)
Gulf Coast	5	15
Southwest	10	30

Source: SRI

ENTRENCHMENT

In addition to overall lowering of the basins by denudation, entrenchment of streams is another mechanism that could possibly result in a breach of the geologic containment. Past rates of entrenchment for the two study areas are discussed in the section entitled Description of the Study Areas. This section extends that analysis.

Gulf Coast

A simple way to estimate maximum entrenchment rates for the Mississippi River or other coastal streams is to assume that entrenchment will keep pace with lowering of sea level during a glacial period. Estimates of the maximum lowering of sea level during the Pleistocene full glacial intervals vary from 80-140 m (Bloom 1978). The coastline during a full glacial interview, however, would be several hundred kilometers south of its present location. Fisk (1947) reconstructed the late-glacial history of the Mississippi River Valley near Natchez, Mississippi (1,200 km upstream from the mouth). From his analysis, it can be estimated that maximum entrenchment at Natchez was probably less than 50 m when the sea level was 120 m below its present level. At that time, the Mississippi was a braided stream overloaded with gravel. Such a condition encourages widening of a valley rather than entrenchment of a channel.

Several hundred kilometers upstream in Alabama, rates of entrenchment during the Pleistocene have been estimated at 7 cm/10^3 yr (Maxwell 1971). This rate is much lower than those estimated downstream.

Fisk (1947) estimated the valley slope near Natchez at maximum sea-level lowering to be 0.16 m/km. The present valley slope at Natchez is estimated at 0.11 m/km. Studies have shown that when rivers of a given discharge are compared, braided channels occur on steeper slopes than do meanders (Leopold et al. 1964). In addition, slope tends to decrease as bankfull discharge increases.

Given the available data, the estimates for average and maximum entrenchment are shown in Table 10. For a worst case, entrenchment at the present mouth of the Mississippi River could be assumed to equal maximum sea-level lowering. The maximum valley slope gives an indication of how fast the entrenchment is transmitted upstream. Rates are estimated by assuming that a full-glacial interval will last from 10,000 to 20,000 years and that maximum entrenchment (coinciding with maximum sea-level lowering) will occur over a period of 5,000 years or less.

Southwest

The Colorado River provides a dramatic example of entrenchment where it flows through the Grand Canyon. As discussed in the section entitled Description of the Study Areas, rates of downcutting vary from a high of 0.3 $m/10^3$ yr to a low of 0.01 $m/10^3$ yr at present (see Table 3). Although these rates are much slower than those estimated for the Gulf Coast during a full glacial interval, it must be remembered that the duration of downcutting in the Grand Canyon extends over several million years rather than several thousand years, as in the former case. Table 10 presents the estimates of average and maximum downcutting of the Colorado River by assuming uplift rates similar to those existing in the Mesozoic and Early Cenzoic. If information supplied by other consultants indicates that these rates are slower than those expected in the future, downcutting rates should be estimated by assuming that downcutting will equal uplift.

AGGRADATION

Aggradation of river beds occurs when the sediment load increases relative to discharge or when the slope flattens to a point when downcutting can no longer occur. Braided streams provide maximum aggradation and occur primarily in periglacial environments. In arid and semiarid environments, aggradation occurs in the form of alluvial fans and bajadas.

Gulf Coast

The alluvial valley of the lower Mississippi is a broad lowland varying from 40 to 200 km in width. Fisk (1947, 1951) reconstructed the late-glacial history of the Mississippi River near Natchez and postulated that the valley slope decreased from 0.16 to 0.11 m/km as the sea level returned to its present elevation. More than 100 m of alluvium has been deposited in some parts of the valley. Rates of aggradation in large part depend on rates of sea level change. During the most rapid phase of deglaciation, from about 10,000 to 7,000 years B.P., sea level may have risen at a rate of 1 cm/yr (Bloom 1978).

TABLE 10. Estimates of Rates of Entrenchment

	Entrenchment (m)		Rates of Entrenchment ($m/10^3/yr$)		Valley Slope (m/km)	
	Average	Maximum	Average	Maximum	Average	Maximum
Gulf Coast--Mississippi River Mouth	100	150	50*	75†	0.16	0.30
200 km upstream	30	40	6*	20†	0.14	0.20
Southwest--Colorado River--Grand Canyon	--	--	0.20‡	1‡	--	--

* Assumes 5,000 years for period of entrenchment.
† Assumes 2,000 years for period of entrenchment.
‡ Assuming average and maximum rates of uplift comparable to late Mesozoic and early Cenozoic rates. Present rates are estimated at 1-2 $cm/10^3$ yr.

