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shoreline ecology of lake powell

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National Science Foundation
Research Applied to National Needs

LAKE POWELL RESEARCH PROJECT BULLETIN

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SHORELINE ECOLOGY OF LAKE POWELL

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September 1976

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreation Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

The biogeologic setting for Lake Powell and its conversion from river to reservoir are discussed. The surface materials along the lakeshore were divided into seven major types and the entire 1800 miles of shoreline were mapped at four contours at a scale of 13 inches per mile. The effect of fluctuating water level on shoreline types is discussed. Biomass and species composition of the principal vegetational communities is given.

The successional aspect of invasion of shoreline vegetation into the seasonal drawdown zone is compared to that of river terraces. Tamarisk is a principal species and persistent invader and has a great variety of adaptations to overcome the adversities of a fluctuating shoreline. The relative breakdown and decomposition of native vegetation and tamarisk after submergence are discussed, as is the importance of the rapid development of a mantle of benthic organisms. An experiment on submergence of young seedlings indicates a possible control. However, with increasing age, tamarisk rapidly becomes resistant to submergence mortality. The need is stressed for some shoreline management in order to preserve the desirable sandy shores for recreational use, rather than allowing their development into impenetrable thickets with noxious insects and with submerged off-shore masses of flooded vegetation.

SETTING OF LAKE POWELL

Geology and Physiography

A brief discussion of the geology and physiography of the Colorado Plateau is essential as a base for understanding the current shoreline ecology of the reservoir occupying the lower part of a deeply cut river system.

The depositions of sedimentary material, both by inland seas and by winds, during the late Paleozoic, Mesozoic, and early Cenozoic were uplifted and deformed during much of the Tertiary. The faulting, folding, and uplifting formed mountains, cliffs, and plateaus from coastal plains and the bed of inland seas. A drainage pattern developed, which by middle Miocene had established the general course of the Colorado River and its principal tributaries. The early Miocene channel is today represented by the broad upper gorge with its own steep cliffs in the upper sediments, its talus slopes, and its frequently extensive flat terraces.

Into this channel a second cutting cycle took place in the Pliocene and Pleistocene, carving an inner gorge throughout much of the region into the Glen Canyon group--Navajo, Kayenta, and Wingate sandstones. The overlying, marine-deposited Carmel sandstone was left to form a broad irregular platform between the inner and outer gorges. On several levels of terraces were left alluvial mantles of cobble and gravel of the Pleistocene stream activity. Above rise the massive walls of mesas, buttes, and monuments of Entrada, Summerville, and Morrison formations, for example, to the plateau of Cummings Mesa to the south. To the north talus slopes and vertical cliffs of upper Cretaceous sediments rise even higher to the Kaiparowits Plateau. Major physiographic features are indicated in Figure 1. These formations comprise the maze of buttressed and recessed cliffs of the outer gorge of the southern part of Glen Canyon.

Cataract Canyon is the area of the Colorado River from the junction of the Green River to the mouth of the Dirty Devil River. Glen Canyon is that portion of the Colorado River from the Dirty Devil River to Lee's Ferry. In cutting a deep trench through the heart of the Colorado Plateau the drainage pattern has been controlled by uplifts. While Cataract Canyon lies across major anticlinal features and has a gradient of about 8 feet per mile (with rapids), Glen Canyon is aligned with a depression formed by the flanks of the Henry and Kaiparowits Basins and between the Circle Cliffs uplift to the northwest and the western flank of the Monument upwarp and the laccolithic Navajo Mountain to the southeast. This has resulted in a low average gradient of the Colorado River bed of 2 feet per mile through Glen Canyon. However, these major structural features are the cause of uplift and dip of strata with the resulting appearance and disappearance as seen along the shoreline.

Glen Canyon was the longest continuous canyon along the Colorado River. Because of an overall dip of strata to the west, the river bed which started on Permian Cedar Mesa sandstone at the Dirty Devil ended at the present damsite on the younger Jurassic Navajo sandstone.

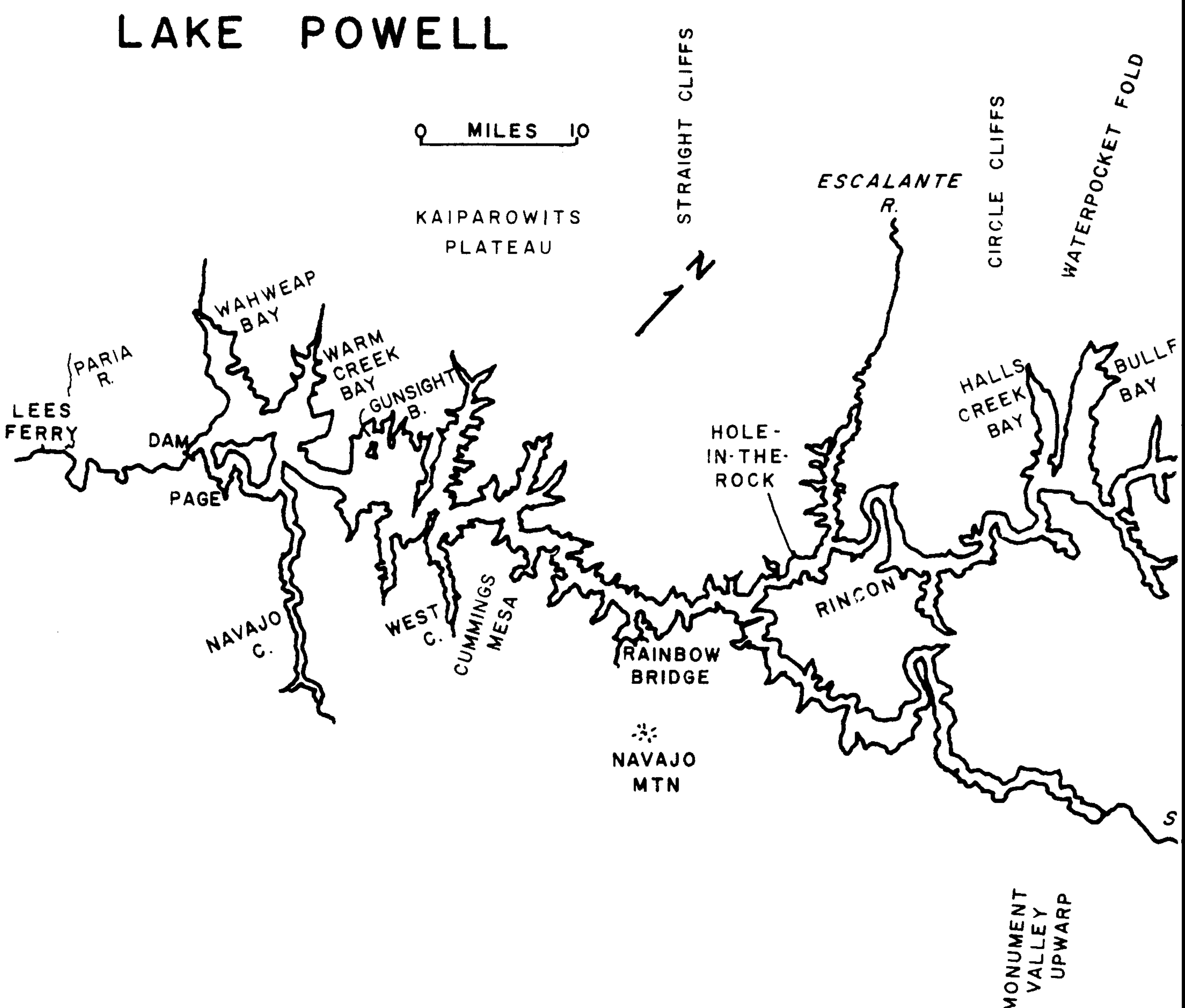
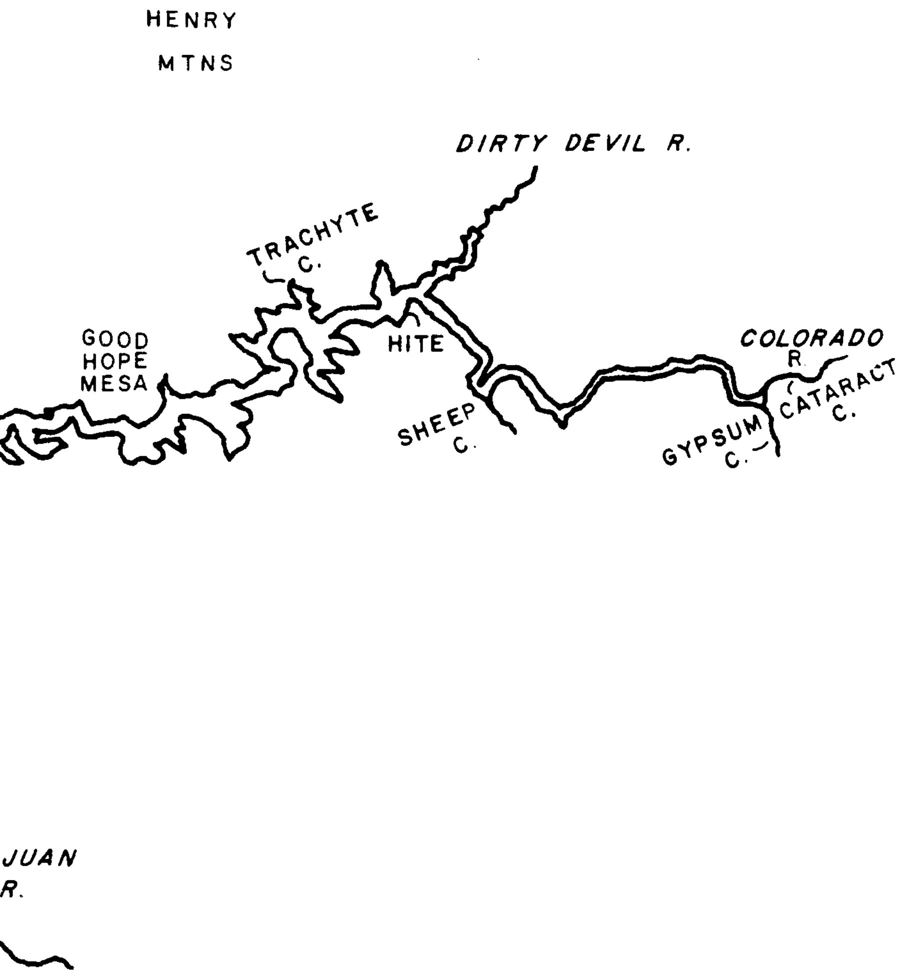


Figure 1. Map of Lake Powell showing features referred to in the text.


HENRY
MTNS
DIRTY DEVIL R.
TRACHYTE C.
GOOD HOPE MESA
HITE
SHEEP C.
COLORADO R.
CATARACT C.
GYPSUM C.
JUAN R.

Thus, from the top of the Kaiparowits Plateau to the beds of the Colorado River and the San Juan River at the upper end of Lake Powell there is exposed a cross-section of 200 to 300 million years of sediment and erosional history (Figure 2). From the top down, the cross-section includes Cretaceous Straight Cliffs sandstone, Tropic or Mancos shale, and Dakota sandstone; Jurassic Morrison formation; the San Rafael group of Bluff sandstone, Summerville formation, Entrada sandstone, and Carmel formation; the Jurassic-Triassic Glen Canyon group of Navajo sandstone, Kayenta formation, Moenave formation, and Wingate sandstone; the complex middle and lower Triassic Chinle formation with the lowest member of the Shinarump conglomerate, and the Moenkopi formation; the Permian Cutler formation of White Rim sandstone, Organ Rock sandstone, Cedar Mesa sandstone, and Halgaito tongue; the transitional marine to non-marine Rico formation; and finally the Pennsylvanian Hermosa formation and the gypsiferous Paradox beds. The upper part of this sequence from Straight Cliffs sandstone to Navajo sandstone is illustrated in Figure 3.

Looking north from the lower end of Lake Powell one sees the cliffs of Cretaceous yellow and brownish sandstones and grey shales rising 4000 to 5000 feet to a platform summit of the peninsular-like Kaiparowits Plateau, which is between the Paria River to the west and the Escalante River to the east. Its strata include the Wahweap sandstone, yellowish-gray and massive; the coal-bearing Straight Cliffs sandstone; the gray fossiliferous marine Tropic shale; the coal-bearing light-colored Dakota sandstone; and the complex multi-strata Morrison formation with

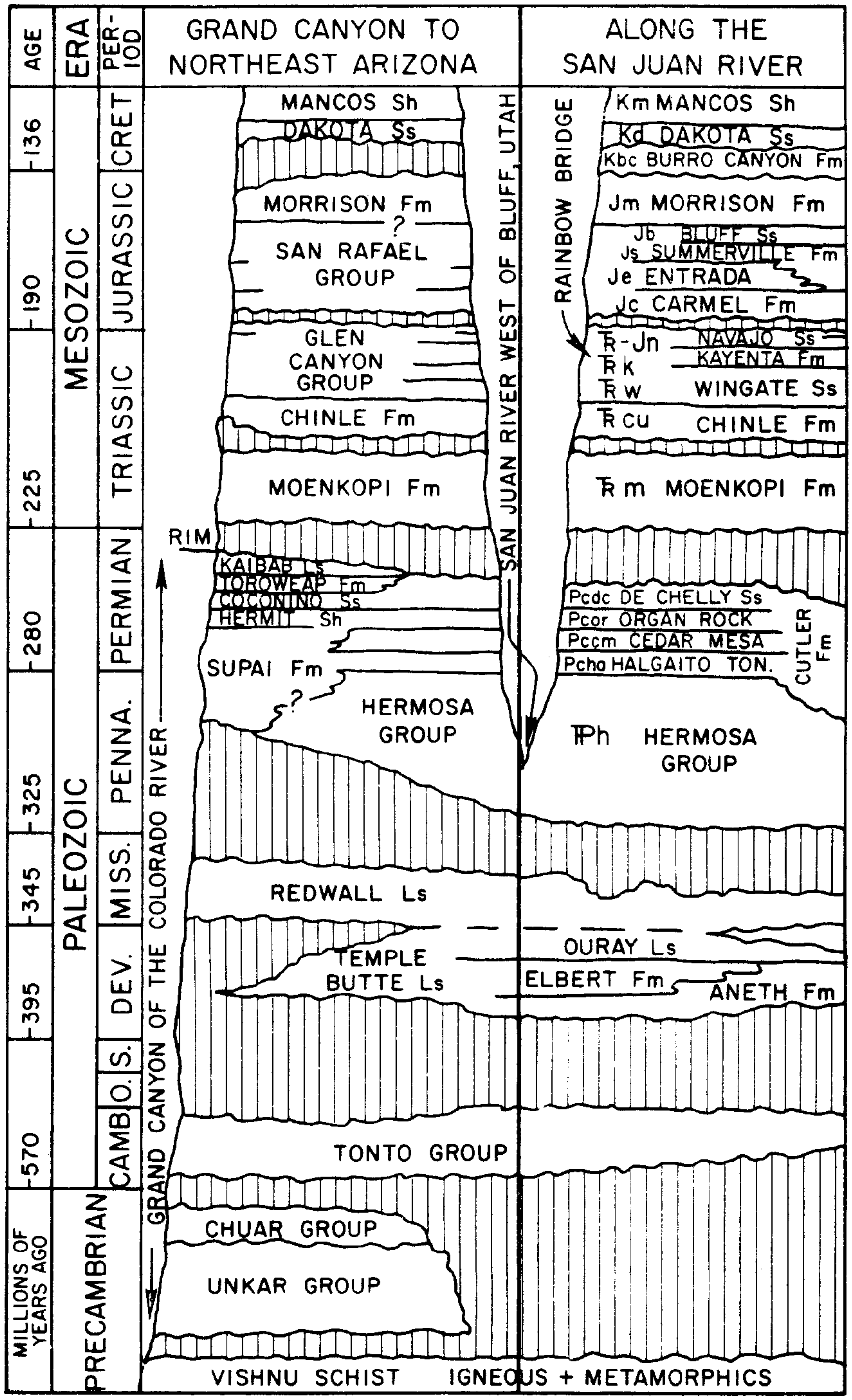


Figure 2. Geological columns for the Grand Canyon and Glen Canyon regions, Arizona and Utah. (From Molenaar, C.M. 1969. Nomenclature chart of the Grand Canyon and adjacent areas, p. 68. In D. Baars (Ed.), Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc. Guidebook, Durango, Colorado.)

Figure 3. Geological strata from the Straight Cliffs sandstone on top of the Kaiparowits Plateau down through Tropic or Mancos shale, Dakota sandstone, Morrison formation, San Rafael group, Summerville formation, Entrada sandstone, Carmel, to Navajo sandstone in the foreground.

fluvial and lacustrine mudstone, siltstone, and sandstone. Below these cliffs are the Summerville formation of thin-bedded siltstone and the smooth-weathering, non-marine, Entrada siltstone and sandstone which form the light-colored shoreline of Wahweap Bay (Figure 4). They weather into a light-colored sand and in some areas to a gray-colored silt which causes a cloudy silting of the shoreline waters upon disturbance.

For a considerable distance above Warm Creek Bay and at other areas to the east there are extensive level terraces capped by the marine-deposited Carmel sandstone. This caprock is composed of marine limestone, shale, calcareous sandstone, and gypsum. It frequently contains ripple marks. Because of the flatness of the Carmel platform, its mantle of weathered material and its relatively favorable fertility, these areas are usually well vegetated (Figure 5) and exemplary of the regional dominant vegetation of blackbrush (*Coleogyne ramosissima*) and Mormon tea (*Ephedra* spp.). These terraces at one time served as transportation routes, allowing easy passage once a way was found to get up and down the relatively steep, and often inaccessible, Navajo sandstone exposed between the platform and the Colorado River. Many of the chipped steps and trails, both prehistoric and historic, lead from the river up to this platform. Grazing was available principally here or on top of the higher mesas, such as Cummings Mesa.

At the lower end of the reservoir is exposed the most extensive area of the upper part of the Navajo sandstone, which, because of its thin cross-bedding of red siltstone and sandstone,

Figure 4. Entrada sandstone and siltstone in Wahweap Bay. Weathering results in a light-colored sand and a gray-colored silt.

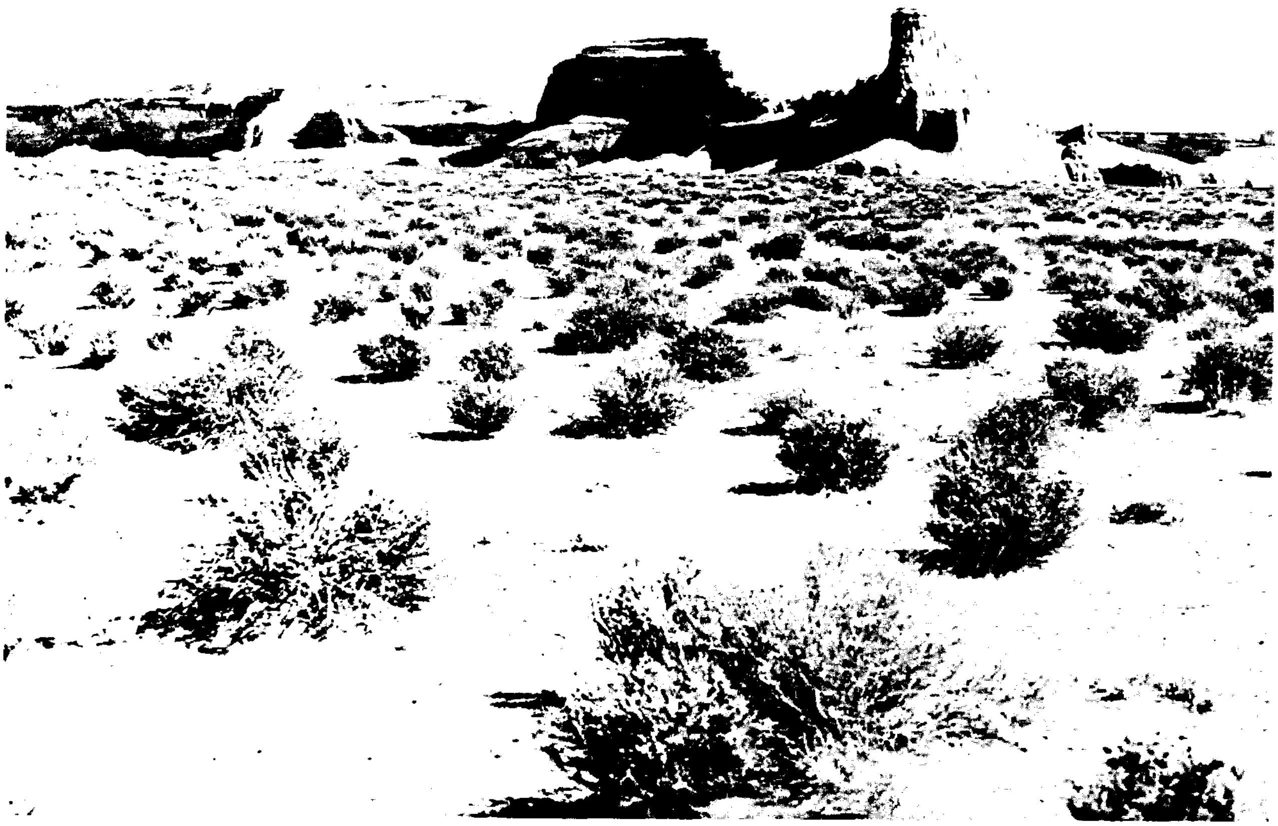


Figure 5. Flat expanse of the Carmel platform and typical regional vegetation of blackbrush (Coleogyne) and Mormon tea (Ephedra).

forms tilted shelfy terraces. This stratum also occurs in a limited area near Bullfrog Creek where the dip of the Henry Basin brings Carmel and Entrada sandstones into view.

The principal shoreline type of the lower portion of the reservoir (also seen as a dominant upper cliff wall in the upper portion) is the very thick, richly colored Navajo sandstone. From above, it is seen as soft domes, or "beehive hills," and it exhibits parallel fracture lines into which weathered particles accumulate to provide a soil for distinctive rows of vegetation, including many woody species with deep tap roots (Figure 6). Tributary streams have cut into these fractures to carve out perpendicular and overhanging cliffs, amphitheaters and alcoves, and steep-sided wedge-shaped recesses along joints. The large-scale cross-bedding characterizes this deep, extensive stratum formed during the existence of a widespread Jurassic desert.

Because of the structural condition characteristic of Navajo sandstone, softening by a seepage layer causes progressively enlarged cavate alcoves to develop along vertical cliff faces. These sometimes result in deep cave recesses and, if joined from the opposite side, a passageway covered by a natural bridge or arch.

Below the Navajo sandstone is the easily eroded purplish-red Kayenta sandstone, which forms weak terraces. The Kayenta is composed of a variety of interbedded coarse and fine-grained sandstones, clay-pebble conglomerate, shale, siltstone, and limestone deposited under streams and small lakes. It is elevated in the area of Navajo Mountain, dips, and then disappears below the mouth

Figure 6. Rectangular fracturing of the surface of Navajo sandstone. Development of tap-rooted shrubs in the fractures accentuates their presence.

of the San Juan River. It sometimes forms extensive platforms.

Below Kayenta is the massive, resistant, fine-grained, dark, blocky Wingate sandstone which forms smooth, vertical cliffs and large, rectangular blocks, commonly stained with desert varnish. Although less spectacularly cross-bedded than is Navajo sandstone, it is considered to be the result of wind deposition. The above three sandstone types are illustrated in Figure 7. These are involved in the largest fault in Glen Canyon which at Hole-in-the-Rock has been eroded into a deep notch that provided a precarious descent for a Mormon party in 1880.

In the area of the Rincon, where the Circle Cliffs uplift and Waterpocket fold have caused an uplift of underlying strata and the steepest dip in Glen Canyon, is exposed the Chinle formation which includes unstable, hydrophilic mudstones and siltstones, variably colored maroon, gray-green, gray, and purplish-gray. Triassic fossils of dinosaurs and petrified wood from swamp forests are common. The importance of this stratum to water quality is illustrated by the aerial view of the Rincon (Figure 8) showing a silt plume entering the main channel from Chinle mudstone. Softening by rising water levels causes the collapse of the overlying Wingate into great rock slides and huge spalls from the vertically fractured sandstones. Farther north in the area of Good Hope Mesa and up the San Juan River the colorful Chinle and Shinarump conglomerate of fluvial sandstone are again exposed due to uplifts (Figure 9). Also conspicuous in this area is the underlying Triassic Moenkopi formation which occurs in alternating layers of red, light brown, and

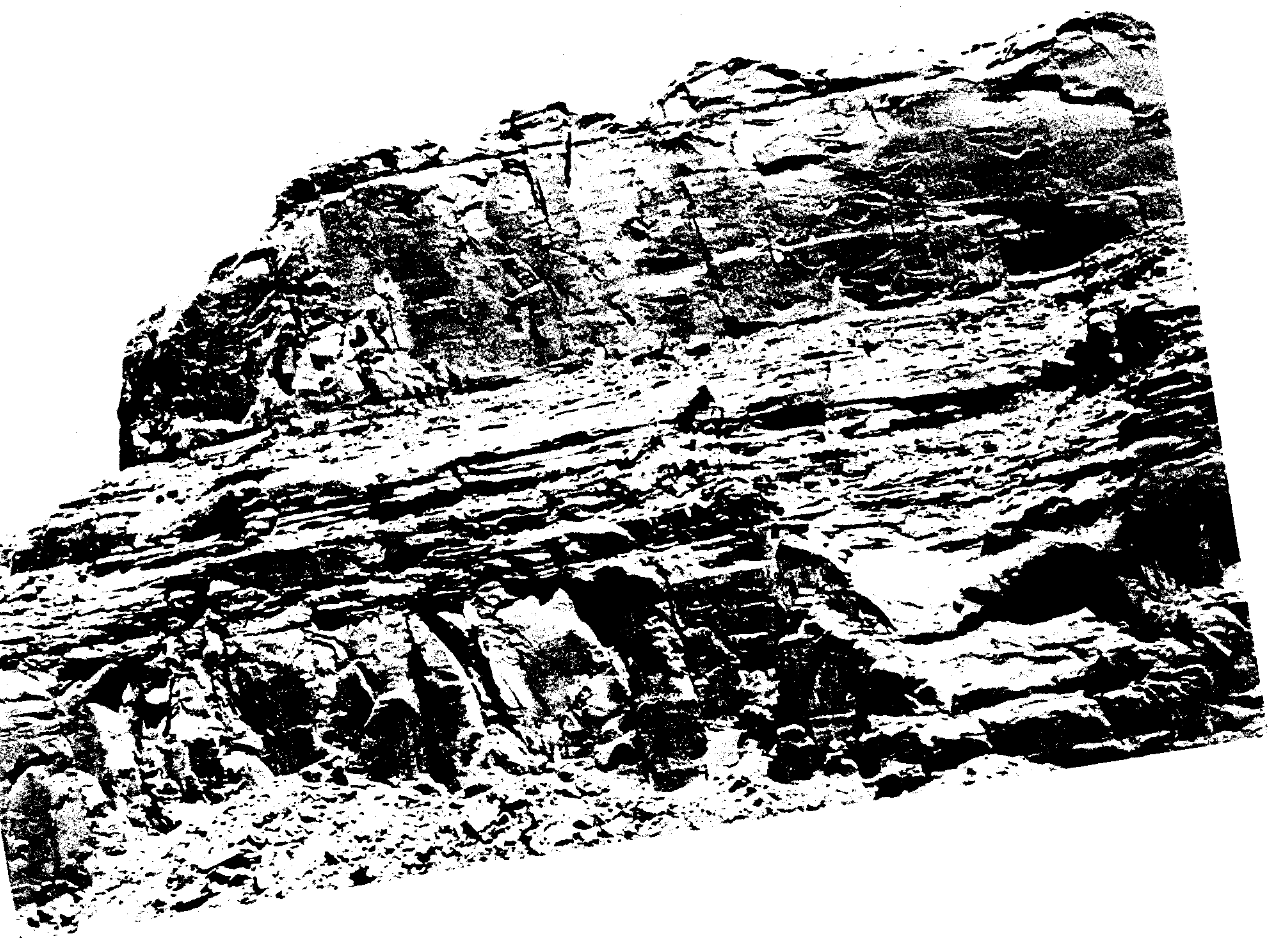


Figure 7. Navajo sandstone with domed surface erosion overlying shelfy Kayenta sandstone and basal cliffs of massive, blocky Wingate sandstone.

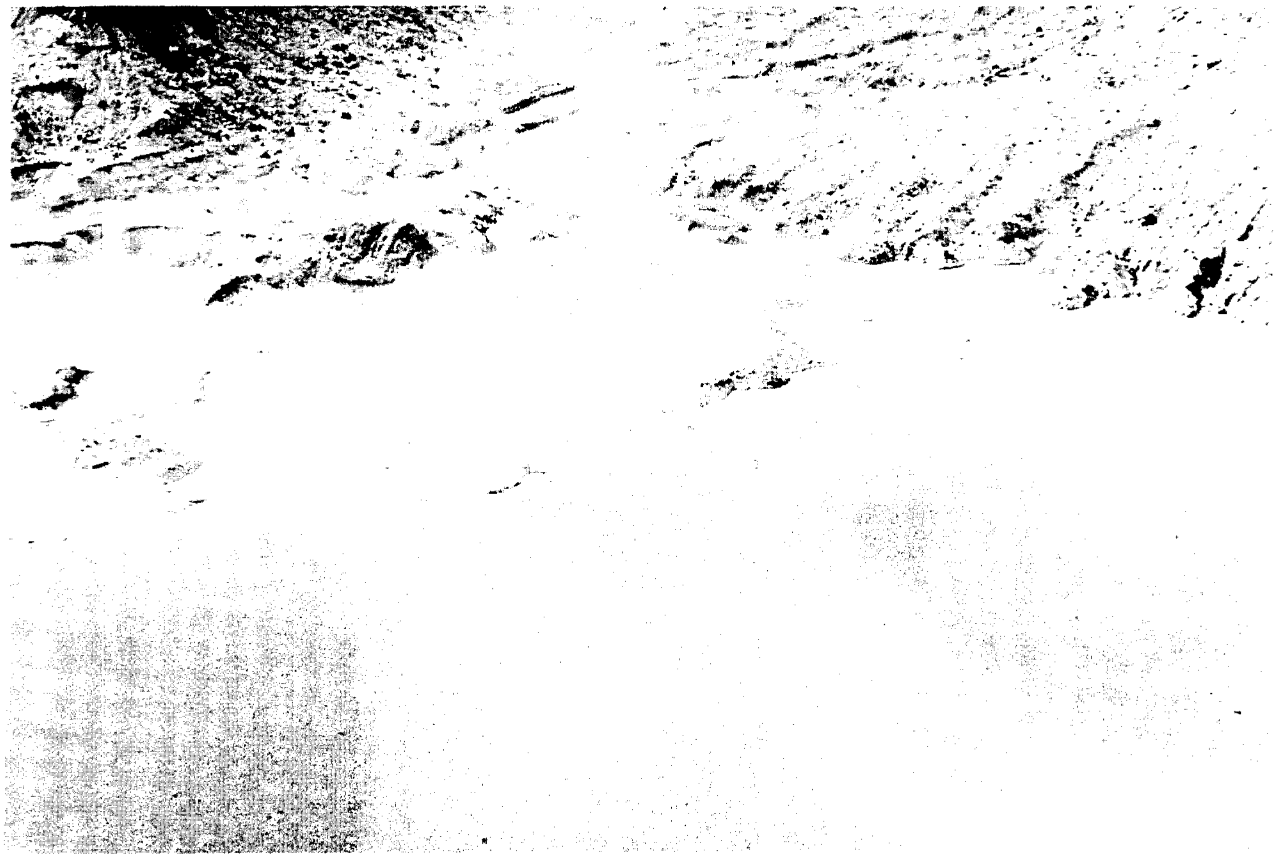


Figure 8. Silting from the mudstone of Chinle formation at the Rincon, 1970.

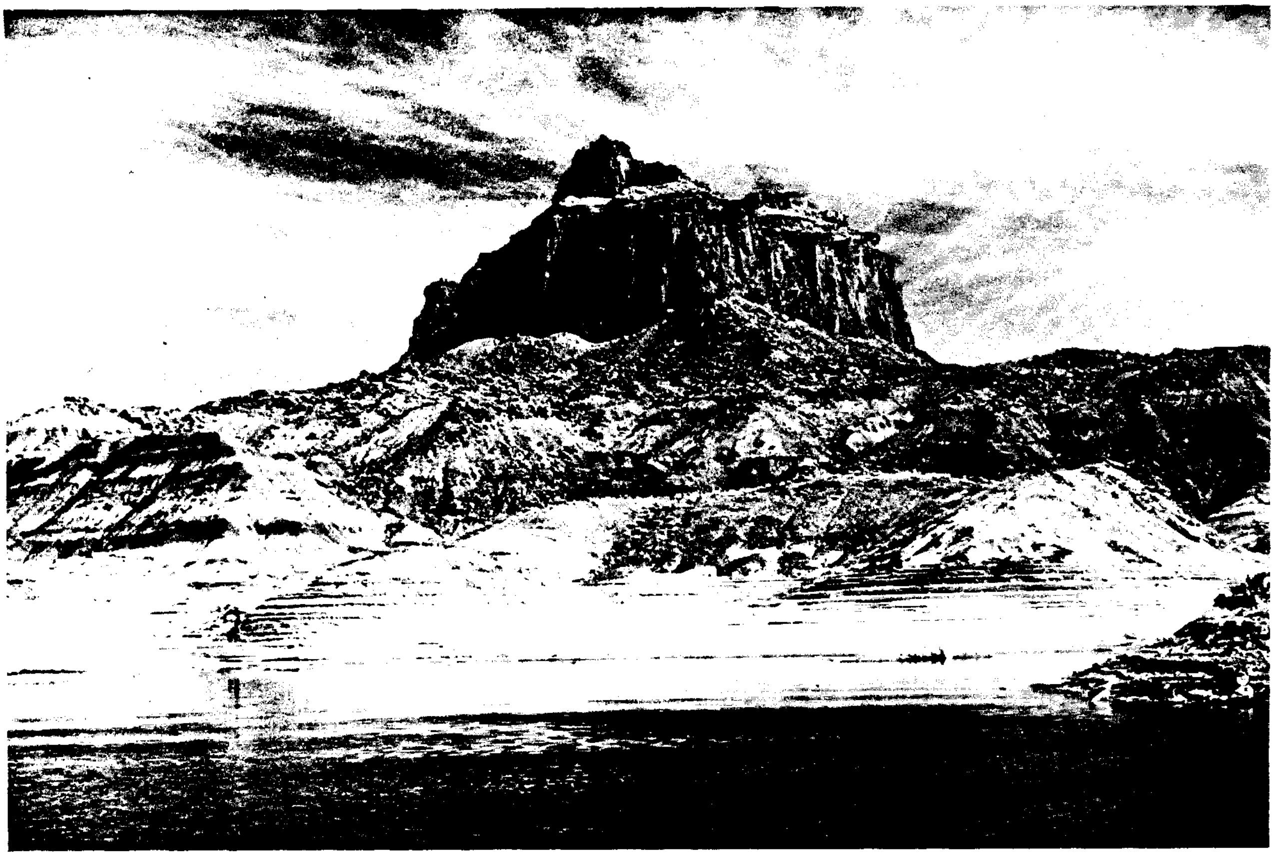


Figure 9. Colorful, eroded, many-hued strata of the Chinle formation underlying cliff-forming Wingate sandstone.

greenish brown sandstone and siltstone, frequently concealed by travertine (Figure 10). This formation is conspicuous along the shoreline to above Trachyte Canyon.

The effect of the Monument uplift is sufficient to expose Permian and Pennsylvanian sediments above Trachyte Canyon. Because of the steepness of the dip there are several exposures in the short distance from Trachyte Canyon to above the Dirty Devil River. Progressively upstream are seen the members of the Permian Cutler formation: namely, the White Rim sandstone, light gray and uniform textured; Organ Rock sandstone; and the light buff-colored, cross-bedded Cedar Mesa sandstone up to thicknesses of 1,200 feet (Rigby et al. 1971). The last member is the conspicuous stratum at the mouth of the Dirty Devil River (Figure 11).

In Narrow and Cataract canyons the transitional non-marine to marine Rico formation of gray to grayish-purple sandstone, siltstone, and limestone is exposed. Within a short distance around Mille Crag Bend and Sheep Canyon the underlying Pennsylvanian Hermosa formation of limestone and sandstone forming vertical cliffs is exposed (Figure 12). This formation extends along the shoreline to the head of Lake Powell above Gypsum Canyon.

In addition to the main axis of Lake Powell extending up the Colorado River, the lake extends approximately 75 miles up the San Juan River. The Glen Canyon National Recreation Area extends further to include the Goosenecks of the San Juan. The Hermosa is exposed in the middle part of the Halgaito anticline in

Figure 10. Multi-layered, reddish-brown Moenkopi formation.

Figure 11. Gorge of the mouth of the Dirty Devil River cut into the thick light-colored Cedar Mesa sandstone.

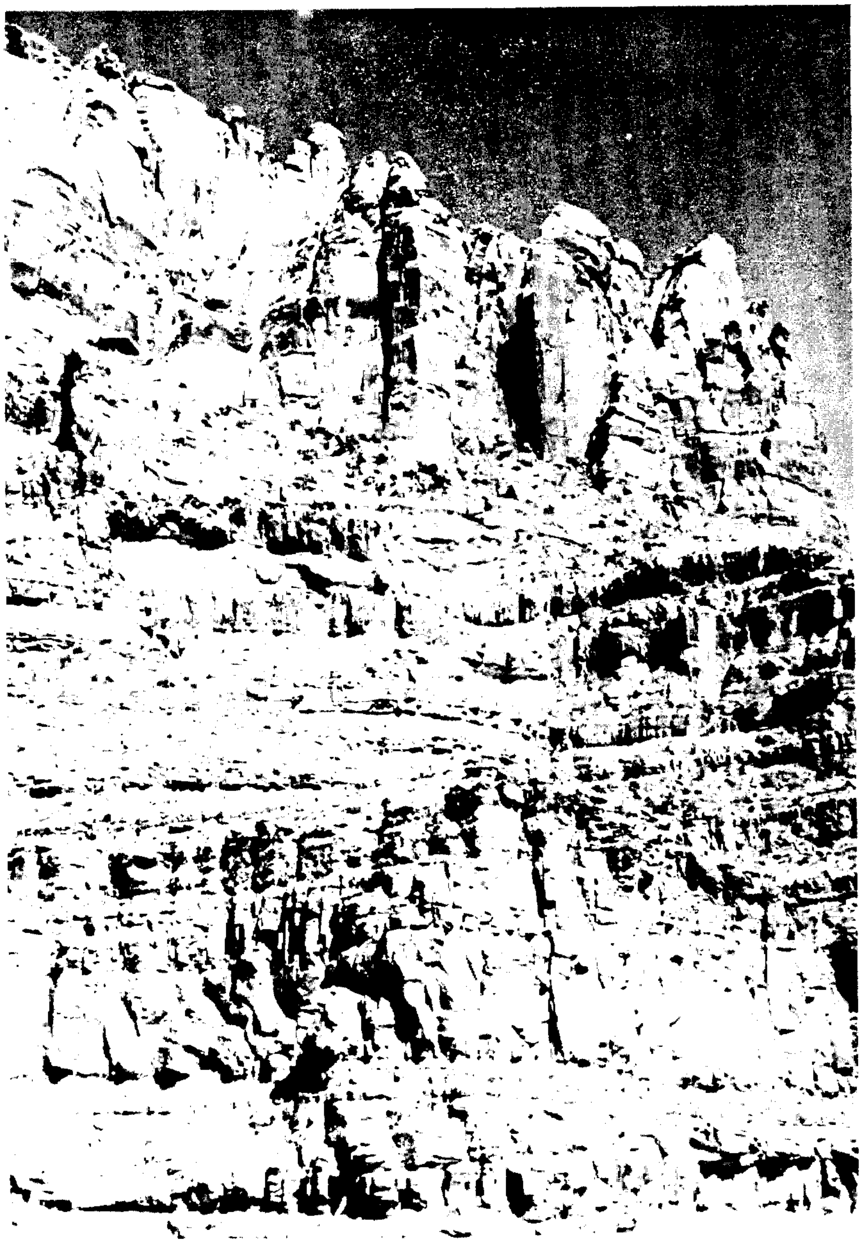


Figure 12. Steep cliff walls of Rico and Hermosa formations underlying Cedar Mesa sandstone in Narrow Canyon.

area of the Goosenecks, which provides a structural high point in the broad Monument upwarp. Here is a V-shaped gorge with a depth of 1500 feet (Figure 13). The steeply cut, thick limestone beds of the Hermosa are seen in the inner gorge; then come the smaller cliffs and benches tapering upward to the stripped plain of the top of the Rico limestone, shale, and sandstone. The Hermosa is rich in Permian marine fossils and within this area may be exposures of the gypsiferous Paradox beds. On the north side, an extensive Rico platform extends back to the Halgaito tongue which forms a sloping base to the vertical cliff of Cedar Mesa sandstone rising to the plateau of Cedar Mesa.

In contrast to the erosion of box canyons with a U-shaped profile common to cutting into weakly resistant, uniform-textured sediments, the cutting into more resistant Permian and Pennsylvanian sediments, as seen in Cataract Canyon of the Colorado River and the Goosenecks of the San Juan, results in V-shaped canyons.