Source: SRI

A simple way to account for aggradation in a model of a geologic system is to assume that the trenching that takes place during the simulated glacial interval is entirely filled in with alluvium during the waning stages of glaciation. Therefore, whether or not a breach in the geologic containment occurs will depend on the maximum lowering of sea level and the associated entrenchment of the river. Following entrenchment, aggradation will occur and the cycle will be repeated during the next glacial interval. No evidence exists to suggest that aggradation following entrenchment results in a net lowering of the river valley greater than that accomplished by denudation. However, if uplift operates concurrently with entrenchment, net lowering could occur. In other words, the elevation of the river bed following a period of aggradation might, in that case, be lower than the elevation of the river bed at the beginning of the preceding period of entrenchment.

Southwest

Aggradation similar to that associated with periglacial environments is not expected to occur in the Southwest within the next million years. However, aggradation in the form of alluvial fans will occur.

The alluvial fans of Death Valley have been analyzed as equilibrium landforms (Denny 1965, 1967). Each fan has an area equal to one-third to one-half of the mountain watershed that feeds it. Fans grow until their surface area becomes so large that the rate of sediment supply from the mountain is balanced by the rate of erosion of the fan surface.

Although alluvial fans and bajadas (coalescing fans) are important local geomorphic features, they are not expected to effect estimated rates of denudation and entrenchment substantially. Therefore, aggradation in the Southwest need not be included in the simulation model.

LONG-TERM ESTIMATES OF CATASTROPHIC EVENTS

A catastrophe can be defined as "a sudden, violent change in the physical conditions of the earth's surface" (American Geological Institute 1976). By definition, the duration of such events is brief in a geological sense. Thus, the inclusion of catastrophic events in a long-term simulation model with 100-year time steps is a difficult task for both the theorist and the practitioner. Nevertheless, these events must be examined to determine whether or not inclusion is required.

LANDSLIDES

Mass movement in the form of landslides is an important mechanism in the weathering process in certain regions of the United States. In a periglacial environment, for example, the total mass moved has been shown to be comparable to that removed by chemical weathering (see Table 11). Landslides can occur when any or all of the following conditions exist: oversteepened rock face, water saturation, incompetent lithologic units, diurnal freezing and thawing, and tectonic instability.

Although small localized landslides (primarily earth slides) may occur in the Gulf Coast, no major landslides are expected to occur in that region in the next million years. The Southwest, however, has known occurrence of fairly large landslides (especially debris flows) and should be evaluated further.

Landslides in the Southwest are of two major types: debris flows and gravitational spreading. Debris flows are generally a type of rotational slide. The debris flows investigated in the arid portions (areas of internal drainage) of California and Nevada are rarely larger than 50 km^2. The maximum mass of material involved commonly ranges from 500,000 to 1,000,000 m^3. In unpublished studies, Radbruch-Hall has found that landslides resulting from gravitational spreading are found in mountainous areas of the Southwest that were glaciated during the Pleistocene. The mass involved is usually large (70,000,000 m^3) and movement is very small (tens of meters). Two large landslides resulting from failure by lateral spreading have been identified in Utah along the ancient shoreline of Pleistocene Lake Bonneville near Salt Lake

TABLE 11. Relative Importance of Geomorphic Processes in a Periglacial Environment

Process	Tons Moved per Vertical m
Rockfalls	20,000
Avalanches	22,000
Earthslides	96,000
Talus creep	2,700
Solifluction	5,300
Dissolved load	137,000

Source: From Rapp (1961), cited in Thornes and Brunsden (1977)

City (Van Horn 1975). The younger landslide covers about 9 km^2 and is probably less than 2,000 years old; the older one covers at least 8 km^2 and is between 2,000 and 5,000 years old. Both landslides occurred as a result of undercutting of the shoreline by wave action, water saturation, and initiation of movement along an incompetent lithologic unit.

Although a landslide releases significant energy, most of the energy is absorbed in breaking up the mass of material. No known cases exist of a landslide triggering seismic activity.

To put this analysis in the proper perspective, Table 12 is presented. Note that these landslides and floods--some of the largest ever recorded--do not account for substantially larger volumes of sediment than do normal rates of denudation. Given that the location and size of landslides are impossible to predict, that the largest landslides are in areas of internal drainage, and that the seismic effect is unknown, we recommend that such events not be included in the long-term simulation model.