The Glen Canyon area of the Canyonlands section of the Colorado Plateau, frequently called the "Escalante Country," is a most rugged and inaccessible region. Expanses are vast, desolate, and relatively uninhabited. Plateaus are deeply incised by tortuous, vertical-walled gorges, or saw-cut canyons, especially distinctive in such rocks as Navajo and Wingate sandstones. Where the cutting through these layers is into softer materials, such as the Chinle, Moenkopi, and Cutler formations, box canyons develop as in the spectacular lower San

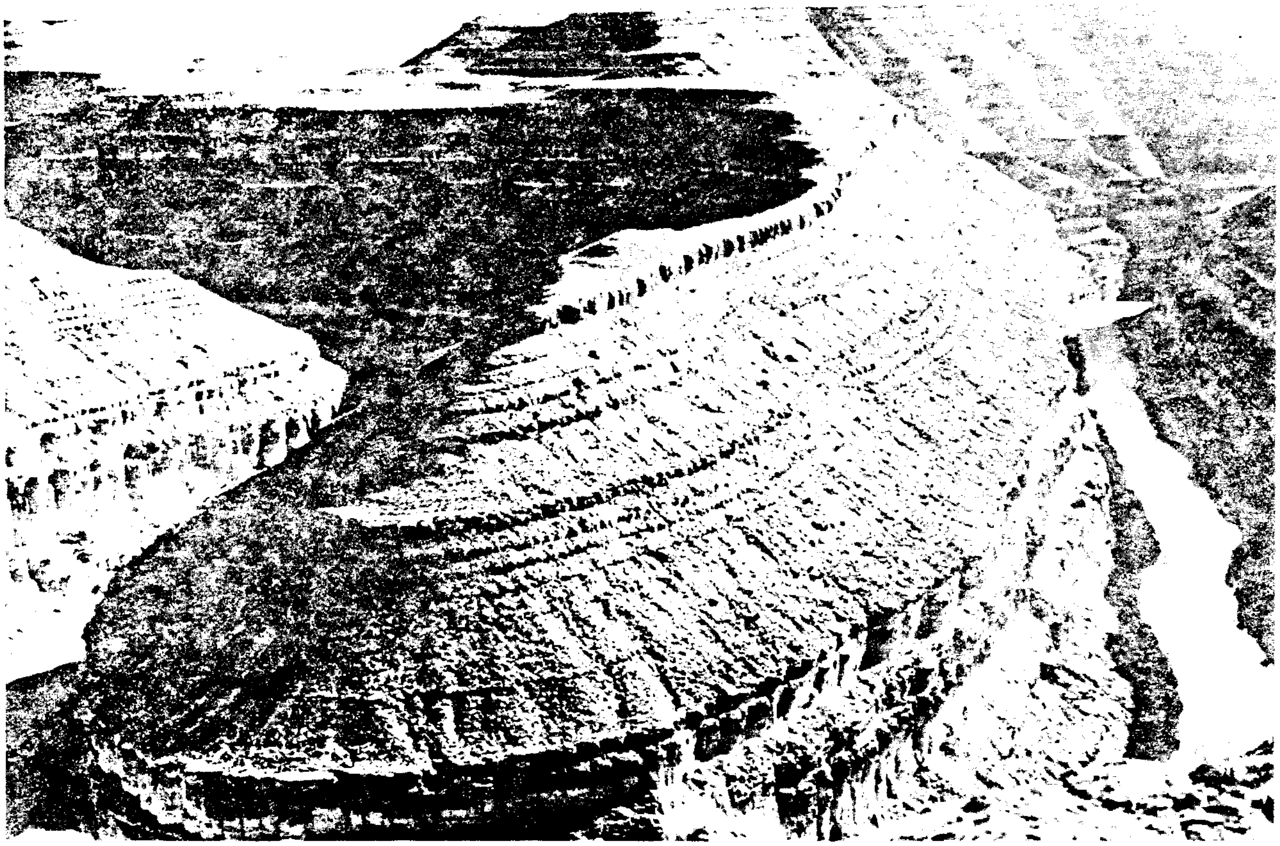


Figure 13. Oldest rock exposures in Glen Canyon National Recreation Area at Goosenecks of San Juan River. Steep inner gorge is cut vertically into Hermosa limestone. The plateau is the top of the Rico formation.

Juan Canyon. Erosional remnants of plateaus remain as isolated mesas or buttes. Upthrust areas, or laccolithic structures, appear as steeply rising mountains, e.g., the Henry Mountains and Navajo Mountain. The sparseness of vegetation, the erodability of the sandstone, and the force of intense summer thunderstorms result in a rapid run-off, the scouring and polishing of surfaces to form "slickrock," and the accumulation of eroded sand into shallow basins to form sandpockets which become the "garden spots" of the area (Figure 14). As the run-off water accumulates on the plateaus it develops a shallow drainage pattern moving downslope across the mesas, pouring across a lip at the edge, and then alternately streaming across the steep surface of the cliff face and swirling out erosional pits in soft spots (Figure 15). These pits vary from shallow, temporally wet depressions to deep, extensive ponds with marsh vegetation. Some occur at the base of waterfalls several hundred feet high which may flow only occasionally after a severe local rainstorm (Figure 16). The physiography of the Glen Canyon area and the previous geological studies have been summarized by Cooley (1958, 1959a, 1959b).

Figure 14. Sandpocket and "desert garden" in shallow basin of domed terrace.

Figure 15. Erosional pits, often retaining pools of water, in tributary drainage.

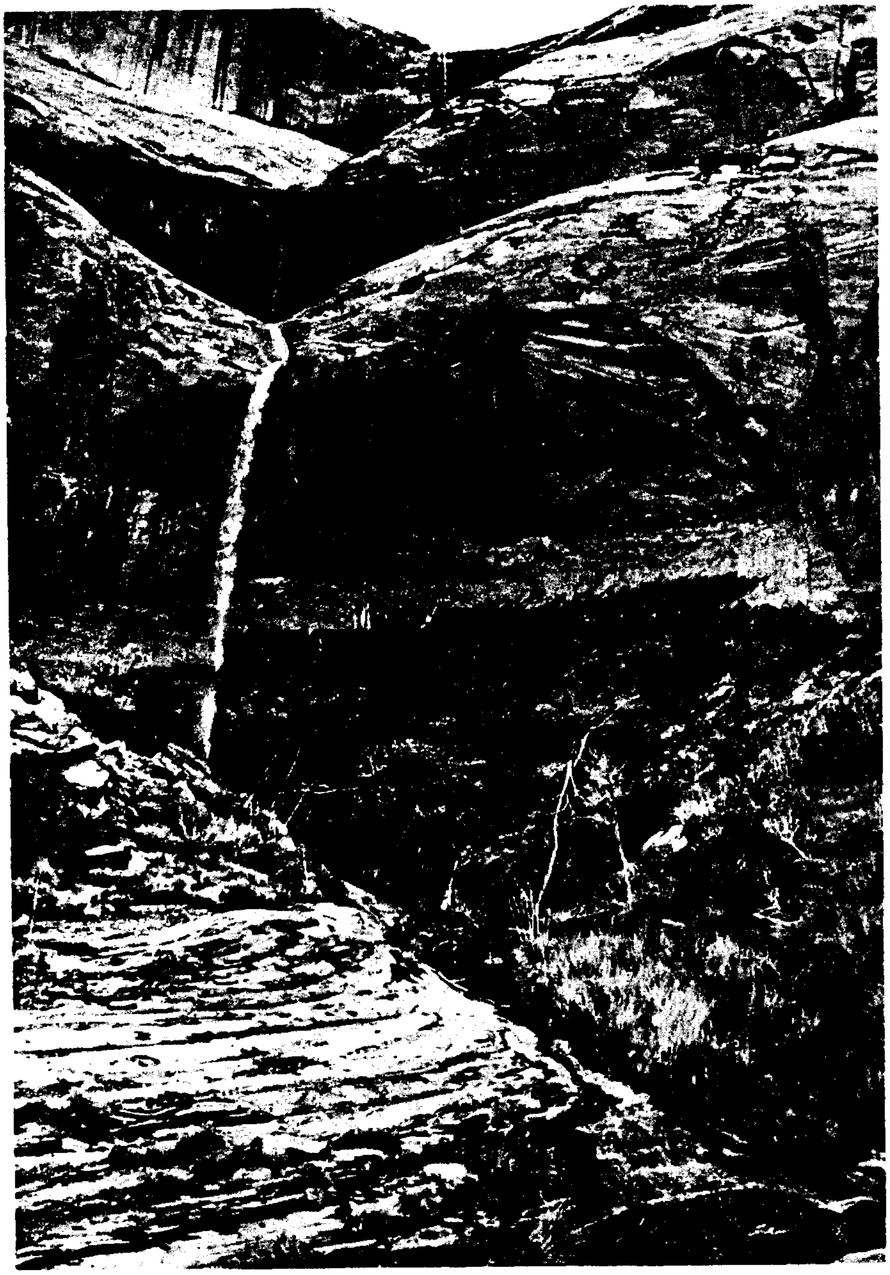


Figure 16. Temporary waterfalls after a summer thunderstorm. Splash pools and seeps below contain the most mesic vegetation of the area.

Climate

Because of the great differences in elevation within the Lake Powell region there are varying climatic conditions. The Henry Mountains to the northwest of the upper end of Lake Powell have peaks rising to elevations of 11,615 feet (Mt. Ellen). The lower portion of the lake is affected by the extensive high plateaus, e.g., the Kaiparowits to the north and Navajo Mountain rising to 10,388 feet to the southeast. The mountain peaks are high enough to have alpine conditions with high radiation, desiccating winds, and long periods of snow cover. The sub-alpine and montane slopes below supporting spruce-fir (Picea-Abies) and western yellow pine--Douglas-fir (Pinus ponderosa-Pseudotsuga menziesii) are cool and moist with local rainstorms, lowered temperatures, and reduced evaporation. Snow may occur here from September to May.

The lower mountain slopes, intermediate mesas, and high plains of 5000 to 7000 feet are transitional areas of oak (Quercus), pinyon-juniper (Pinus-Juniperus) woodland, and grassland. Annual precipitation averages about 10 inches.

Most of the Lake Powell area is in the zone classified as Upper Sonoran, at elevations of 3000 to 5000 feet. Late summer thunderstorms from air masses of the Gulf of Mexico account for the highest monthly precipitation in August and September. December and May precipitation are next high in amount. Based on 8 years of record at Wahweap the annual average precipitation is 4.78 inches. The erratic aspect of the rainfall is illustrated by that of October 1972 when nearly 4.0 inches, almost the yearly average, was received in that month. Winter rains from Pacific air masses are usually slow drizzles accompanied by snow flurries.

Also from the 8-year record at Wahweap the average maximum temperatures occur in July at 97°F but the maximum record is in June at 115°F. The average minimum is in January at 24°F and the record low is -4°F in the same month. The comfort factor in the summer when hot days often exceed 100°F is somewhat ameliorated by the cooling effect of the dry air when in the shade but the effect of the brilliant sunlight in the clear air can be extremely enervating. Its searing intensity is amplified by the high amount of reflectivity from light-colored, smooth canyon walls and the surface of the lake. Comfort at night is largely affected by the physiographic situation as it controls air movement. Vast expanses of barren sandstone heated during the day cool off slowly, and box canyons have a semblance of a kiln.

Strong continuous winds are most common from February to May, while summer winds are strong and gusty with the possibility of accompanying thunderstorms in the afternoon. Except for occasional storm fronts, the fall and early winter periods are generally calm. Surface water temperatures of the lake vary from 79°F in July and August to a low of 44°F in January.

Regional Vegetation

Within the canyonland area of Lake Powell are such mountains as Navajo Mountain to the south and the Henry Mountains to the north. Because of their elevation, these receive annual precipitation of over 10 inches, both as summer thunderstorms and as winter snow. The resulting vegetation ranges from subalpine grassland meadows, spruce-fir forest, western yellow pine--Douglas-fir forest, to pinyon-juniper woodland. The upland plateau areas are principally pinyon-juniper woodland plus a complex of types often classified as Northern Desert Shrub and including associations of big sagebrush (*Artemisia tridentata*), shadscale (*Atriplex confertifolia*), blackbrush, sand sagebrush (*Artemisia filifolia*), mat saltbush (*Atriplex corrugata*), and salt desert shrubs. Kuchler (1964) indicates the potential climax vegetation of most of the region around the lake as a blackbrush association typical of the Painted Desert, with the low, saline areas to the west and north of the lower part of Lake Powell classified as saltbush-greasewood (*Atriplex-Sarcobatus*). However, Kleiner and Harper (1972) consider the grassland plateaus to the northeast to be northern representations of desert grassland.

Because moisture is the prime limiting factor for plant growth and many species are close to their moisture tolerance limits, any features of topography, soils, or slope exposure which influence the moisture regime of the microclimate become dramatically important in affecting the nature of the vegetation.

A widespread uniform vegetational type in response to climate is not obtained in this canyonland topography. Thus, deep, shaded canyons surrounded by high vertical walls have a changed local climate featuring less aridity and a correspondingly more mesic vegetation. This trend is further developed where cavation results in overhanging alcoves and especially where these coincide, as they usually do, with a seepage line where water may perennially or seasonally flow to the surface and result in a mesic, calciphilous vegetation dominated by maidenhair fern (Adiantum capillus-veneris) or rock mat (Petrophytum caespitosum). Or, the process of weathering of cliff walls into rockslides or talus slopes provides a more receptive soil, with the advantages of both coarse and fine texture, and a resulting increase in woody, deep-rooted shrubs. Sandy soils, once stabilized, provide for deep moisture infiltration, excellent root growth, and high biomass production. Stabilization of alluvial soils along tributary canyons has led to their development into the only areas with a true soil profile. The organically enriched alluvium supports stands of oak woods with typical forest litter and understory vegetation.

The most mesic vegetation occurs at the heads of tributaries or large alcoves where water supplied from springs, seeps, or the periodic runoff from an extensive upland watershed funnels into a depression in a cliff wall and cascades down off the cliff into pools below. There, temporary ponds with marshy vegetation may develop, surrounded by a deciduous woody grove--the counterpart of a moist eastern deciduous forest stand.

HISTORICAL CHANGES

Previous Natural Science Surveys

In anticipation of the construction of four dams planned for the Upper Colorado River system, the Upper Colorado River Basin Archeological Salvage Project was sponsored by the National Park Service. Research in the Glen Canyon area was a cooperative effort between the University of Utah and the Museum of Northern Arizona. The former was responsible for archeological studies of the main Colorado River and all tributaries above the San Juan River, the right tributaries below the San Juan, and the historical and ecological research of the entire area. The Museum was responsible for the archeological studies of the San Juan, the left tributaries of the Colorado below the San Juan, and the geological research of the entire area.

Reports of early explorations of the Colorado include Ives (1861), Powell (1875), and Darrah (1951). Reports relating to the ecology of the surrounding area include a geologic reconnaissance by Gregory (1938); ecological studies of plateaus by Dixon (1935); biological studies of Navajo Mountain by Benson (1935), of the La Sal Mountains by Tanner and Hayward (1934), and of the Kaiparowits region by Tanner (1940); and a survey of recreational resources by the U.S. National Park Service (1950). Earlier faunistic studies of the Colorado River include the mammalian studies by Allen (1893) and Kelson (1951) and avian studies by Woodbury and Russel (1945) and Behle (1948). One of a few floristic studies was that of Clover and Jotter (1944).

From 1957 to 1965, personnel of the University of Utah and the Museum of Northern Arizona amassed an amazing amount of data on geology, climatology, archaeology, and biology. These data were regularly reported as a series of Glen Canyon Bulletins at each institution. Of special interest to the present Bulletin were the ecological studies of the flora and fauna in Glen Canyon by Woodbury et al. (1959) which included a summary of surveys of mammals, birds, fishes, amphibians, reptiles, endoparasites, aquatic insects, algae, and vascular plants. The entire project was excellently summarized by Jennings (1966). Other related publications on the plant ecology of the area included those of Gaines (1957; 1960); Haskell (1958); Hayward, Beck, and Tanner (1958); McDougall (1959); Haring (1961); and Porter (1963).

From a River to a Lake

Many of the aspects of the Colorado River as it was before Lake Powell can be seen today in areas of Cataract Canyon and above it. The principal source of flow is from the spring melt of snow from the Rocky Mountains, with about 70% of the annual runoff during April to July. A secondary time of inflow occurs during summer thunderstorms when there is rapid runoff from the sedimentary rock strata with minimal absorptive soils. The rush of water out of tributary canyons results in the formation of alluvial fans at their mouths through which continued flow cuts a channel. These fans may cause deflections of the main channel, or during flood stage the fan may be cut into by the river which is increased in silt burden.

At the mouths of steep tributaries, fractured blocks of rock and Pleistocene alluvium of boulders and gravel left on terraces may be washed out into the Colorado River bed to form barriers across the channel. These result in the formation of rapids in the river.

Old, stranded river terraces, some 25 feet above the river bed, provide a stabilized soil horizon added to by wind-blown sand and local fluvial material. Here a dense woody vegetation may develop (Figure 17). Below is a lower floodplain terrace occasionally covered during flood stage. The scouring effect of the silt-laden, rushing water and tumbling rocks effectively destroys most of the vegetation which has developed during low-water stages. With the retreat of the floodwaters, an ideal,

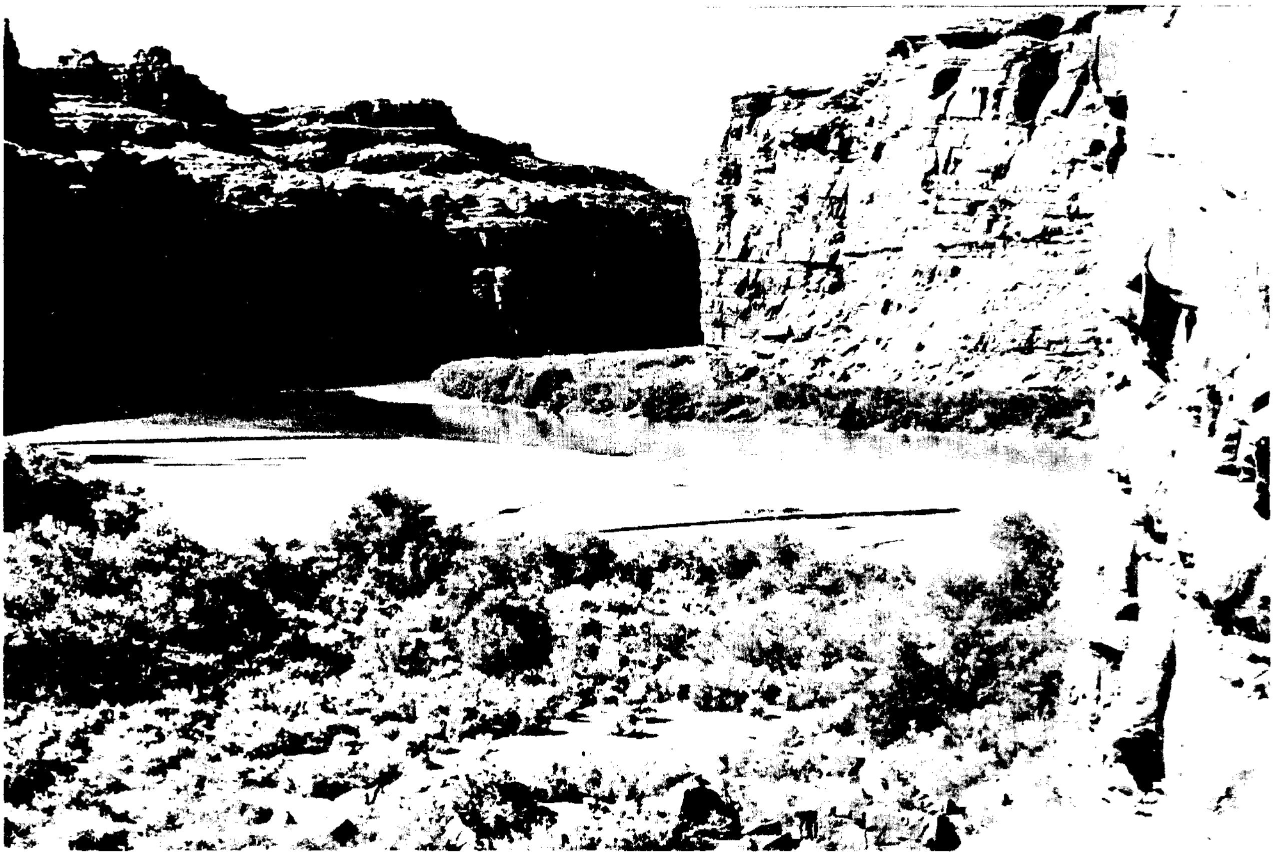


Figure 17. Quiet stretch of water of Colorado River with sand-bars and vegetation typical of that of Glen Canyon before flooding.

newly silted, moist seedbed is available for the typical plant species of sandbar and river floodplain succession. In addition to willow (Salix spp.), tamarisk or salt cedar (Tamarix pentandra) is now a common dominant pioneer, as shown in Figure 18, where, after 3 months, seedlings of this exotic form a solid green mat on the lower terrace.

The riparian, or streambank, woody vegetation varies from nothing along cliff walls to broad expanses on sandbars left by the meandering river. Woodbury et al. (1959) described the groves as being dominated by coyote willow (Salix exigua), black willow (S. goodingii), Emory baccharis (Baccharis emoryi), tamarisk, and arrowweed pluchea (Pluchea sericea). Occasionally on higher terraces and talus along the main channel, but more commonly at the mouths of and within tributaries, are found groves of Gambel oak (Quercus gambelii), netleaf hackberry or palo-blanco (Celtis reticulata), and Fremont cottonwood (Populus fremontii).

In open, damp, and marshy areas a variety of grasses, e.g., species of saltgrass (Distichlis), muhly (Muhlenbergia), common reed (Phragmites communis), and witch grass (Panicum), as well as horse's tail (Equisetum), flat sedge (Cyperus), sedge (Carex), and rush (Juncus) form saline meadows. Shrubs of rose (Rosa) and sumac (Rhus) provide an intermediate growth form.

Above the level of Lake Powell the river remains the same as it has been. Where the river flows into the lake the changes are variable. Previously established shoreline vegetation becomes permanently submerged and a new seasonal cycle of flood-

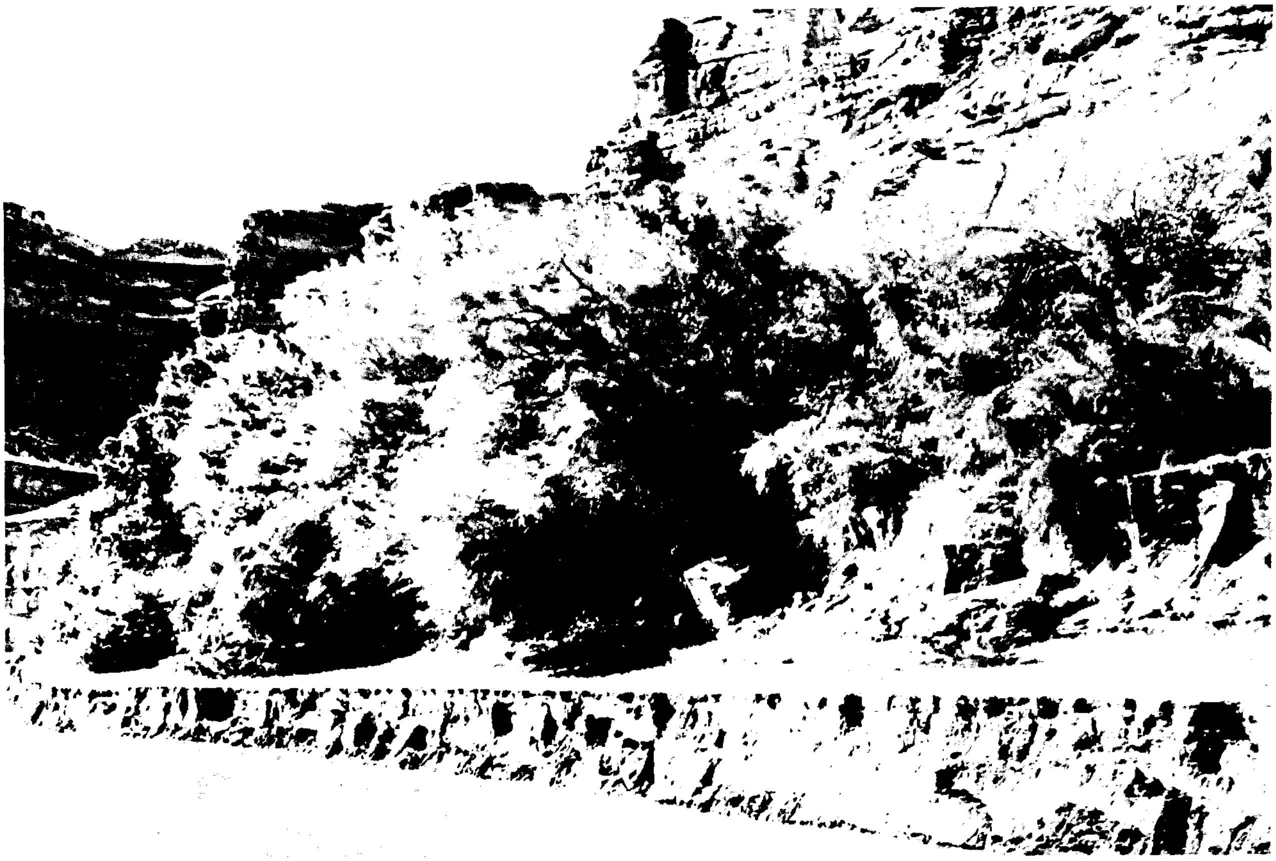


Figure 18. Invasion of tamarisk (Tamarix pentandra) on river terrace of Colorado River, Cataract Canyon. Note dense woody thicket on upper terrace. Lower flood-plain is covered solidly with tamarisk seedlings.

ing occurs, with lake level fluctuations without the impact of rushing floodwaters. In some areas there is silt deposition and throughout the lake there is the occasional impact of wave action. Water levels of the lake now are the result of controlled releases at the dam superimposed upon natural inflow rates and evaporational losses. On entering the lake the force of the current diminishes; the silt load gradually settles; and turbid, cold, saline water tends to sink toward the bottom of the lake. The boater coming down Cataract Canyon suffers a definite aesthetic let-down. From a roaring, exhilarating, enthralling, vivacious river charging its way through the canyons and over rapids the mood changes to flatness, quiet, and lack of motion which in contrast is dull and lifeless.

The transition from river characteristics to those of a lake (involving such features as flow, salinity, temperature, and biological regimes) is reported in bulletins on physical and biological limnology (Reynolds and Johnson, 1974; Hansmann, Kidd, and Gilbert, 1974; and Kidd, 1976). In spite of the great length and volume of the lake, it exhibits lateral transport and mixing features typical of a river.

Glen Canyon Dam, a structure to a height of 583 feet above the former river bed, was designed to form a reservoir which, at a 3700-foot elevation, will contain 28,040,000 acre-feet of water in a 164,000-acre area 186 miles long with a total shoreline of about 1800 miles. There is an abrupt change from lake back to river immediately below the dam. From the dam and some 15 miles through lower Glen Canyon to Lee's Ferry, which is the division between the Lower and Upper Colorado River Basins, the river has taken on new characteristics and will continue to do so.

Behind the dam, the lower depths of the reservoir become cold, nutrient-rich, higher in salinity, and low in oxygen. The intakes for the turbines are at 3470 feet, an elevation 10 feet above the estimated height of the silt level expected to occur within 100 years. (If correct, this estimate would mean a fill of 325 feet of silt in 100 years.)

The flow of water below the dam is no longer under the control of nature but of the Bureau of Reclamation. Almost none of the upstream sediment is in the river water below the dam. For example, at Lee's Ferry the median sediment concentration has decreased from 1500 to 7 ppm. The river formerly averaged 140 million tons of suspended sediment per year (0.38 million tons per day) between 1935 and 1948 (Smith, Vetter, and Cummings, 1960), but this has now been reduced to about 80,000 tons per day in Grand Canyon. The magnitude of water level fluctuation and floods has been greatly reduced, so that the upper terraces are no longer inundated and enriched by silt. The several levels of these terraces represent several common peak pre-dam flood levels. These levels now support a permanent, woody, forest vegetation. Below these terraces the pre-dam fluctuating water scoured and buried any developing vegetation. However, with the control of water releases from the dam, this area is no longer inundated and a successional vegetation is becoming established between the upper terraces and the level attained at highest post-dam discharge (about 30,000 cfs).

Figure 19 illustrates the dual-aged stands between the dam and Lee's Ferry. The large tamarisk trees in the background are pre-dam at levels above the scouring action of flood stages; the younger stand along the shoreline, which is at a water level 1 to 2 feet below post-dam flood stage, is tamarisk growth since 1963, and its height is 20 feet. The latter forms a nearly impenetrable stand of 1- to 2-inch-diameter stems. Almost as dense are the stands of sandbar willow which also produce thickets by development of root sprouts. Although they provide shade, these dense thickets are of questionable value in the improvement of campsites because of the density and the increase of associated noxious insects. The daily fluctuation of water level of 5 to 7 feet in the summer also creates a problem in mooring a boat at high level, with the possibility of having it stranded at low level. The impact of change in water erosion and deposition and man's use of the river in Grand Canyon have been reported by Dolan, Howard, and Gallenson (1974).

The balance of deposition of tributary alluvial fans and the erosion and deposition of the Colorado River downstream from the dam have been altered to a degree which may seriously affect the navigability of some stretches of white water and make the nature and use of potential campsites quite different. The release of clean water through the dam has resulted in a loss of the depositional stage of the river cycle, which is essential to form new sandbars and beaches. The erosion of finer materials is resulting in the cutting away of sand bars and in the removal of fine materials from cobble and rocky

Figure 19. Large tamarisk trees in background of an upper pre-dam terrace level; lower level is of younger thicket on post-dam terrace, Colorado River below Glen Canyon Dam.

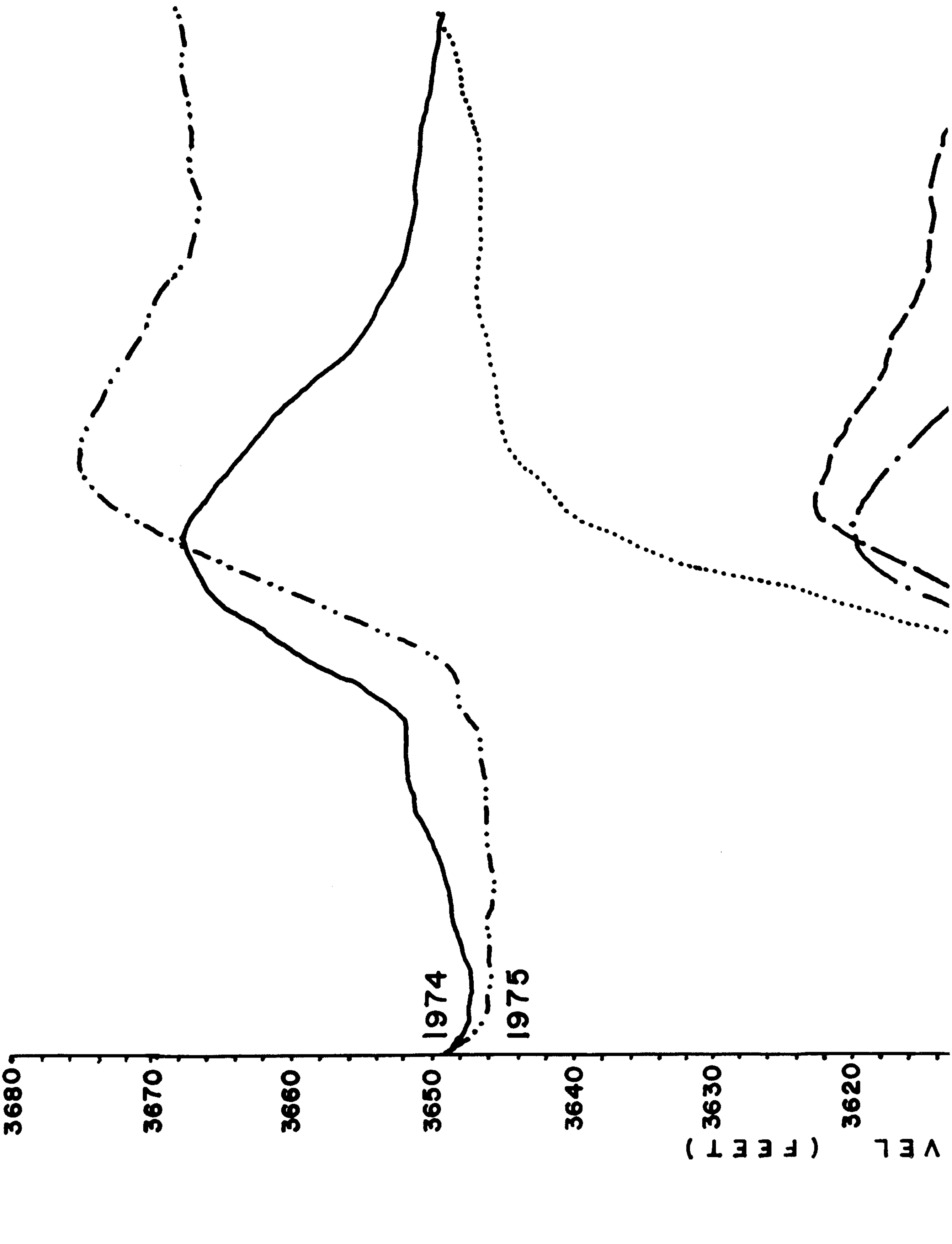
shorelines--a process also occurring along the lake shore due to wave action.

Because the water is released from the bottom of the reservoir, it is nutrient-rich and its clarity allows for increased light penetration. These factors have resulted in a great stimulation of growth of filamentous green algae across the surface of the river bed. In many areas of shallow water and for miles below the dam, the bottom is solid with long streamers of waving, verdant, matted growth. This growth would have been removed by seasonal scouring of the bottom under natural river conditions. Also of biological concern is the effect of the clear, cold water on the composition of fish species in the river below the dam.

SHORELINE SURFACE MATERIALS

Introduction

During the period of this study the reservoir has been in the process of filling--with patterns of yearly net gains, normal seasonal fluctuations due to runoff and then release with no net gain in level, and an unusual year of rapid drawdown and then filling related to a court decision and reversal. These changes are illustrated in Figure 20. The lowest seasonal level usually occurs in January with a second dip in April. The year 1970 illustrates a pattern of filling during the spring and early summer runoff when water levels rose from 3567 to 3602 feet. During 1971, levels fluctuated from 3599 to 3622 feet--a peak level which was not attained by the 3620-foot peak in 1972. Levels at the end of the season would have been even lower had it not been for the unusual 6 inches of rain from October to December 1972. In early 1973 the water level was lowered to 3590 in response to a court order that the maximum level must not exceed 3606, above which the lake would flood into the area of Rainbow Bridge National Monument. The 16-foot difference was essential to contain anticipated spring runoff. During this time there was a maximal production of hydroelectric power at Glen Canyon Dam. In late April 1973, there was a stay of the court order; the release of water through the dam and resultant power production were minimized; the reservoir filled at a new rate; and the usual drawdown after midyear never occurred. During the spring and summer, releases of water were controlled


1974
1975
3680
3670
3660
3650
3640
3630
3620
(FEET)

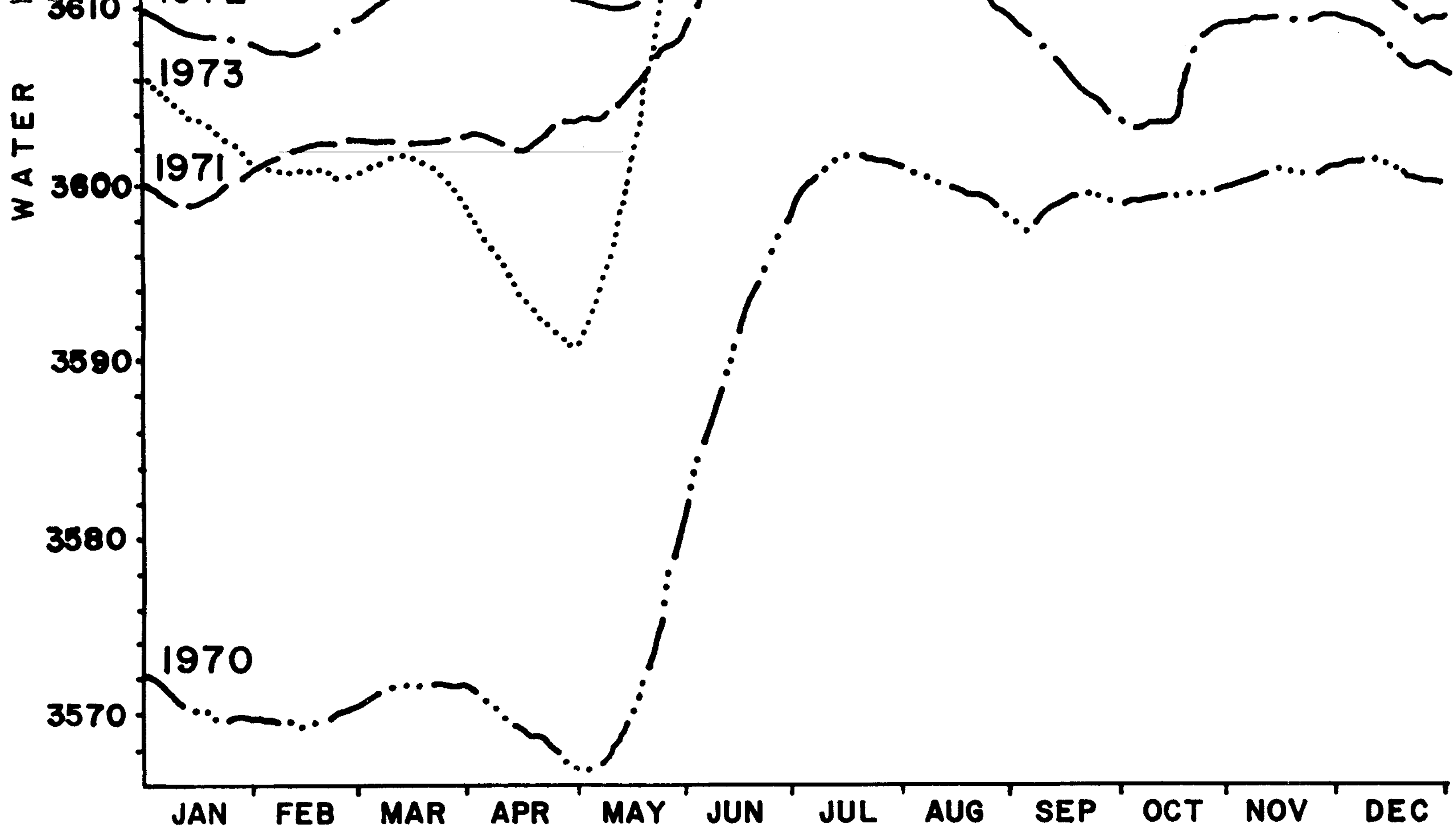


Figure 20. Seasonal water level fluctuations and filling pattern of Lake Powell, 1970-1975.

to an allowable minimum to provide required flow downstream. The reservoir level rose from 3590 to 3649 feet--this during the period of time of the alleged "energy crisis." The reservoir levels for 1974 exhibit a "no-gain" pattern starting with a low of 3647, filling to a peak at 3667, and returning to 3648. Of course, vertical fluctuations require differing volumes of water at different elevations because of the changes in contour of the basin of the reservoir. Although the total area of the reservoir and its volume always increase with increased water level elevation, they may not increase at a fixed rate because of the varying slope of shoreline provided by the various physiographic landforms (cliff, talus, terraces, etc.) along the shoreline. And, because of the tilting and warping of the sedimentary rocks, different formations and landforms are involved at any level throughout the extent of the lake. While increased levels in one tributary may result in a shift to extensive shallow bays with great increases in surface area, this is usually balanced by other areas where the shoreline becomes steeper with little increase in area. The relationship of filling of the reservoir to both surface area and volume capacity is illustrated in Figure 21. Early stages of filling within the inner channel resulted in minimal increases in capacity or area; these effects increased greatly between 3400 and 3600 feet; and above 3600 feet the increases are nearly a straight line relationship. Calculations of the percentages of the area contained in the littoral zone also show a nearly constant percentage area at elevations between 3600 and 3700

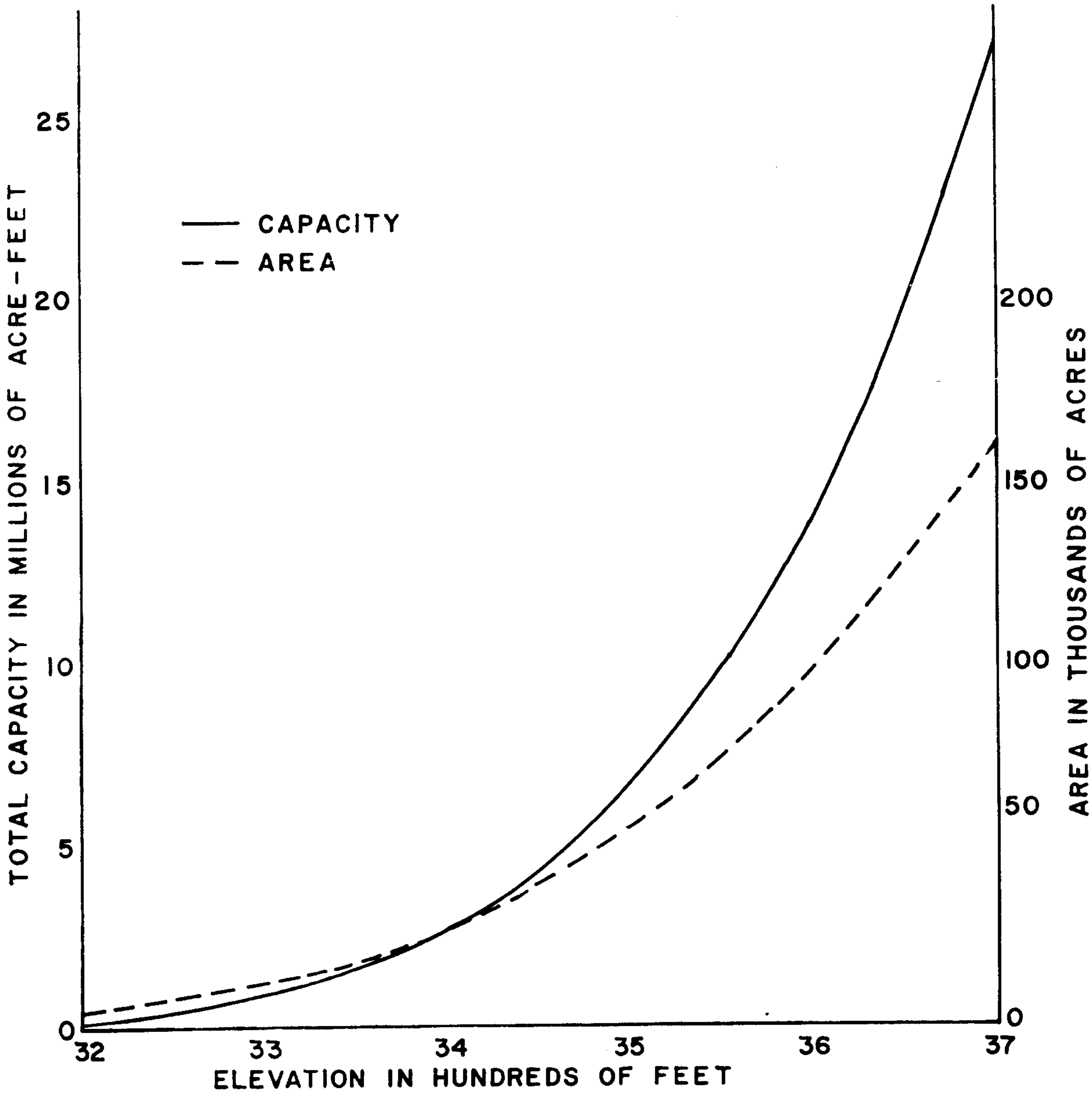


Figure 21. The correlation of reservoir capacity and surface area from 3200- to 3700-foot elevation.

feet. The nature of the surface materials of the shoreline, the physiography, texture, rock composition, and erosion obviously affect the importance of the shoreline for aesthetics, boat mooring, camping, shoreline recreation, and vegetational development above the water line and of the seasonal drawdown zone. There is also a significant effect, both direct and indirect, on the physical and biological features of the reservoir itself as there are changes in sedimentation, turbidity, wave action, aquatic vegetation, nutrient addition, and fisheries.

Shoreline Mapping

The shoreline surface types were divided into seven basic categories: cliff face, domed terrace, shelfy terrace, talus, alluvium, sand, and rockslide. Each is indicated by a type symbol when mapping. A variation was added if a thin mantle of talus, alluvium, or sand was found over a basic type (usually over domed terrace). The mantle was added in parentheses to the type symbol. After mapping portions of the reservoir at several different scales, the entire shoreline of about 1800 miles was mapped in detail on 10-foot contour maps at a scale of 1:4,000 or 13.6 inches per mile. Type differences as small as 200 feet, represented on the map as 0.5 inch, were mapped. Mapping was done to represent the shoreline types at 20-foot intervals from 3620 to 3700 feet, using up to a three-tiered classification when necessary. In a final published map only the generalized classifications for the 3620- to 3660-foot and 3660- to 3700-foot levels will be indicated because of reduction problems and expense.