FLOODING

As shown in Table 12, catastrophic floods have been responsible for rapid movement of large volumes of sediment. The erosive power of such events

TABLE 12. Estimates of Erosion from Various Catastrophic Events Compared to Denudation Rates

Event	Total Erosion (10^6 m^3)	Source of Data
Rapid City flood (6/72)	0.018	Mara 1975
Big Thompson flood (7/76)	1.3	Balog 1978
St. John-Vianney landslide (5/71)	7.0	Cornell and Surowiecki 1972
St. Francis Dam (1928)	21.0	Mara 1975
Gros Ventre landslide (1909)	38.0	Schreve 1968
Alaska earthquake (3/64)	92.0	Mara 1975
Blackhawk landslide (L. Tertiary)	283.0	Schreve 1968
Vaiont landslide, Italy (1963)	298.0	Schreve 1968
Bangladesh flood (11/70)	313.0	Mara 1975
Lake Bonneville flood (L. Pleistocene)	2,300.0	Malde 1968
	Denudation Rates (10^6 m^3/yr)	
Colorado River	92.0	Judson and Ritter 1964
Mississippi River	161.0	Judson and Ritter 1964

greatly supersedes that of landslides and is evident in the Snake River Plain and the channeled scablands of eastern Washington.

The Lake Missoula floods, for example, probably involved the largest discharges of fresh water that have been documented in the geologic record (Baker 1973). The major flood, which created the channeled scablands, resulted from the catastrophic release of an estimated 2,000 km^3 of water from glacial Lake Missoula in western Montana (Bretz et al. 1956, Baker 1973). The extremely high head (600 m) and the sudden release (breaking of an ice dam) resulted in an estimated peak discharge of 40 km^2/hr. Giant ripple marks, higher than 2 m, were observed, and boulders more than 10 m in diameter were transported some distance (Baker 1973). This flood far exceeded the Lake Bonneville flood (caused by rapid release of water into the Snake River Plain from Pleistocene Lake Bonneville; refer to Table 12) and discharged at a rate 30 times faster.

Another type of catastrophic flood, called jökulhlaup, is common in Iceland and occurs when volcanic activity or solar melting cause glaciers to sunder, thereby releasing vast quantities of rock, gravel, and mud to be carried across the land (Thorarinsson 1958). Similar occurrences in the United States have not been documented.

There are no known cases of catastrophic flooding in the Gulf Coast or the Southwest similar to those described. Although the catastrophic release of Lake Bonneville occurred close to our area of study, existing and probably future drainage conditions make it highly unlikely that flooding to the south will occur. Volcanic activity in portions of northern Arizona and New Mexico could conceivably initiate small-scale catastrophic flooding (jökulhlaup) during a glacial period; however, the overall erosive effect would be minimal. Therefore, the potential for a catastrophic flood in the Southwest and the Gulf Coast during the next million years is remote and should not be included in the long-term simulation model.

ASHFALL

Ashfall may result from widespread (or long-term) volcanic activity and may denude the landscape. Erosion rates would be affected by two factors: removal of vegetation, and changes in the characteristics of the top layer of erosive material.

Removal of vegetation has been shown repeatedly (e.g., Ursic and Densy 1963, Schumm 1974, Mara 1974) to increase erosion significantly by reducing infiltration, by increasing runoff velocity and volume, and by decreasing land surface stability. Erosion has been shown to increase by as many as three orders of magnitude in the semiarid climate of the Southwest. Increases as high as two orders of magnitude in the Gulf Coast are not uncommon.

The deposition of a layer of ash on the land surface, however, could have a countering effect. Although the ash's particle size is fine, the ash probably has a strong pozzuolanic effect that significantly reduces its ability to erode. Nevertheless, where slopes are moderately steep and precipitation occurs in intense, convectional storms (as in a semiarid climate), sheet wash erosion and gullying would take place.

A worst case would occur if the ash was assumed to have no counterbalancing effect on the denudation of vegetation. In that case, erosion rates in the Southwest could be expected to increase by as many as three orders of magnitude, whereas rates in the Gulf Coast would increase by as many as two orders of magnitude. The probability of a widespread ashfall occurring in the two study areas is being addressed by another consultant to PNL.

APPLICABILITY TO SITE-SPECIFIC ANALYSIS

The current version of the simulation model will be used to simulate long-term changes within a region. Consequently, the geologic consultants to PNL have been encouraged to develop regional values for rates and processes for input to the model. Ultimately, the simulation model will be adapted for site-specific analysis, and thus some discussion of the applicability of this research to such analysis is required.