Description

Cliff

The cliff face is the shoreline type for which the Canyonlands and Glen Canyon area, particularly, are most famous. The classification was used for both sheer vertical cliffs and for those too steep on which to easily land a boat and get ashore. Both types are illustrated in Figure 22, where massive vertical walls of Navajo overlie Kayenta. These cliffs are most common in areas of Navajo, Wingate, and Cedar Mesa sandstones. Also illustrated are several stages of alcove development which occurs when an underlying layer of limestone enrichment serves as a stratum of horizontal water movement and the solution of the calcium carbonate cementing material weakens its supportive capacity. At the surface of a cliff face the overlying sandstone caves in, producing an arch whose size is ever-increasing and a recessed cavate alcove. Navajo sandstone most commonly demonstrates this feature, producing great alcoves, arches, and natural bridges.

Many of the largest of these recessed alcoves, hundreds of feet wide, high, and deep, have been submerged with the rising water level. The deeply incised glens, for which the area was named, cut by rapidly descending tributaries and formerly most distinctive at the heads of canyons have now been flooded far up their course, and the cliff walls are less high and most common in the upper tributaries (Figure 23). With the rising

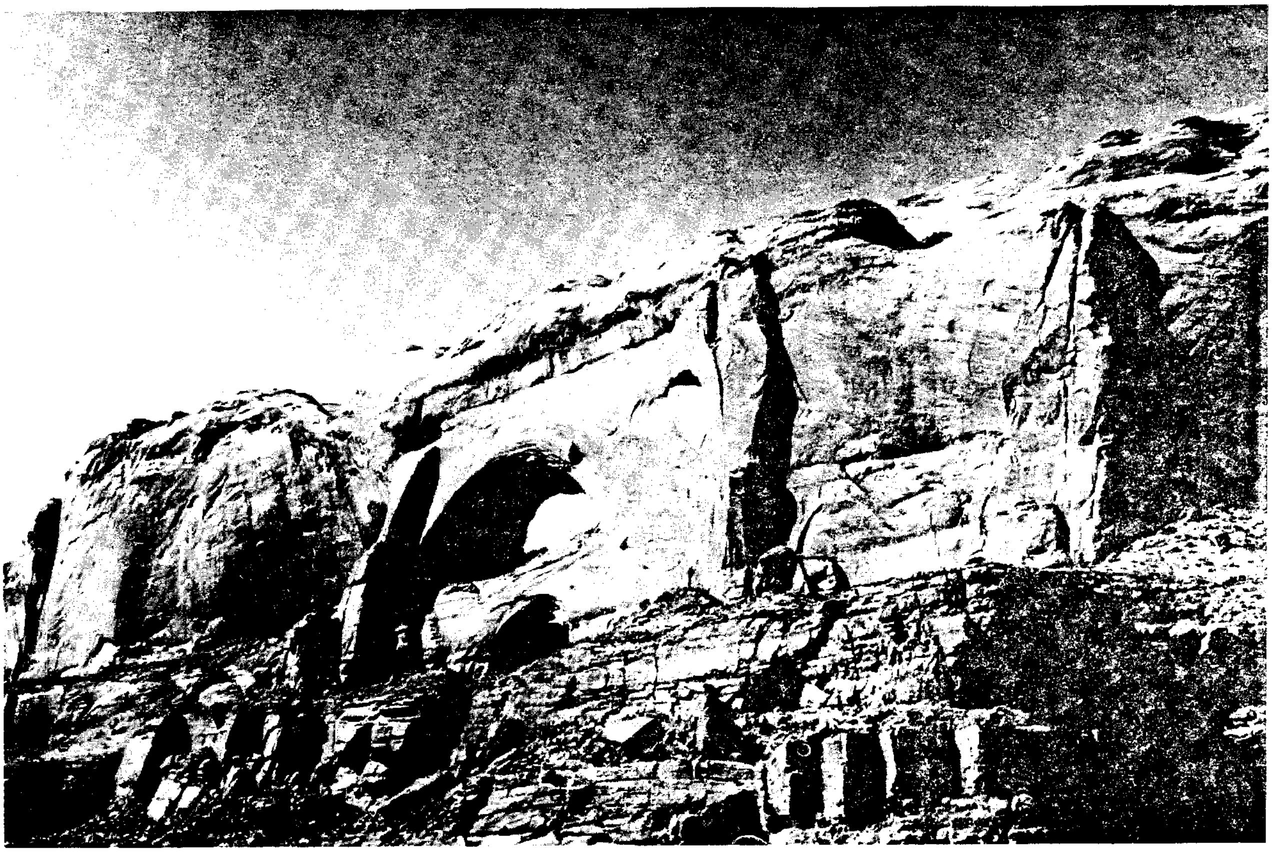


Figure 22. Cliff walls and steeply terraced slopes as exemplified by Navajo sandstone. Alcove development is common to this stratum.

Figure 23. Overhanging cliff walls of narrow glen off West Canyon.

water level and the possibility of approaching by boat, one frequently sees a variety of erosional patterns on cliff walls (Figure 24), many of which were formed during the cutting periods thousands and millions of years ago, and upon which is superimposed the continuing deposition and chemical action of highly charged mineral waters which have flowed down over the face of cliffs, frequently evaporating before reaching the base. Various patterns and shadings of patinas or desert varnish result. Alternate wetting and drying and wide temperature ranges result in exfoliation, which in this view more clearly shows the basic cross-bedding structure.

The cliff faces and alcoves are the sites of seeps. Some seeps have a perennial flow, others are sporadic, depending upon the irregular precipitation of the surrounding area which supplies the water to recharge the porous overlying sandstone aquifers. The correlation of time of increased precipitation to increased seepage at varying depths below the surface is not known to the writer. A relatively simple example is known, however, where a small catchment basin located on a plateau surface but near a cliff wall seasonally impounds water which then filters out through an enriched limestone area for a distance of several rods to a seep line along the cliff until the pond is dry.

A spectacular demonstration of the seepage of water through the porous upper Navajo sandstone of shelfy terrace topography east of Warm Creek Bay is illustrated in Figure 25. The depression shown on the left is about 15 feet deep and about 150 feet in diameter. It is separated from the rising waters of

Figure 24. Erosional pattern on vertical cliff wall exposed since Pleistocene canyon cutting.

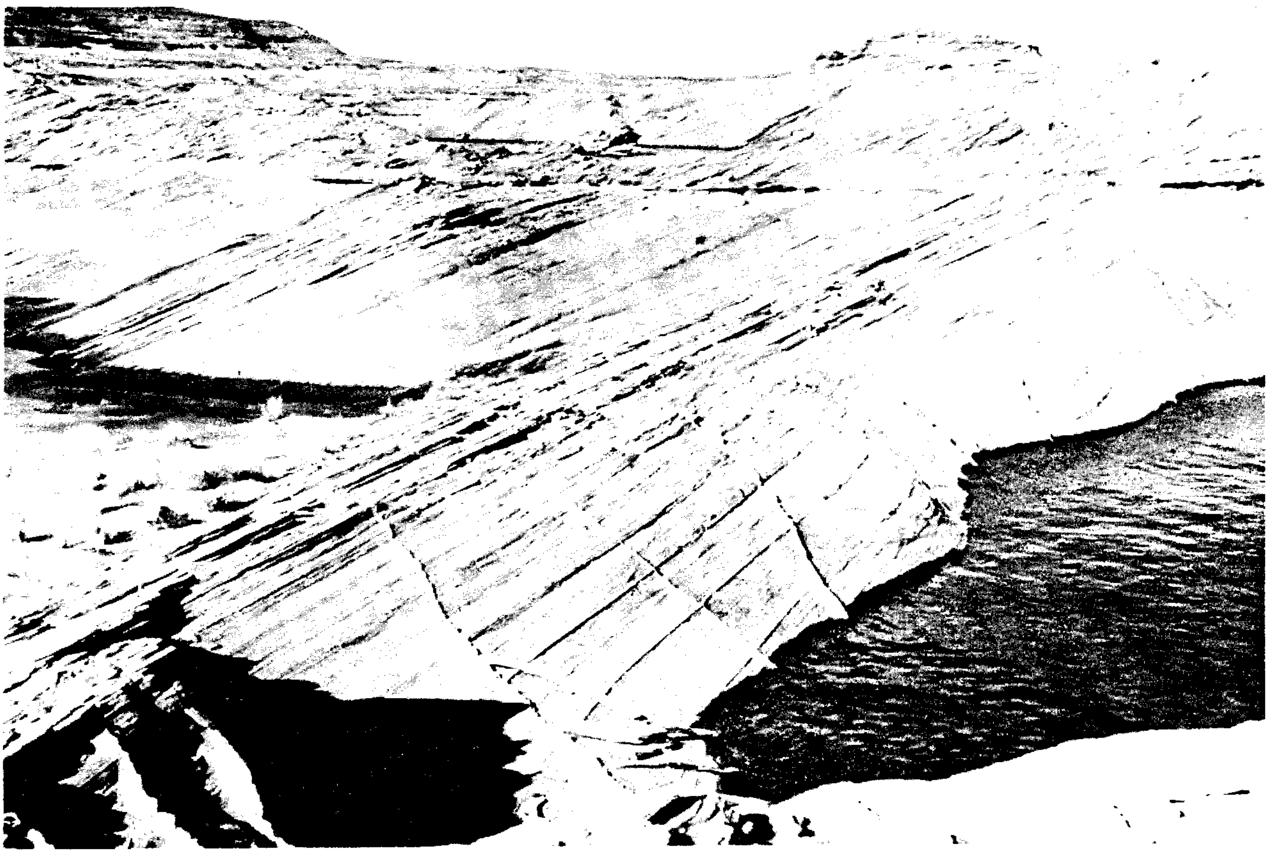


Figure 25. A natural sandstone dam separating a depression from rising waters of Lake Powell illustrates the porous nature of Navajo sandstone.

Lake Powell on the right by a sandstone dam about 100 feet long and 50 feet wide at the base tapering to a narrow crest at the top. At this place the dip of the thin, cross-bedded sandstone is toward the pond. At right angles across the dam are obliquely oriented vertical fractures which have been filled with resistant, calcite-cemented material. These are more resistant to erosion and project above the weathered surface like knife edges. During filling a differential of about 3 feet in water level was maintained by water seeping through the sandstone. An indication of the amount of seepage is revealed by Figure 26 which shows the lower side of the sandstone dam and the erosional drainage pattern cut into the sand by the water seeping through the dam.

Where a vertical series of seeps occurs at the head of a steeply descending tributary, the multi-tiered alcoves and ledges may form the headwall of a box canyon (Figure 27).

With the rising water in the reservoir there have been changes in pressure and support for vertical columns of rock along cliff faces which have resulted in opening of fracture lines, block slumps of varying vertical distances, and extensive spalls. One of the largest rock spalls along the shoreline is that on the east side of the main channel north of Iceberg Canyon (Figure 28). The north (left) half had broken off before July 1970. It was estimated to be 250 to 300 feet high, equally as wide, and about 20 feet thick. In late May 1974, the right half (illustrated) spalled off and created a wave which flattened out the vegetation on the opposite shore and picked up a boat, carried it shoreward, and left it stranded inland and

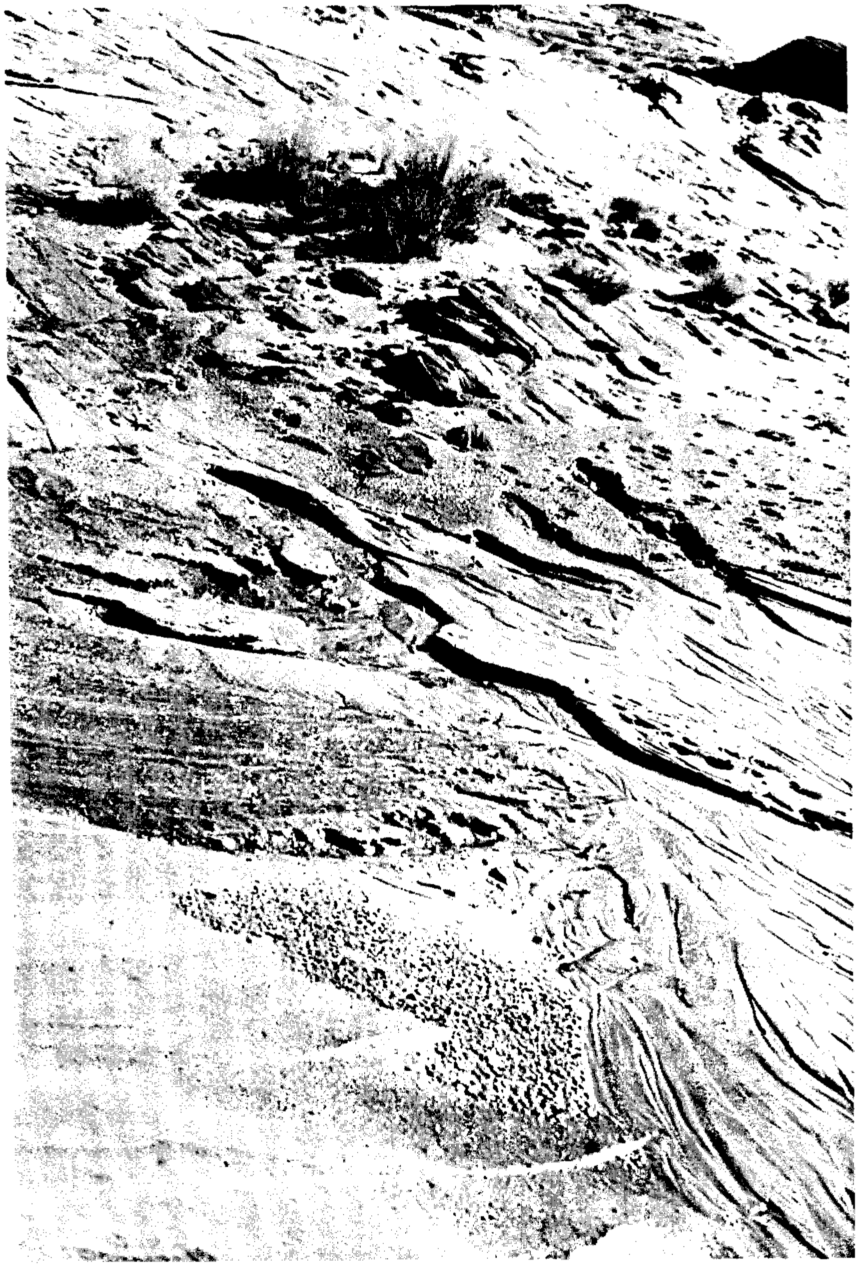


Figure 26. Evidence of seepage water passing through the sandstone dam of Figure 25.

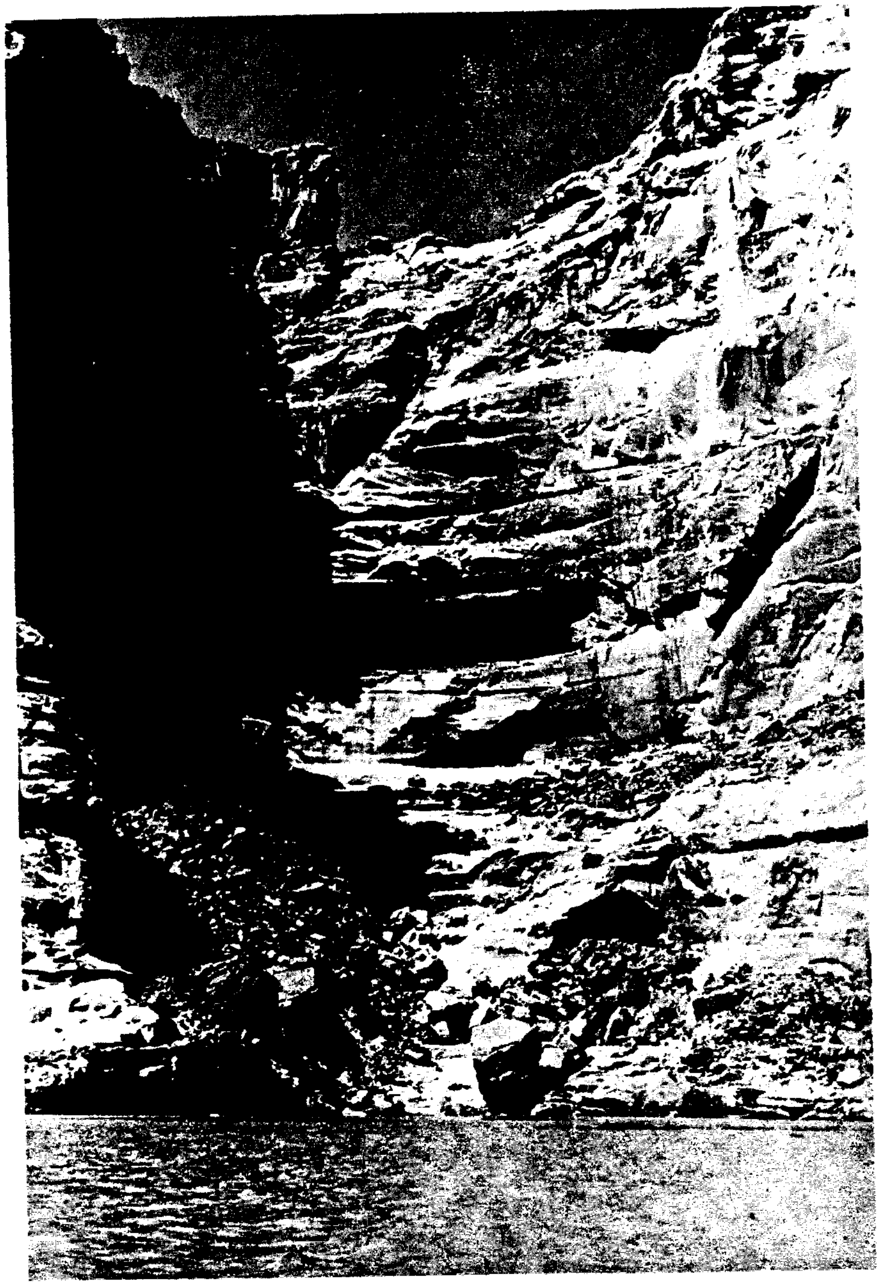


Figure 27. Headwall of a box canyon of a steeply descending tributary.

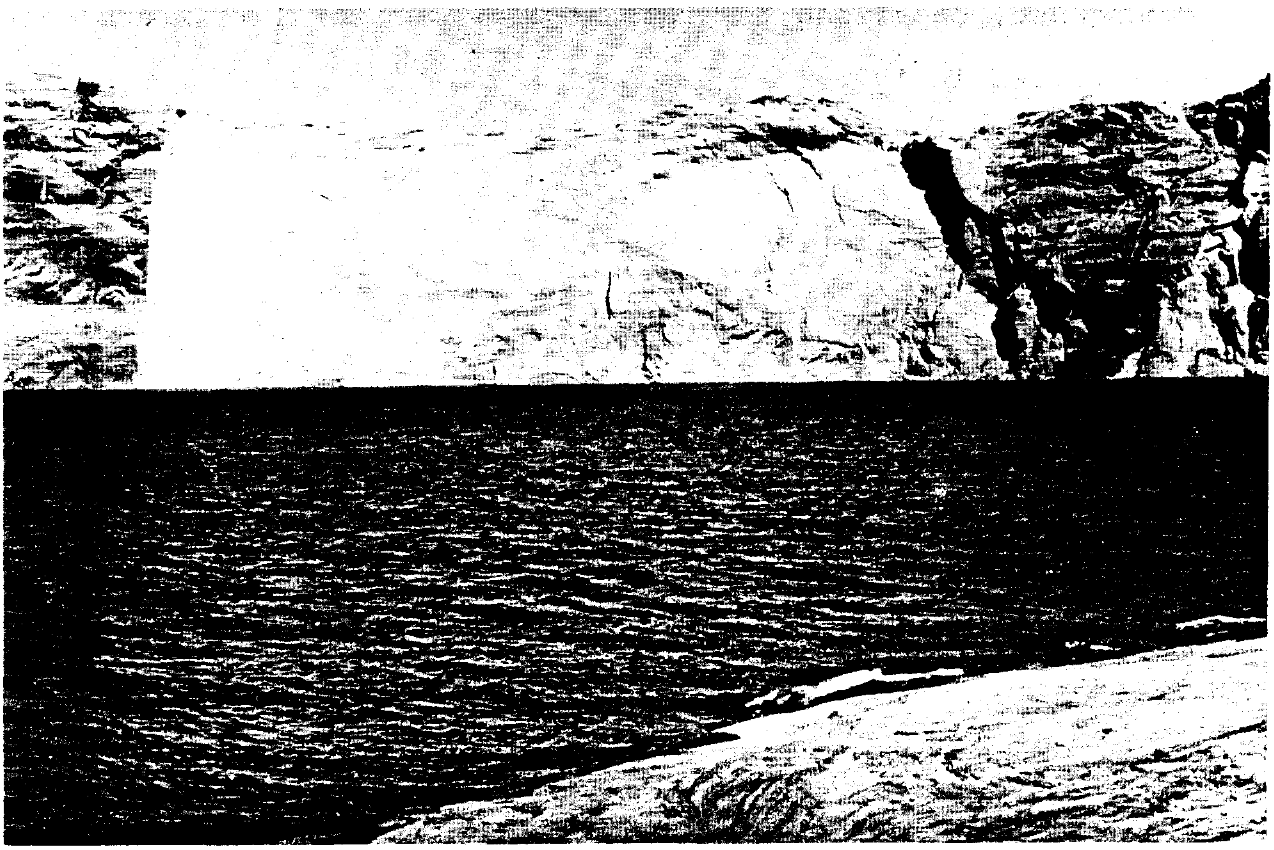


Figure 28. Result of two large adjacent rock spalls in 1970 and 1974 hundreds of feet high and wide.

about 10 feet above the water level with only the outer unit of the inboard-outboard motor damaged. The mathematical chance of a spall occurring when a boat is nearby (resulting in direct submergence, capsizing, or fatality) is a natural risk and such has occurred in 1975.

Domed Terrace

This classification refers to the smooth undulating contours that result in domes with sloping sides and gently carved-out depressions between. Navajo sandstone with its particular particle size and cross-bedding is apt to be eroded into this form. The type frequently fulfills the criteria necessary for rock campsites. By selecting the gently sloping areas between domes a boat can be safely beached and moored, especially with the aid of pitons. The rock bottom is usually smooth, unjagged, and minimally encumbered with boulders (Figure 29). Finding a level place on which to sleep is the principal problem.

This type is frequently mantled by one of a variety of other materials. Where the mantle is relatively thin and not the dominant feature it was added as a subclassification to domed terrace, e.g., domed terrace with mantle of alluvium or dune sand.

Shelfy Terrace

This is a shoreline type of limited extent and is most common to the lower end of the reservoir where the upper levels of Navajo sandstone, just below the thin layer of marine-deposited Carmel sandstone, may occur at lakeshore level. It is finely cross-bedded with alternate hard and soft layers which are fre-

Figure 29. Topography of domed terrace shoreline type. Such areas provide the best "slickrock" campsites.

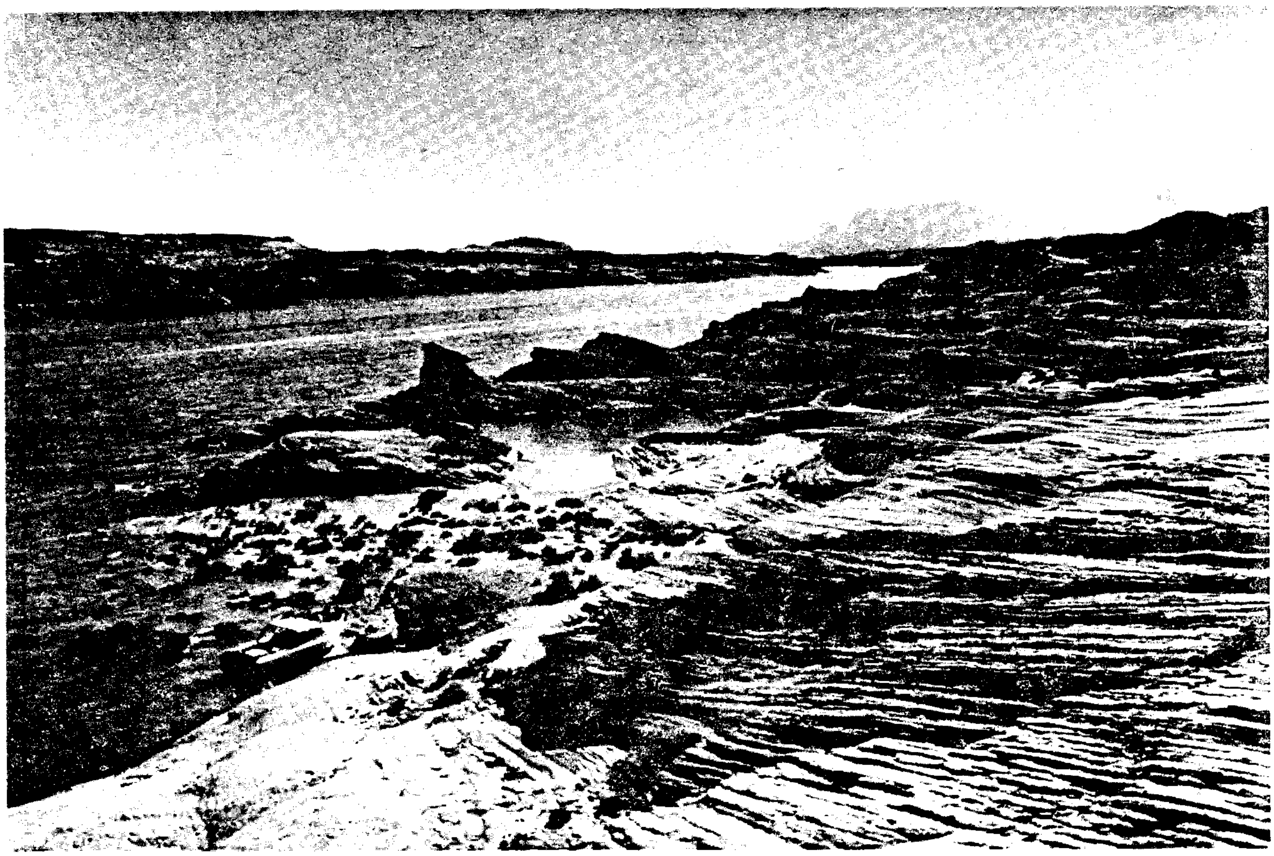


Figure 30. Shoreline of thin, cross-bedded upper Navajo sandstone forming shelfy terrace.

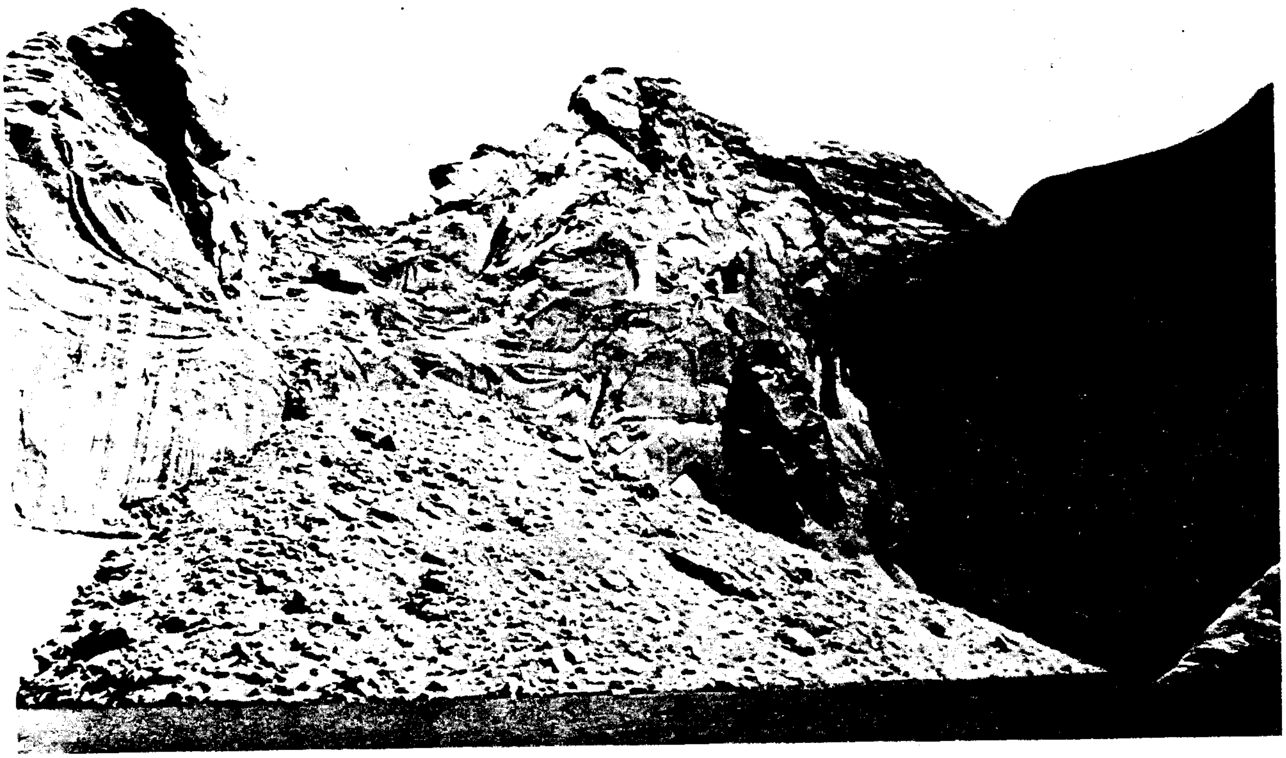


Figure 31. A typical large talus slope composed of weathered sandstone.

Figure 32. Shoreline of deep deposits of dune sand, here partially stabilized by vegetation.

with bedroll and food makes these sites least desirable.

Alluvium

Throughout the extent of Lake Powell there are areas geologically designated as Pleistocene alluvium and frequently consisting of coarse gravel and boulder mantles over old river terraces, especially domed terraces and the Carmel platform. In some areas the alluvium is relatively deep and has its own erosional contours. In a few areas there are also lacustrine deposits as developed behind beaver dams, e.g., in Lake Canyon. Now that the reservoir is nearly filled, more recent alluvium is found as a shoreline material, only toward the heads of the tributary creeks and canyons which are relatively wide and have provided opportunity for the deposition of alluvial terraces. These frequently exhibit several levels, like the main channel of the Colorado River. They provide for the richest vegetation and the highest nutrient source upon flooding by the reservoir (Figure 33).

Rockslides

These areas are of minor extent and were distinguished from coarse talus slopes by the inclusion of large blocky masses of rock which had slid downslope from their stratigraphic position. Such slides are most common in areas of exposure of the soft, crumbling, Chinle formation underlying the blocky Wingate sandstone which fractures and tumbles down over the eroded slopes of the Chinle.

Figure 33. Alluvial and lacustrine deposits showing soil horizons of previous vegetational stability.

Extent of Shoreline Types

After several seasons of field-mapping the shoreline physiographic types (at a scale of 1:4000 and guided by color-coded contour lines), the linear distances along four contours (3620, 3660, 3680, and 3700 feet) were measured. This was accomplished by the use of a map measurer along each contour line for each of the 291 maps covering the reservoir. The resulting linear distances by types are given in Table 1 for the four contours, for each of the major tributary rivers, named canyons, and for the main channel of the reservoir.

In the varying water levels from 3620 to 3700 feet there are shifts in the importance of the shoreline materials, especially cliff, terrace, and talus, within some tributaries. However, because of the several major upwarps and the general dip slope of the sedimentary layers there is no consistent shift throughout the reservoir from cliff to terrace, or vice versa. Only very minor shifts are indicated as the reservoir fills to the 3700-foot level. While regions at the upper end of the reservoir, e.g., Bullfrog Bay, seem, with increasing water levels, to exhibit the development of extensive areas of shallow waters, other regions have terraces which have already been covered, and the area is confined by cliffs. There appears to be a slight trend toward a higher percentage of the shoreline confined by cliff and talus with a corresponding decrease in domed terrace. The percentages of each type of shoreline for the four levels are summarized in Table 2. The 74% of the shoreline

Table 1. Shoreline surface types in miles at four contour levels and for each major tributary, named canyon, and the main channel of the reservoir.

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
			Domed Terrace									
				Mantle of								
		Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
Main Channel	3620	241.96	55.45		.37	35.81	24.62	85.98	5.83	1.80	6.57	458.39
	3660	259.06	54.05		.29	29.10	26.86	87.00	6.46	1.39	5.69	469.90
	3680	261.89	46.93		.29	41.10	26.20	99.11	7.12	1.91	3.78	488.33
	3700	263.76	46.82		.26	44.44	26.82	100.91	6.79	1.65	3.89	495.34
Wahweap Bay	3620	15.26	6.94		1.03	11.74	.48		14.60	3.78	.07	53.90
	3660	20.07	7.34		1.10	11.93	.29		13.76	4.55	.07	59.11
	3680	26.86	15.34		1.76	9.25	.88		11.71	.88	.04	66.72
	3700	27.52	14.68		1.32	5.39	.99		11.45	.62	.04	62.01
Antelope C.	3620	3.41										3.41
	3660	4.37										4.37
	3680	3.19					.81					4.00
	3700	3.71					1.39					5.10
Navajo C.	3620	39.67	3.49				.11	.55	.73	.70		45.25
	3660	40.84	3.85				.11	.44	.44	5.03		50.71
	3680	49.46	4.44				.07	.40	.26			54.63
	3700	54.93	5.47				.07	.37	.26			61.10

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
			Domed Terrace									
				Mantle of								
		Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
Warm Creek Bay	3620	4.15	7.16		.88	9.03	2.24	.29	12.07	5.32		41.14
	3660	4.11	6.83		2.97	14.60	1.98	.44	11.74	6.72		49.39
	3680	3.38	2.31		4.66	21.76	1.98		11.38	10.09		55.56
	3700	4.55	1.87		6.02	26.20	1.98		10.93	10.27		61.82
Labyrinth C.	3620	3.89	4.00				.18					8.07
	3660	4.04	3.78				.07					7.89
	3680		7.67				.07					7.74
	3700		8.26				.07					8.33
Gunsight C.	3620	2.61	1.47			6.05		1.36	.51			12.00
	3660	4.92	1.06			6.53		1.36	.48			14.35
	3680	3.93	2.57			4.62		1.10	2.72			14.94
	3700	3.74	2.50			4.40		1.10	3.67			15.41
Padre Bay	3620	21.10	8.40		5.91	8.48	2.72	3.60	4.81	4.04		59.06
	3660	21.98	7.60		5.80	4.29	3.49	3.12	4.00	5.76		56.04
	3680	26.60	10.86		3.85	10.42	3.71	4.62	2.05			62.11
	3700	27.30	11.63		1.83	9.25	3.34	4.48	2.20			60.03
Face C.	3620	13.76	2.13				4.48		.15			20.52
	3660	14.90	1.76				4.66		.29			21.61
	3680	15.04	1.21			2.68	4.07					23.00
	3700	17.32	1.03			2.68	4.22					25.25

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
			Domed Terrace									
				Mantle of								
		Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
Last Chance Bay	3620	44.47	4.00			.84		21.69	.26		1.21	72.47
	3660	46.09	3.08			.59		25.10	.07	1.69	1.14	77.76
	3680	51.19	.84	.66		.73		17.69			1.32	72.43
	3700	52.91	.92	.70		.88		18.60			1.32	75.33
West C.	3620	12.99	9.69	.29	.07	3.41		.70	.04			27.19
	3660	15.26	11.27	.07	.11	2.72		.66	.04			30.13
	3680	19.45	7.63			3.30			.04			30.42
	3700	24.92	7.60			2.79			.04			35.35
Friendship Cove	3620	.84			.26			3.23	1.17		.33	5.83
	3660	.70			.59	.88		2.61	1.03		.33	6.14
	3680	3.60			.62			2.39				6.61
	3700	3.67			.51			2.09				6.27
Rock Creek	3620	21.39	1.17		.99	5.98		11.16	.84	.22	.11	41.86
	3660	26.82	1.69		.51	9.43		11.19	.18	.22	.07	50.11
	3680	40.14	2.79		.51	4.70		5.58	.18	.22		54.12
	3700	42.53	2.68		.48	5.28		6.13	.11	.33		57.54

Table 1 (continued)

Area	Contour (feet)	Cliff	Domed Terrace: Barren	Domed Terrace: Mantle of Talus	Domed Terrace: Mantle of Sand	Domed Terrace: Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
		Shoreline Surface Types (distance in miles)										
Dungeon C.	3620	1.06	.55			2.09		.48	.22			4.40
	3660	1.47	.48			3.19		.92	.07			6.13
	3680					.66		4.55	.04			5.25
	3700					.51		5.25	.04			5.80
Wetherill C.	3620	6.57	5.10									11.67
	3660	7.60	4.95									12.55
	3680	10.02	3.23			.07						13.32
	3700	10.24	3.41			.07						13.72
Cornerstone C.	3620	.11					1.03					1.14
	3660	.11					.84					.95
	3680						.81	.15				.96
	3700						.73	.15				.88
Dangling Rope C.	3620	7.60	1.76				.37					9.73
	3660	8.62	1.47				.84					10.92
	3680	9.98	1.36				1.21	.07				12.62
	3700	10.05	1.39				1.43	.07				12.94
Mountain Sheep C.	3620	3.12	6.86									9.98
	3660	4.33	8.04									12.37
	3680	6.05	6.90									12.95
	3700	6.53	6.94									13.47

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles): Cliff	Domed Terrace: Barren	Domed Terrace, Mantle of: Talus	Domed Terrace, Mantle of: Sand	Domed Terrace, Mantle of: Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
Balanced Rock C.	3620	.84	.22									1.06
	3660	1.21	.51									1.72
	3680	2.28	.66									2.94
	3700	2.42	.88									3.30
Little Arch C.	3620	.99										.99
	3660	1.10										1.10
	3680	1.39										1.39
	3700	1.47										1.47
Cathedral C.	3620	8.22	4.04					.44				12.70
	3660	9.98	4.18					.55				14.71
	3680	10.57	3.38									13.95
	3700	11.60	3.12									14.72
Driftwood C.	3620	2.28	.73									3.01
	3660	2.72	.62									3.34
	3680	2.97	.40									3.37
	3700	3.01	.40									3.41

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles). Cliff	Domed Terrace: Barren	Domed Terrace: Mantle of Talus	Domed Terrace: Mantle of Sand	Domed Terrace: Alluvium	Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
Cascade C.	3620	2.79	.07									2.86
	3660	3.56	.11									3.67
	3680	3.93	.04									3.97
	3700	4.00	.04									4.04
Forbidding C.	3620	13.43				.29		.04				13.76
	3660	15.63				.29		.04				15.96
	3680	18.02										18.02
	3700	18.64										18.64
Twilight C. (Navajo V.)	3620	5.65										5.65
	3660	6.90										6.90
	3680	7.63										7.63
	3700	8.22										8.22
Secret C.	3620	2.09				.26						2.35
	3660	1.98				.44						2.42
	3680	2.94	.33									3.27
	3700	2.39	.33									2.72
Oak C.	3620	1.17						.04				1.21
	3660	1.17						.73				1.90
	3680	2.79										2.79
	3700	3.45										3.45

Table 1 (continued)

		Shoreline Surface Types (distance in miles)										
			Domed Terrace									
				Mantle of								
Area	Contour (feet)	Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
Anasazi C. (Mystery)	3620	6.83	.18									7.01
	3660	6.90	.22									7.12
	3680	8.15										8.15
	3700	8.15										8.15
Hidden Passage C.	3620	3.38	.37									3.75
	3660	3.89	.37									4.26
	3680	4.48										4.48
	3700	4.59										4.59
Reflection C.	3620	5.14	.59					1.76		.04	.04	7.57
	3660	5.54	.70					2.24		.66	.04	9.18
	3680	8.66	.44					.95			.07	10.12
	3700	8.92	.37					.95			.07	10.31
San Juan R.	3620	88.73	5.87			21.12		81.44	.38	.38	.57	198.49
	3660	98.86	5.40			33.81		87.31	.38	.38	.57	226.71
	3680	100.28	4.07			27.75		101.23	4.07		.76	238.16
	3700	114.49	3.50			32.48		102.75	3.22		.76	257.20

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
			Domed Terrace									
				Mantle of								
		Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
Llewellyn Gulch	3620	2.72			.15	.37		.37				3.61
	3660	2.64			.22	.51		.33		.07		3.77
	3680	1.98			.22	1.17		1.47				4.84
	3700	2.09			.22	1.65		2.02				5.98
Cottonwood C.	3620	1.47						.70				2.17
	3660	3.01						.88				3.89
	3680	2.05				.84		2.35				5.24
	3700	2.42				.81		2.94				6.17
Ribbon C.	3620	1.69						.51			.04	2.24
	3660	1.76						.70			.04	2.50
	3680	1.50						1.14			.04	2.68
	3700	1.47						1.47			.04	2.98
Escalante R.	3620	65.94	4.44		.11	2.46		10.60	.84	.15	.66	85.20
	3660	76.03	4.44		.11	2.39		12.07	1.25	.44	.70	97.43
	3680	84.40	4.15		.04	.33		9.87	.62		.55	99.96
	3700	90.60	4.07		.04	.26		10.49	.59		.62	106.67
Long C. (Navajo Cr.)	3620	2.94										2.94
	3660	3.38										3.38
	3680	3.74										3.74
	3700	3.89										3.89

Table 1 (continued)

Area	Contour (feet)	Cliff	Domed Terrace: Barren	Domed Terrace: Mantle of Talus	Domed Terrace: Mantle of Sand	Domed Terrace: Mantle of Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
		Shoreline Surface Types (distance in miles)										
Iceberg C.	3620	7.93	.29					3.34			.22	11.78
	3660	8.15	.26					5.06		.88	.37	14.72
	3680	11.71						2.83		1.98	.59	17.11
	3700	13.61						3.08		2.94	.51	20.14
Slick Rock C.	3620	.33						2.16			.15	2.64
	3660	.40						3.16			.11	3.67
	3680	.44						3.16			.07	3.67
	3700	.44						3.23			.07	3.74
Annies C.	3620	.15						.07				.22
	3660	.15						.07				.22
	3680	.22										.22
	3700	.22										.22
Lake C.	3620	8.95	1.50					.07		.88		11.40
	3660	8.88	2.61					.04		2.31		13.84
	3680	9.76	6.68					.04				16.48
	3700	11.23	7.63					.04				18.90

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
			Domed Terrace				Shelfy Terrace					
				Mantle of								
		Cliff	Barren	Talus	Sand	Alluvium	Talus	Sand	Alluv-ium	Rock Slide	Total
Lost Eden C.	3620	3.93									3.93
	3660	4.07									4.07
	3680	4.62									4.62
	3700	4.77									4.77
Halls Creek Bay	3620	3.56	4.22			12.11	.07		1.91		21.87
	3660	3.45	4.40			13.76	.07		7.12		28.80
	3680	5.76	4.15			10.46	9.43				29.80
	3700	4.81	3.93			9.32	13.76				31.82
Bullfrog Bay	3620	6.31	2.02		1.28	29.65	2.57		.22		42.05
	3660	9.43	2.24		1.83	41.17	1.91		1.76		58.34
	3680	8.15	3.63		2.20	45.79	1.32				61.09
	3700	9.17	4.62		2.13	42.27	1.32				59.51
Moqui C. & North Gulch	3620	11.30	.07				1.25	1.06	.07		13.75
	3660	12.00	.04				1.39	2.42	.07		15.92
	3680	17.61									17.61
	3700	19.01									19.01
Hansen Creek C.	3620	4.15	2.42			.04	.15	.26	.48		7.50
	3660	4.70	2.83			.26	.07	.29	1.91		10.06
	3680	4.59	3.78			.18	.40	.26	1.43	1.32	11.96
	3700	5.83	4.18			.37	.33	.26	1.39	1.32	13.68