The goal of every simulation model is to reduce natural phenomena to mathematical expressions by determining relationships among all significant variables that affect the phenomenon of interest. However, geologic phenomena are notably resistant to this type of analysis.

As discussed in the section entitled Problem Formulation, the longer the time frame, the smaller the number of variables that must be considered in evaluating drainage basin changes. However, the relationships among these variables have never been determined over long time frames (>100 yr).

A simple model of global denudation rates was developed by Fournier (1960, as cited in Thornes and Brunsden 1977). It is based on demonstrated differences in climate and relief. The empirical equation follows:

$$\log F = 2.65 \log \frac{p^2}{P} + 0.46 \log \bar{H} \tan\Theta - 1.56$$

where:

- F = suspended sediment yield per year
- p = rainfall in the wettest month
- P = mean annual precipitation
- $\bar{H}$ = mean relief
- Θ = mean slope in drainage basin.

Fournier's equation is not applicable to site-specific analysis of denudation or erosion. Consequently, we have developed general equations that identify the important variables and that recognize the functional relationship among these variables.

Over long time periods, erosion is a function of four variables (or conditions) as follows:

$$nE_t = f\ (E_{to},\ T,\ El,\ C)$$

where:

nE_t = normal erosion rate at time t
E_{to} = erosion rate at time to
T = predicted tectonic change
El = predicted elevation
C = predicted climatic characteristics.

Ideally, the functional relationship between erosion and each of the variables should be definable to allow the model to simulate changes in erosion by basing them on other changes occurring over time. Some of these relationships have been established. Figure 3 presents the relationship of denudation rates to drainage-basin relief. By including equations for the appropriate curve in the simulation model, denudation rates could be adjusted upward or downward as relief changes over time. The effect of climate on sediment yield is shown in Figure 4. If the simulated climate changed from semiarid to arid, for example, the sediment yield that is based on this curve (converted to denudation rate) for the area could be reduced proportionately.

The question of whether erosion or sedimentation will predominate in a drainage basin becomes important when dealing with a site. Although sedimentation is not easy to quantify on a regional basis (see the section entitled Long-Term Estimates of Continuous Geomorphic Processes), it is quite possible to quantify it for a single site. Sedimentation can be expressed as a function of four variables:

$$S_t = f\ (S_{to},\ [nE_t + cE_t],\ El,\ A)$$

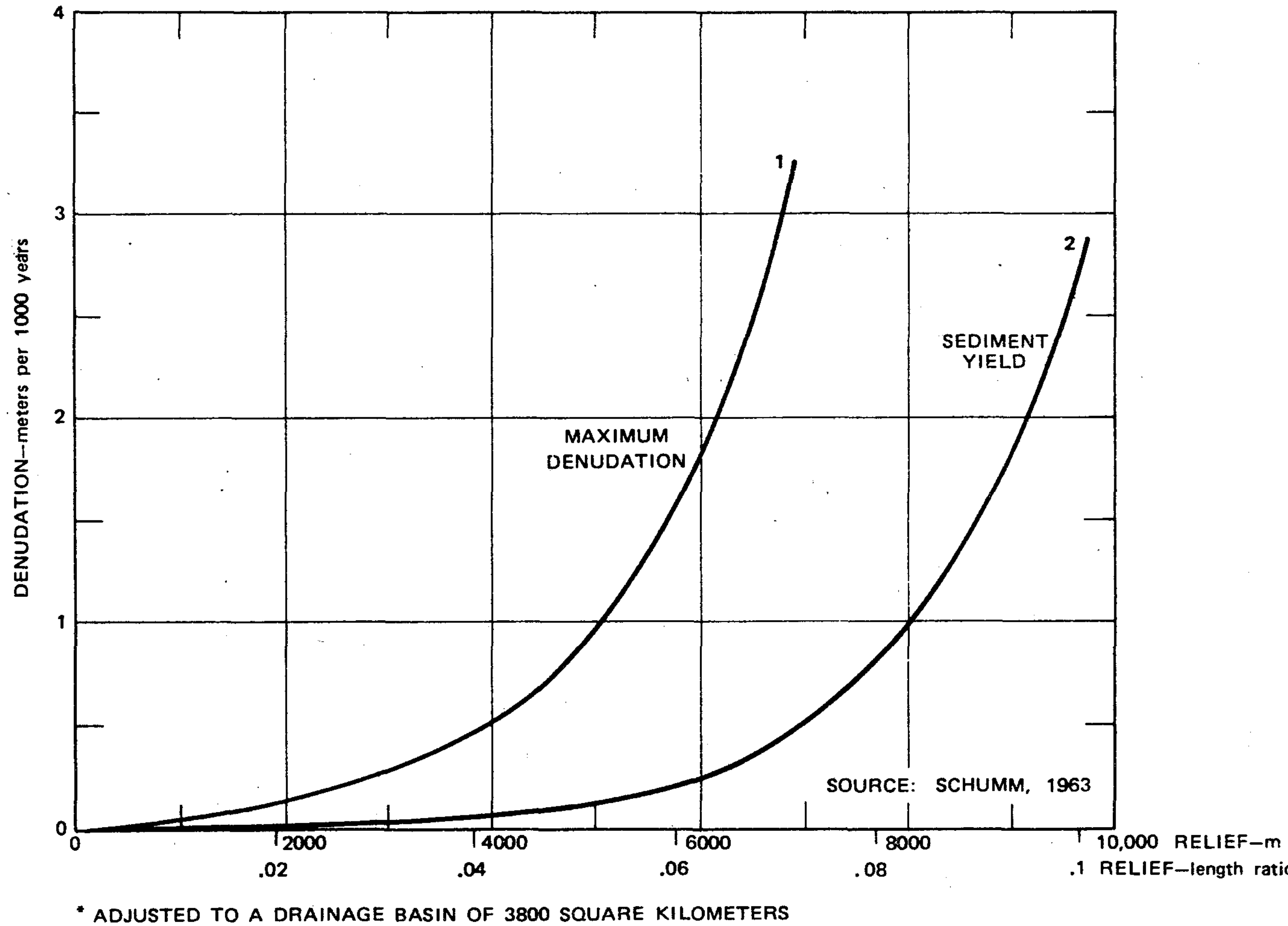
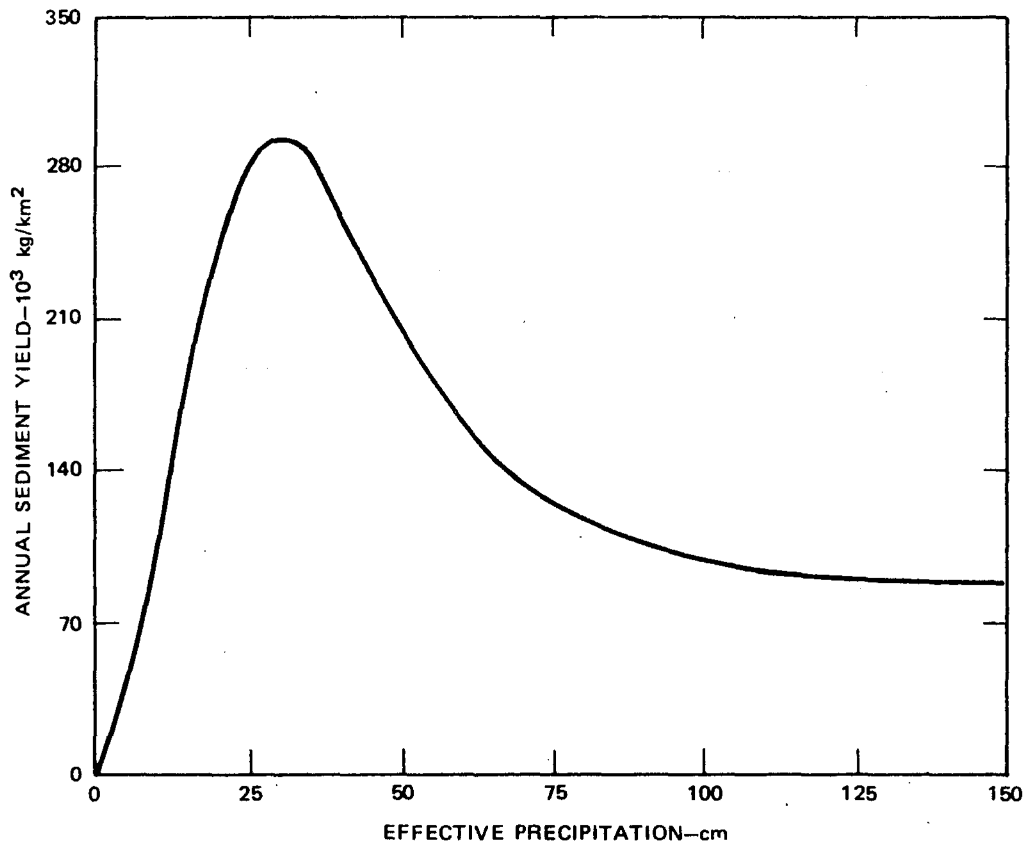