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles): Cliff	Domed Terrace: Barren	Domed Terrace, Mantle of: Talus	Domed Terrace, Mantle of: Sand	Domed Terrace, Mantle of: Alluvium	Shelfy Terrace	Talus	Sand	Alluv- ium	Rock Slide	Total
Crystal Spring C.	3620	5.03	.29					.40				5.72
	3660	5.14	.26					.40				5.80
	3680	5.17	.81					.07				6.05
	3700	5.32	.81					.11				6.24
Smith Fork C.	3620	5.72	.51					.15				6.38
	3660	5.87	.95					.37				7.19
	3680	8.22	.15									8.37
	3700	8.73	.29									9.02
Forgotten C.	3620	7.34						1.06				8.40
	3660	8.95						1.06				10.01
	3680	10.79	1.54					.55				12.88
	3700	11.82	2.20					.55				14.57
Knowles C.	3620	1.69					.07	1.47	.11		.81	4.15
	3660	1.87					.15	2.20	.15		.92	5.29
	3680	3.27						1.72			.95	5.94
	3700	3.27						2.39			.95	6.61

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles)										
		Cliff	Domed Terrace	Domed Terrace: Mantle of			Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
			Barren	Talus	Sand	Alluvium						
Warm Spring C.	3620	2.35						.18				2.53
	3660	2.35						.18				2.53
	3680	2.42										2.42
	3700	2.42										2.42
Cedar C.	3620	3.56	.15					.84			.48	5.03
	3660	4.84	.07					.92			.59	6.42
	3680	5.69	.04					.62			.37	6.72
	3700	6.20	.04					.62			.44	7.30
Sevenmile C.	3620	2.97						.73				3.70
	3660	3.82						.95				4.77
	3680	5.06						.59				5.65
	3700	5.94						.73				6.67
Ticaboo C.	3620	.92						1.76		.07	.62	3.37
	3660	1.25						1.54		.15	.62	3.56
	3680	1.69						1.91			.40	4.00
	3700	1.87						1.91			.40	4.18
Red C.	3620	4.62	.07			3.30		2.68			.44	11.11
	3660	7.41	.15			3.19		3.05			.44	14.24
	3680	3.96				1.83		9.91				15.70
	3700	6.72				2.20		11.52				20.44

Table 1 (continued)

Area	Contour (feet)	Cliff	Domed Terrace: Barren	Domed Terrace: Mantle of Talus	Domed Terrace: Mantle of Sand	Domed Terrace: Mantle of Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
		Shoreline Surface Types (distance in miles)										
Blue Notch C.	3620	.66						5.14		.04		5.84
	3660	2.13						5.50				7.63
	3680							8.51				8.51
	3700							8.48				8.48
Fourmile C.	3620	.66				.11		1.65		.26	.29	2.97
	3660	.37				.37		2.02		.22	.22	3.20
	3680							3.52			.22	3.74
	3700							4.62			.22	4.84
Twomile C.	3620	.48						1.50				1.98
	3660	.51						1.91				2.42
	3680	1.39						1.21				2.60
	3700	1.47						1.32				2.79
Trachyte C.	3620	2.86				3.85		4.73		.29	.59	12.32
	3660	2.64				2.64		3.63		2.05	.48	11.44
	3680					.07		13.06			.59	13.72
	3700							14.09			.59	14.68

Table 1 (continued)

Area	Contour (feet)	Shoreline Surface Types (distance in miles): Cliff	Domed Terrace: Barren	Domed Terrace: Mantle of Talus	Domed Terrace: Mantle of Sand	Domed Terrace: Alluvium	Shelfy Terrace	Talus	Sand	Alluv-ium	Rock Slide	Total
White C.	3620	8.44						3.85		.51	.44	13.24
	3660	9.69						4.07		3.89	.44	18.09
	3680	5.80				2.64		11.34				19.78
	3700	6.46				3.23		13.65				23.34
Farley C.	3620	3.30				1.10		.77				5.17
	3660	4.48				3.38		.81				8.67
	3680	1.25				5.39		1.10				7.74
	3700	1.25				7.85		1.14				10.24
North Wash	3620	2.09				1.72		2.75		.07	.07	6.70
	3660	2.31				1.36		3.34		.07	.11	7.19
	3680	6.27						2.16			.11	8.54
	3700	6.75						2.16			.11	9.02
Dirty Devil R.	3620	14.60	.62			1.61		.07			.55	17.45
	3660	16.26	.48			2.42		.11			.59	19.86
	3680	9.10	5.91			.81		.77			.37	16.96
	3700	9.28	6.35			.81		.84			.44	17.72
Total	3620	774	147	0.3	11	161	36	264	44	21	14	1472
	3660	863	148	0.1	14	188	39	282	43	47	14	1638
	3680	931	154	0.7	14	197	40	327	40	17	12	1733
	3700	992	158	0.7	13	203	41	346	40	17	12	1823

Table 2. The percentage of each shoreline type and the total mileage of shoreline at each of four contours, 3620, 3660, 3680, and 3700 feet.

Contour	Total Shoreline Surface Types										Mileage
	Percent Distance										
		Domed Terrace									
			Mantle of								
(feet)	Cliff	Barren	Talus	Sand	Alluvium	Shelfy Terrace	Talus	Sand	Alluvium	Rock Slide	Total
3620	52.58	9.99	.02	.75	10.94	2.45	17.93	2.99	1.43	.95	1472
3660	52.69	9.04	.01	.85	11.48	2.38	17.22	2.63	2.87	.85	1638
3680	53.72	8.89	.04	.81	11.37	2.31	18.87	2.31	.98	.69	1733
3700	54.42	8.67	.04	.71	11.14	2.25	18.98	2.19	.93	.66	1823

composed of cliff, talus, and rock slide (54, 19, and 1%, respectively) provide much of the scenic aspect of the shoreline, but from the viewpoint of recreational shoreline use is of little significance. It is the 21% domed terrace, a portion of which is low enough in gradient to be used for shoreline recreation, and especially the 3% that is sand and alluvium which receive the major recreational impact. These are also the areas which are most readily invaded by such growth as tamarisk when exposed as a drawdown zone.

Details of the shoreline mapping will be published at a later date in the form of an atlas.

SHORELINE VEGETATION

Biomass Studies

The entire area of Lake Powell is within the region designated by Kuchler (1964) as Type No. 59, blackbrush shrub. A variety of associations occur in differing physiographic situations dependent principally upon the depth of weathered soil, the soil texture, the microclimatic conditions, and the availability of water. Because of the major influence of physiography and surface materials on vegetation, the studies of biomass were conducted under the same classification as the types used in mapping the surface materials around the lake. Included were domed terrace, shelfy terrace, talus, dune sand, and exposed sandy shoreline resulting from the annual drawdown.

Analysis of biomass for the terrace types was based on 100 clip plots each 1 square meter in area and taken at five different sites, a total of 500 per type. Dune sand and sandy drawdown zones were represented by five sites of 50 plots each, and the talus slopes by 50 plots. Vegetational analysis included total foliage cover, relative foliage cover of principal taxa, total oven-dry weight, relative weight by taxa, and the measurement of randomness of distribution (called frequency index).

An ecological measure which provides a value giving equal weight to density (or in this case to weight of biomass), foliage cover, and randomness of distribution was derived for each taxa by the average of the three values of relative biomass, relative coverage, and relative frequency, and is listed in Tables

3 through 7 as the Importance Percent. Because the study concerned principally biomass, the taxa are ranked according to this measure, with taxa of minor importance merely listed as a footnote with the small percentage represented by all.

Domed Terrace

The average total foliage cover of the domed terrace type is only 1.5% (Table 3), with an average oven-dry biomass of 13.8 grams per square meter. About 30% of the biomass is composed of blackbrush which is most characteristic of areas of thin weathered soil throughout the region and provides the principal long-lived, woody, shrub (Figure 34). About 40% of the cover is divided between hairworm snakeweed (Gutierrezia microcephala), two species of Mormon tea (Ephedra torreyana and E. viridis), and indigo bush (Dalea fremontii). These species and the next several in order of decreasing biomass are typical of sandy soils which in the areas of domed terraces accumulate to a few inches in depth in small basins.

Shrubby vegetation commonly is linearly aligned along fracture lines (Figure 35), the pattern of which thus becomes visible in aerial views of the area. Here the deep penetrating taproots profit from the accumulation of weathered soil which washes into the cracks from the barren rock surface and from the concentration of the limited rainfall, which as runoff water from extensive rock surfaces penetrates deep into the fractures where the moisture is protected from evaporation, which is so rapid and great on the surface. The vegetative cover of these

Table 3. Analyses of vegetation of domed terraces.

Species	Biomass Dry Weight grams/ 100m²	Biomass Dry Weight Relative %	Foliage Cover %	Frequency Index %	Importance Percent
Coleogyne ramosissima	408	29.2	13.0	8.5	16.9
Gutierrezia microcephala	219	15.7	28.8	13.0	19.2
Ephedra torreyana	167	11.9	4.8	3.6	6.8
Dalea fremontii	140	10.0	5.0	0.8	5.3
Ephedra viridis	118	8.4	6.7	3.5	6.2
Yucca angustissima	72	5.2	2.5	2.0	3.2
Encelia farinosa	69	4.9	5.3	4.3	4.8
Oryzopsis hymenoides	30	2.2	4.4	1.2	2.6
Eriogonum aureum	25	1.8	2.2	2.5	2.2
Lygodesmia sp.	19	1.4	3.0	3.7	2.7
Andropogon hallii	18	1.3	1.9	2.4	1.9
Eriogonum spp.	17	1.2	3.0	1.2	1.8
Hymenopappus pauciflorus	16	1.1	2.9	3.6	2.5
Aristida sp.	16	1.1	3.5	9.3	4.6
Sclerocactus sp.	12	0.8	0.3	2.3	1.1
Misc. herbs	11	0.8	-	-	-
Stipa neomexicana	9	0.7	0.6	1.1	0.8
Unidentified compositae	9	0.7	0.7	2.7	1.4
Sporobolus cryptandrus	8	0.5	1.0	2.1	1.2
Rhus trilobata	5	0.4	0.3	0.5	0.4

Total average oven dry biomass: 13.8 grams per square meter
Total average foliage cover: 1.5%

Other species of minor importance (total of 0.7% of biomass): Asclepias sp., Astragalas ensiformis, Astragalus sp., Atriplex canescens, Bromus rubens, Coldenia hispidissima, Dalea sp., Eriogonum inflatum, Euphorbia sp., Gilia multiflora, Hilaria jamesii, Mentzelia sp., Opuntia sp., Phacelia ivesiana, Psoralea juncea, Streptanthella longirostris, Tamarix pentandra.

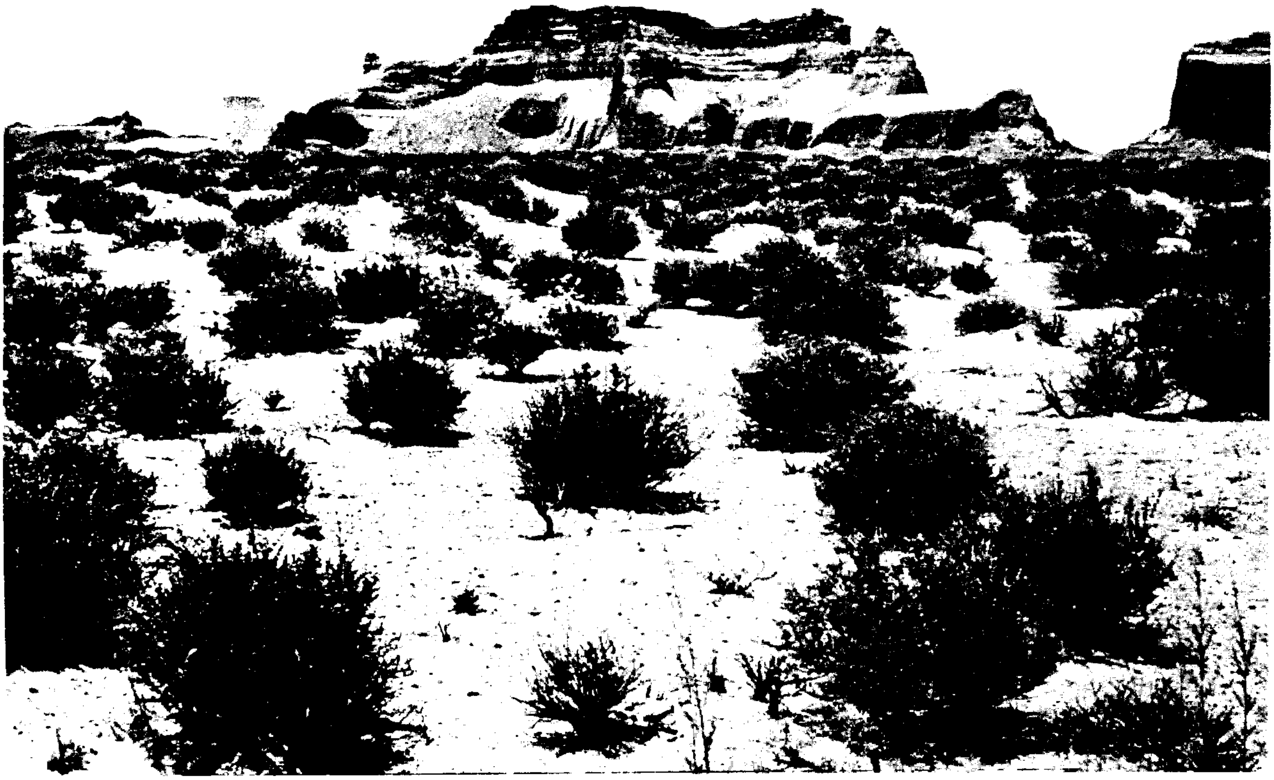


Figure 34. Stand of blackbrush (*Coleogyne ramosissima*) principal woody shrub.

Figure 35. Shrubby vegetation typical of fracture lines in Navajo sandstone and of domed terraces.

fractures is principally that of shrubs; about 85% consists of blackbrush, hairworm snakeweed, scurfy mortonia (Mortonia scabrella), goldenweed (Haplopappus drummondii), singleleaf ash (Fraxinus anomala), and turpentine broom (Thamnosma montana).

Shelfy Terraces

The shelfy terraces are dominated by an even higher biomass percentage of blackbrush (40%)(Table 4). The other two principal taxa are snakeweed and Mormon tea. Generally, shrubby species are more common in shelfy than in domed terraces. This is due to the increased amount of area available for tap-rooted, woody species in the fractures (both vertical and horizontal) in the more porous cross-bedding of the upper Navajo sandstone to which shelfy terraces are most distinctive. Total biomass and foliage cover are only slightly less than in domed terrace areas.

Talus

The talus slopes included in the vegetational analysis were those consisting of rock debris below cliff faces and did not include those where sand had blown over the cliff face to form large areas of falling dune talus slopes. Amidst the rocky boulders are a variety of micro-habitats provided by shading, protection from surface evaporation, and a mixture of textures making up the soil (Figure 31). Such sites favor clumps of vegetation, especially of species which are deep-rooted. Moisture running off the rocks collects underneath and is

Table 4. Analyses of vegetation of shelfy terraces.

Species	Biomass Dry Weight grams/ $100m^2$	Biomass Dry Weight Relative %	Foliage Cover %	Frequency Index %	Importance Percent
Coleogyne ramosissima	468	40.0	17.0	10.5	22.5
Gutierrezia microcephala	198	16.9	20.3	13.5	16.9
Ephedra torreyana	103	8.8	12.7	72.2	31.2
Lygodesmia sp.	64	5.5	7.1	2.3	5.0
Opuntia sp.	50	4.2	1.2	2.3	2.6
Aristida sp.	47	4.0	5.0	8.6	5.9
Encelia farinosa	38	3.2	3.1	2.1	2.8
Eriogonum aureum	31	2.6	3.9	2.7	3.1
Dalea fremontii	24	2.0	2.1	0.4	1.5
Unidentified composite(a)	18	1.6	3.4	3.1	2.7
Thamnosma montana	18	1.5	2.1	0.8	1.5
Psoralea juncea	14	1.2	2.3	0.6	1.4
Baccharis sp.	13	1.1	0.3	0.4	0.6
Misc. herbs	11	0.9	-	-	-
Atriplex confertifolia	10	0.9	2.2	1.3	1.5
Unidentified composite(b)	9	0.8	0.6	0.8	0.7
Haplopappus drummondii	8	0.7	2.4	2.2	1.8
Bouteloua eriopoda	7	0.6	2.4	1.7	1.6
Hilaria jamesii	6	0.5	2.6	3.3	2.1
Hymenopappus pauciflorus	6	0.5	1.1	1.3	1.0
Oryzopsis hymenoides	6	0.5	1.7	4.2	2.1

Total average oven dry biomass: 11.7 grams per square meter
Total average foliage cover: 1.4%

Other species of minor importance (total of 2.0% of biomass): Abronia elliptica, Astragalus sp., Bouteloua curtipendula, Bromus arizonicus, Eriogonum sp., Euphorbia sp., Festuca sp., Lycium sp., Phacelia crenulata, Phacelia ivesiana, Phacelia sp., Plantago argyraea, Sphaeralcea coccinea, Sporobolus cryptandrus, Streptanthella longirostris.

protected from evaporative loss. About 78% of the biomass results from three shrubby species--goldenweed, shadscale, and blackbrush (Table 5). These slopes are the most common locations for echinocereus (Echinocereus spp.) and fishhook cactus (Sclerocactus whipplei). The total foliage cover and biomass of talus slopes is about three and four times greater than that of the terraces because of the extensive areas of bare rock in the latter areas.

Sand

The richest vegetation, both in biomass and in number of species represented, of the shoreline types sampled was that of the sandy shore composed of dune sand. The areas sampled did not represent active sand dunes but were all located in areas of varying depth of uniform-textured dune sand. Sand which has weathered and blown off the upland sandstone plateaus frequently collects on lower elevation terraces and becomes distributed as gently undulating sandy plains overlying the terraced sandstone. The biomass weight of 86.5 grams per square meter and 5% total foliage cover (Table 6) indicate the relatively favorable growth conditions of the dune sand. In these areas, there is deep infiltration of precipitation and almost no runoff. Only severe summer thunderstorms result in gully erosion. Although the water-holding capacity of dune sand is low, almost all of that is available for plant growth. As the surface layers dry out due to evaporation, a surface dry layer of about 10 centimeters develops which intercepts the capillary

Table 5. Analyses of vegetation of talus slopes.

Species	Biomass Dry Weight grams/ $100m^2$	Biomass Dry Weight Relative %	Foliage Cover %	Frequency Index %	Importance Percent
Haplopappus drummondii	1363	30.2	30.9	14.7	25.3
Atriplex confertifolia	1240	27.4	22.4	9.3	19.7
Coleogyne ramosissima	881	19.5	11.7	2.3	11.2
Ephedra torreyana	264	5.8	13.8	2.3	7.3
Sclerocactus sp.	221	4.9	0.8	0.8	2.2
Hilaria jamesii	142	3.1	10.8	24.0	12.6
Ephedra viridis	135	3.0	4.2	3.9	3.7
Atriplex canescens	130	2.9	2.0	0.8	1.9

Total average oven dry biomass: 45.2 grams per square meter
Total average foliage cover: 5.0%

Other species of minor importance (total of 3.2% of biomass): Aristida sp., Astragalus sp., Brickellia sp., Bromus rubens, Coldenia hispidissima, Gilia multiflora, Gutierrezia microcephala, Oryzopsis hymenoides, Phacelia ivesiana, Plantago argyraea, Psoralea juncea, Sporobolus cryptandrus, Streptanthella longirostris, Tridens pulchellus.

Table 6. Analyses of vegetation of dune sand.

Species	Biomass Dry Weight grams/ $100m^2$	Biomass Dry Weight Relative %	Foliage Cover %	Frequency Index %	Importance Percent
Coleogyne ramosissima	3059	35.4	19.7	5.4	20.2
Oryzopsis hymenoides	1188	13.7	24.6	13.3	17.2
Ephedra viridis	948	11.0	11.7	2.9	8.5
Opuntia sp.	704	8.1	3.2	2.4	4.7
Ephedra torreyana	526	6.1	6.4	1.2	4.6
Yucca angustissima	385	4.5	4.6	1.4	3.5
Haplopappus drummondii	324	3.8	4.3	1.0	3.0
Unknown composite	301	3.5	3.7	0.8	2.7
Artemisia filifolia	264	3.1	2.5	0.7	2.1
Misc. herbs	175	2.0	?	?	-
Sporobolus cryptandrus	104	1.2	2.8	2.0	2.0
Gutierrezia microcephala	90	1.0	1.5	1.5	1.3
Dalea fremontii	69	0.8	0.6	0.6	0.7

Total average oven dry biomass: 86.5 grams per square meter
Total average foliage cover: 5.0%

Other species of minor importance (total of 5.8% of biomass): Abronia sp., Allium sp., Ambrosia sp., Aristida sp., Asclepias involucrata, Astragalus sp., Atriplex canescens, Baccharis sp., Bromus rubens, Corispermum hyssopifolium, Croton texensis, Cymopterus fendleri, Erigeron sp., Eriogonum aureum, Eriogonum inflatum, Eriogonum sp., Euphorbia sp., Festuca sp., Gilia multiflora, Helianthus petiolaris, Hilaria jamesii, Lupinus pusillus, Lygodesmia sp., Mentzelia sp., Nama hispidum, Oenothera pallida, Penstemon sp., Phacelia ivesiana, Plantago argyraea, Poliomintha incana, Psoralea juncea, Senecio longilobus, Senecio monoensis, Sphaeralcea coccinea, Streptanthella longirostris.

rise of moisture from below and tends to conserve that deeper moisture. The sand at greater depths also remains cooler. Accompanying these favorable moisture relations is the ideal rooting medium provided by the texture of dune sand.