FIGURE 3. Relation of Denudation Rates* to Relief-Length Ratio and Drainage-Basin Relief



SOURCE: LANGBEIN AND SCHUMM, 1958

FIGURE 4. Effect of Climate on Sediment Yield

where:

S_t = sedimentation rate at time t

S_{to} = sedimentation rate at time to

$nE_t + cE_t$ = combined normal and catastrophic erosion rates

El = elevation of the location with respect to the drainage basin minimum or mean sea level, whichever is higher

A = area of the drainage basin minimum (i.e., lake, reservoir, or delta).

In the case of sedimentation it is important to identify whether a drainage basin minimum exists on the site and, if it does, the area involved.

Catastrophic erosion from landslides may be shown to be extremely important in a particular location. If geologic conditions warrant, the following variables could be used to estimate when such events might occur, and the likely size:

$$cE_t = f\ (E_{to}, T, El, C, I)$$

where:

cE_t = catastrophic erosion rate at time t
E_{to} = erosion rate at time to
T = predicted tectonic change
El = predicted elevation
I = predicted instability, seismic or structural.

Elevation relates to the probable moisture conditions at the site over time, whereas tectonic change influences the elevation and the seismic and structural instability of the region.

Additional research will be required to refine these equations for use in a simulation model. In fact, the value of such an exercise awaits the outcome of the first use of the simulation model developed at PNL. If the model demonstrates that maximum expected erosion rates will have no effect on geologic containment, further research is unwarranted. On the other hand, if local conditions offer reason to suspect that the regional rates estimated are inapplicable, refinement of the equations may be desirable.

GLOSSARY

Aggradation	The process of building up the surface of the land by deposition of sediment.
Alluvial fan	A cone-shaped deposit of alluvium made by a stream where it runs out onto a level plain or meets a slower stream. Fans generally form where streams issue from mountains upon the lowland.
Ashfall	A rain of airborne volcanic ash falling from a cloud formed by a volcanic eruption.
B.P.	Before present.
Bajada	A series of confluent alluvial fans along the base of a mountain range.
Braided streams	Where more sediment is being brought to any part of a stream than it can remove, the building of bars becomes excessive. The stream develops an intricate network of interlacing channels and is said to be braided.
Catastrophic event	An event that causes a sudden, violent change in the physical conditions of the earth's surface (e.g., landslides, floods, volcanic eruption).
Cenozoic	The geologic era lasting from 65 million years ago to present.
Cretaceous	The last geologic period in the Mesozoic era; from 141 to 65 million years ago.
Degradation	The general lowering of the surface of the land by erosive processes.
Denudation	The process of eroding away the surface of the land over a long time period; if continued long enough, it would reduce all surface elevation differences to a uniform base level.
Effective precipitation	The amount of precipitation required to produce the known amount of runoff.
Entrenchment	The process of cutting a deep trough by a stream through the geologic materials.
Erosion	The group of processes whereby soil or rock material is loosened or dissolved and removed from a part of the earth's surface.

Eustatic	Of or pertaining to worldwide sea level.
Geomorphology	That branch of geology which deals with the form of the earth, the general configuration of its surface, and the changes that take place in the evolution of landforms.
Holocene	The geologic epoch lasting from approximately 10,000 years ago to present.
Isostasy	Theoretical balance of all large portions of the earth's crust as if they were floating on a denser underlying layer; thus, removal of material by erosion (especially during glacial periods) is compensated for by uplift in the area.
Mesozoic	The geologic era lasting from 225 to 65 million years ago.
Orogeny	The process of forming mountains.
Periglacial	Refers to areas, conditions, processes, and deposits adjacent to the margin of a glacier.
Pleistocene	The geologic epoch lasting from 1.8 million to 10,000 years ago.
Pliocene	The geologic epoch lasting from 7 to 1.8 million years ago.
Pluvial	Pertaining to deposits formed by rain water or ephemeral streams.
Pozzuolanic	Properties of superior strength and chemical resistance imparted to cement by some natural materials such as volcanic ash.
Quaternary	The geologic period lasting from 1.8 million years ago to present.
Tertiary	The geologic period lasting from 65 to 1.8 million years ago.
Wisconsin	The last of four glacial stages in the Pleistocene in North America.

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