Although blackbrush, because of its woody perennial nature, provides over one-third of the biomass, the greatest coverage is provided by Indian ricegrass (Oryzopsis hymenoides). The latter is a good indicator of sandy soils throughout the West and has a relatively large grass fruit which was harvested and ground into flour by many American Indians. The vegetation is interestingly varied in growth form and in taxonomic composition (Figure 36). The variations are indicative of the more favorable moisture and rooting relations of the sandy soil.

Sandy Drawdown Zone

The principal shoreline type which is invaded by vegetation upon exposure during the seasonal drawdown is the sandy shore. The amount of vegetational biomass and species composition of the 1-year succession of the upper part of this drawdown zone was contrasted to that of the unflooded sandy area above the maximum water level. In the successional zone, the total foliage cover in 1 year was nearly the same, 4.5% versus 5.0%, and the yearly production of vegetal biomass amounted to 13.3 grams per square meter in comparison with 86.5 for the standing accumulated biomass of the unflooded sandy sites (Table 7). The notable addition to the flora was that of salt cedar, or tamarisk, which was not a common part of the flora of the dune sand areas of the main channel during the earlier filling stages of

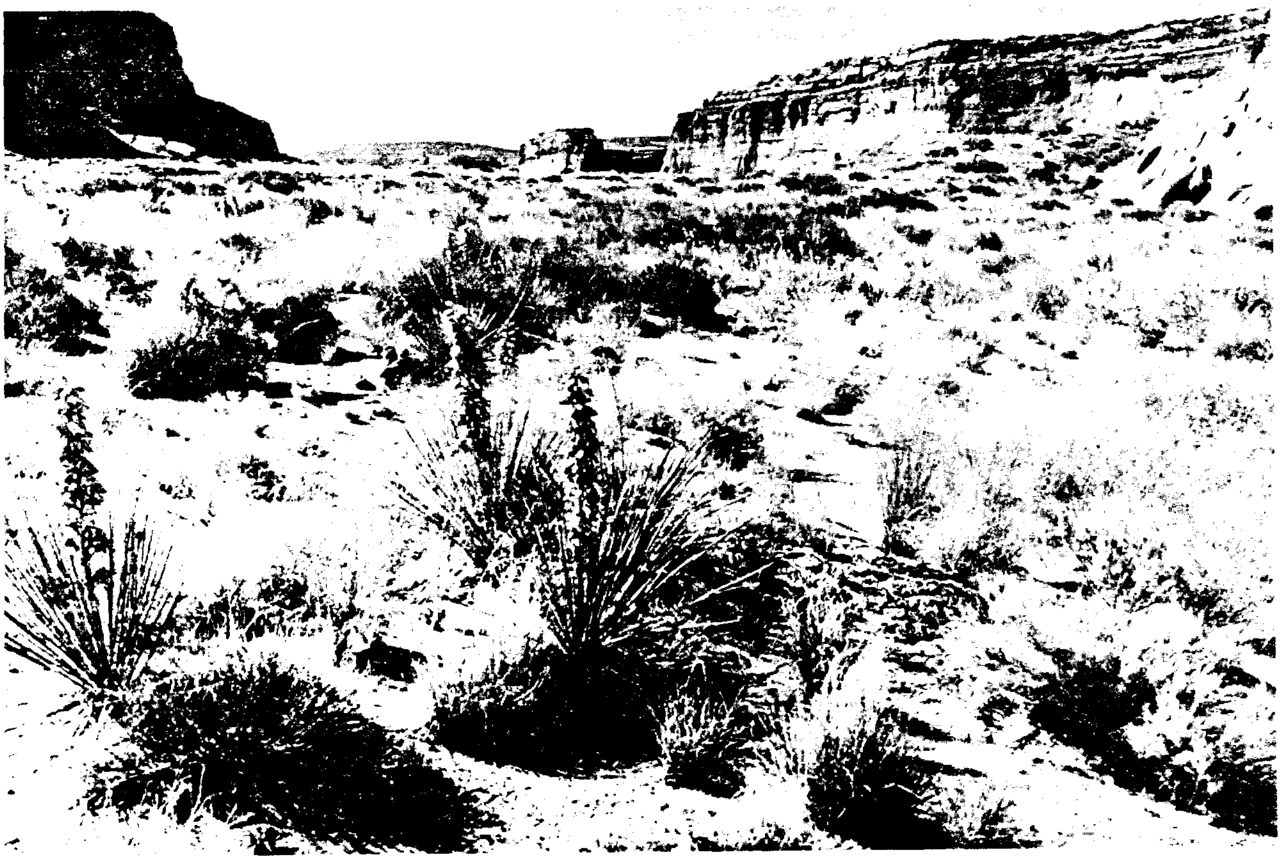


Figure 36. The vegetation of dune sand is the most varied in growth form, richest in species composition, and greatest in standing biomass.

Table 7. Analyses of vegetation of sandy drawdown zone.

Species	Biomass Dry Weight grams/100m²	Biomass Dry Weight Relative %	Foliage Cover %	Frequency Index %	Importance Percent
Tamarix pentandra	877	66.0	55.5	53.0	58.2
Oenothera pallida	319	24.0	19.8	4.6	16.1
Sporobolus cryptandrus	69	5.2	10.2	19.0	11.5
Gutierrezia microcephala	22	1.6	1.1	1.4	1.4
Nama hispidum	20	1.5	4.6	1.2	2.4
Lupinus pusillus	5	0.4	1.4	1.3	1.0
Oryzopsis hymenoides	2	0.2	2.6	8.8	3.9
Sphaeralcea coccinea	2	0.2	1.5	1.1	0.9

Total average oven dry biomass: 13.3 grams per square meter
Total average foliage cover: 4.5%

Other species of minor importance (total of 0.9% of biomass): Artemisia filifolia, Artemisia tridentata, Astragalus sp., Atriplex confertifolia, Bromus rubens, Corispermum hyssopifolium, Gilia multiflora, Hilaria jamesii, Lygodesmia sp., Streptanthella longirostris.

the lake. However, after a temporary maximum, e.g., at 3622 feet in 1971, the seasonal lowering of water level exposed a drawdown zone to a 1-year succession of which tamarisk comprised 66 and 56% of the biomass and foliage cover, respectively. Secondly, there was a great increase of pale primrose (Oenothera pallida) from a minor species to one of second importance in biomass and cover. Apparently the coincidence of a moist, sandy seed bed exposed in late summer and the reduction of competition especially favored this herbaceous species which occupied 20% of the foliage cover. The third most important invader was the grass, sand dropseed (Sporobolus cryptandrus), which is well known for its high rate of seed production and dissemination into sandy areas. In total, about 18 of the 50 taxa from the dune sand area were represented in the 1-year successional drawdown vegetation below. One interesting conspicuous species of the upper drawdown zone is jimsonweed, or sacred thornapple (Datura metaloides).

It is this biomass (Figure 37) which, upon reflooding and decomposition in the spring, will lead to nutrient enrichment of the lake and which meanwhile serves as a growth substrate for a rich periphyton flora and fauna (this will be discussed later). It is also a major factor in recreational use of the favorite sandy shoreline sites. The 1-year growth, dominated by tamarisk, may be up to 6 feet tall. If not flooded for 2 years, it can become 10 to 12 feet tall. When flooded, a submerged woody vegetation will be left offshore, resulting in serious objections by boaters and swimmers.

Figure 37. Rapid invasion and growth of vegetation dominated by tamarisk and pale primrose (Oenothera pallida) in one season on the sandy drawdown zone.

Seasonal Variations--Transects

With the initiation of the Lake Powell Research Project, there were established permanent transects from the waterline, which was at 3620 feet, up the slopes to elevations of 3700, the maximum anticipated water level. These belt transects were 3 feet wide and several hundred feet long. Most of them were examined each summer. Foliage cover, rather than density, was determined as the principal measure because of the large number of clumped and sprouting species, many of which were partially buried in sand--making it unreasonable, if not impossible, to count individuals. Foliage coverage was expressed as a vertical projection of the margins of the foliar area and was recorded in square inches. Data were kept in separate blocks of 3- x 10-foot units as a base for determining randomness of distribution as measured by the frequency index for each species.

All transects were located in areas where (throughout the length of the transect) there were as uniform conditions of soil, physiography, and vegetation as possible, recognizing that as the water level rose the lower part of the transect would not be represented. These studies did not include the area of the drawdown, which was not normally exposed in June when the transects were usually examined.

The data are presented in tabular form and give the total foliage cover of all the vegetation, the relative foliage cover for each species, and the frequency index, which is a percentage of the transect units in which the species occurred.

The climatic conditions for the 4 years of the study were highly variable. This largely accounts for the great fluctuations in coverage values, as well as the erratic appearance and disappearance of some species. The unusually high precipitation of October 1972 was followed in the spring of 1973 by exceptionally lush growth and the sudden appearance of more species than at any other time during the study. Therefore, the data for relative foliage cover for 1973 were used as a basis for arranging the species in decreasing order of rank.

The results are arranged in the following order: an active high dune area, a partially stabilized low dune area, a well-stabilized low dune area, an area having a mantle of several feet of dune sand over sandstone, an alluvial site of rolling topography, two talus slopes of mixed texture, and one domed terrace area.

The vegetation of an active sand dune in the upper part of Gunsight Canyon is given in Appendix A-1. The low species composition and total foliage cover in 1974 were the result of only the upper part of the dune having been left exposed and the water having risen faster than vegetation could move upslope on the dune. Although sand dropseed had the highest coverage, there was no outstanding single dominant. All four of the species of highest coverage--sand dropseed, green ephedra (Ephedra viridis), goldenweed, and Indian ricegrass--are typical of sandy soils. The large diversity of the vegetation, 56 taxa, probably relates to its position immediately adjacent to the stream channel.

The coverage of vegetation of a low-contoured, partially stabilized dune area on the west side of the main channel is given in Appendix A-2. Here three species--green ephedra, Astragalus ensiformis, and desert dandelion (Malacothrix glabrata)--produced 65% of the foliage cover. Many other species were temporal and the total coverage varied from 7.6 to 12.5%.

A well-stabilized, low dune area in the protection of Friendship Cove was analyzed and the results are given in Appendix A-3. The principal dominants here were Indian rice-grass, green ephedra, lupine (Lupinus sp.), and sixweeks fescue (Festuca octoflora). Total foliage coverages varied from 16 to 24%.

On the island south of Gunsight Butte the Navajo sandstone is covered by a several-foot-deep layer of dune sand with low hummocks. The vegetational data for this area are given in Appendix A-4. The four dominants--green ephedra, blackbrush, desert dandelion, and Indian ricegrass--comprised 76% of the total vegetative cover. Total foliage cover varied from 8 to 11%.

One transect representing alluvial material on rolling topography was sampled in Warm Creek (Appendix A-5). The coverage dominance here shifted to Astragalus ensiformis, four-wing saltbush or chamiza (Atriplex canescens), Russian thistle (Salsola kali), globemallow (Sphaeralcea coccinea), and green ephedra. These comprised 65% of the total vegetative cover. Total foliage covers varied from 2 to 8%.

Two examples of talus slopes of mixed texture were sampled. One was in Last Chance Canyon (Appendix A-6). Here goldenweed and Indian ricegrass, four-wing saltbush, and green ephedra comprised 72% of the cover, most of it by the first two species. Total foliage cover varied from 10 to 15%. The other talus slope was in Rock Creek Canyon (Appendix A-7). Here foxtail chess (*Bromus rubens*) and goldenweed produced more than half the cover, followed in lesser importance by sand dropseed and Indian rice-grass. Total foliage cover varied from 6 to 14%.

The domed terrace sites were represented by one transect (Appendix A-8) on the south side of the main channel and east of Warm Creek. The dominant cover was provided by *Ephedra torreyana*, hairworm snakeweed, three-awn grasses (*Aristida* spp.), and turpentine broom. The vegetation of this type was highly localized to fractures in the sandstone and to small basins where a thin layer of weathered material had accumulated. Only 23 taxa were represented and total foliage cover varied from 0.8 to 1.3%.

Special Sites

Seeps

Because the seep water emerging from a lime-rich stratum is highly charged with calcium carbonate, a calciphilous vegetation is especially favored. The supply of water provides the most mesic condition of the region. Because the seeps have frequently resulted in the formation of recessed amphitheaters, they are often shaded from the sun, protected from the wind, and are cooler in the summer. The seep line is often marked by a dense mat of maidenhair fern which accumulates thick, tangled masses of dead rhizomes and leaf bases, with fresh new growth along the margins (Figure 38) with other calciphiles.

One of the most prominent and distinctive species of the seep lines is rock mat which grows in dense clumps and may hang suspended down the cliff wall or from overhanging ledges. At no other place is so much organic matter produced and accumulated. On the moist walls, or the organic mat, one might expect to find such mesic species as helleborine (Epipactis gigantea), cardinal flower (Lobelia cardinalis), monkeyflower (Mimulus eastwoodiae), and primrose (Primula specuicola). Haring (1961) published a list of mosses common to these sites prior to the flooding by Lake Powell.

A variety of mesic species, which are similar to those one would find in a moist eastern deciduous forest, are found within the organic mat, in the enriched rubble and soil below, and as understory extending into moist sites of the shrubby, woody groves. Among the mesic grasses may be water bentgrass (Agrostis semiverticillata), bushy bluestem (Andropogon glomeratus), Jones reedgrass (Calamogrostis scopulorum), Canada wildrye (Elymus canadensis), creeping wildrye (Elymus triticoides), alkali muhly (Muhlenbergia asperifolia), vine-mesquite (Panicum obtusum), switchgrass (Panicum virgatum), common reed, and yellow Indiangrass (Sorghastrum nutans). Grass-like plants of these mesic sites include species of sedge, spikerush (Eleocharis spp.), and rushes (Juncus balticus and J. longistyles). Mesic species of forbs in contrast to the surrounding flora include thistle (Cirsium rydbergii), sticky willowweed or fireweed (Epilobium

Figure 38. Dense hanging clumps of rock-mat (Petrophytum caespitosum) and maidenhair fern (Adiantum capillus-veneris), calciphilous plants, favored by shade of an alcove and seep water from a limestone stratum.

adenocaulon), evening primrose, starry smilac (Smilacina stellata), sowthistle (Sonchus asper), and Yankee speedwell (Veronica americana).

Alcoves

Where limestone seep lines have resulted in cavation of the overlying sandstone and the development of large recessed alcoves, protected moist stands of vegetation develop, which form local thickets of shrubs and trees. Or, if there is seep water part or all of the year, a woody grove develops downslope.

The principal taller trees of these alcove groves are Gambel oak, Fremont cottonwood, and peach-leaf willow (Salix amygdaloides). Understory trees include netleaf hackberry, western redbud (Cercis occidentalis), singleleaf ash, hop-hornbeam (Ostrya knowltonii), wavyleaf oak (Quercus undulata), birchleaf buckthorn (Rhammus betulaefolia), and coyote willow.

In addition to the presence of some shrubs typical of the surrounding area, the moist conditions favor the presence of Emory baccharis, species of Brickellia, squawberry (Rhus trilobata), poison ivy (Rhus radicans), and New Mexican raspberry (Rubus neomexicanus).

Heads of Tributaries

In general, the most extensive stands of vegetation of the tributaries were found at the lower ends, which have now been flooded by Lake Powell. In some drainages there were valleys which part way downslope became widened and reduced in gradient, resulting in alluvial terraces. These became vegetated with groves of trees and were established for periods of time long enough to produce a well-developed soil profile. A few canyons were successfully dammed by beaver to produce ponds or lakes in which were formed rich lacustrine deposits. These sites were of greatest productivity and densest forest growth. Few are left unflooded by the reservoir.

Where the lake has filled into the upper reaches of tributaries most canyons have pinched off into narrow gorges. Some end abruptly in the vertical wall of a box canyon. Others terminate against the steep escarpment of plateaus such as Cummings Mesa. Often the head of a tributary is represented by an alcove, the vegetation of which is discussed above. The flooding of Lake Powell upstream along major tributaries has resulted in fewer changes than up the steep, short, side canyons. The gradient of tributaries such as Wahweap, Warm Creek, Hall's Creek, and others is less and therefore a similar, marginal streamside vegetation developed throughout their extent. The general nature of this vegetation has been previously discussed.

SHORELINE SUCCESSION

Riparian Succession of the Colorado River

Where the Colorado River originally flowed through relatively wide valleys in the Glen Canyon area, the densest and most extensive development of vegetation occurred. Here it was favored by the relatively level river terraces, the enriched soil, and the supply of subsurface water. On the upper terraces, forest stands were dominated by Fremont cottonwood, netleaf hackberry, and Gambel oak. A rather dense cover of understory shrubs was dominated by arrowweed pluchea, four-wing saltbush, seepweed (*Suaeda* sp.), black greasewood (*Sarcobatus vermiculatus*), rabbitbrush (*Chrysothamnus nauseosus* and *C. viscidiflorus*), and sumac (*Rhus trilobata* and *R. utahensis*). A variety of other shrubs were common and Woodbury et al. (1959) list some 15 species of grasses and 89 species of forbs common to the river terraces in Glen Canyon.

Along the lower river terraces and the stream banks was a vegetation typical of sandy shorelines of most southwestern streams. Thickets of willow were dominated by coyote willow and less commonly by black willow. Tamarisk, the ubiquitous introduced exotic, was then and is today a dominant shrub and tree, forming nearly impenetrable thickets and finally forest stands along river terraces both above and below Lake Powell (Figure 18). Common shrubby species also included Emory baccharis and arrowweed pluchea. Where terraces were narrow, or where talus slopes came down to the water's edge, trees typical of the higher terraces were found. Herbaceous vegetation--grasses, rushes, and species of horse's tail--varied depending on the texture of soil and moisture.

Lakeshore Succession of Lake Powell

With the flooding of Glen Canyon many of the above types of streamside vegetation have been almost entirely eliminated. Along the main channel there are no comparable physiographic sites, even though the rising water of the reservoir is now flooding ancient river terraces and meanders. These have been exposed and eroded for thousands of years with the resulting desiccation and eluviation having removed the former vegetation and the soils which had been produced there. Most of the tributary streams or canyons have a steep descent into Glen Canyon so the lake backing into such canyons is not bordered by typical riverbank vegetation. Exceptions would be portions of several of the larger tributaries such as the upper Escalante River and portions of the San Juan River where they open out into broad valleys. Undoubtedly then, the formerly riparian vegetational types most decreased and lacking today as lakeshore types are those which occupied sandbars, floodplains, and lower river terraces. The vegetational types of plateaus, dissected canyons, seeps, alcoves, talus slopes, dunes, and ancient terraces remain much as before.

Effect of Fluctuating Water Levels on Shoreline Types

The impact of the rising water level into an arid desert shrub vegetation is very slight over the vast area of the shoreline represented by cliff wall, domed terrace, and shelfy terrace. Here the changes due to flooding and recession of water level are principally chemical and physical.

Along cliff walls the rising water dissolves some minerals from the surface and subsurface of the sandstone. The capillary rise in the porous sandstone, plus the wash of the waves, results in a darkened line of mineral deposit (Figure 39). This dark line is thought to be similar to the patina staining of cliff faces resulting from the evaporation of water trickling down the cliff face and leaving a deposit of oxides of iron and manganese. With the lowering of the reservoir level there is left a whitish "bathtub ring," shown below the maximum water level. The surface layer consists of a coating of friable, granular deposit rich in calcium carbonate but usually mixed with a large percentage of organic material resulting from the growth of diatoms and blue-green and green algae. Just as these organisms are found enmeshed in floccul-ated silt and carbonate on the bottom, so too they form a crust even on vertical walls and to depths of the light pene-tration in water which, depending on the shading of the walls, the clarity of the water, and season of the year, is commonly found to depths of 10 to 15 meters. While still moist after the lowering of the water level, this encrustation has a yellowish-green color until continuous exposure results in desiccation and degradation of the plant pigments which leaves the whitish crust below the single blackish line at the maximum water level.

Figure 39. "Bathtub ring" left on cliff wall after water level retreats. The light-colored crust is a combination of minerals and remains of diatoms and other algae.

Where the water retreats from areas of domed terrace, any overlying mantle of alluvium or sand may have been washed away. In Figure 40 the effect of lowered water level is shown where a covering of dune sand was washed away exposing the underlying terrace of siltstone and the root system of a woody shrub whose roots had penetrated the sand and then spread out across the surface of the bedrock.

The shelfy terraces of thin-bedded sandstone undergo a physical change due to submergence. This sandstone is very porous and poorly cemented. When wetted the cementing material is partially dissolved, the previously jagged layers (see Figure 30) crumble, and the sharp contours become softened by the edges being rounded off. In this case (Figure 41) the shoreline area becomes safer for the landing of a boat without damage to its hull.

One of the outstanding features of the shoreline is the tremendously large talus slopes which have developed from weathering of canyon walls and from sand blown over the edge from the plateau above. Many of these slopes are hundreds of feet high and rest on a ledge or old river terrace. Having already established an angle of repose consistent with the texture of the talus material they are in balance with gravitational forces. As the water level increases, the base of the talus slope may be softened, as is common where the Chinle formation of relatively soft shales and mudstones becomes wet and plastic, or is even removed in suspension. As water levels rose rapidly in 1973 into the Chinle formation in the area from Good

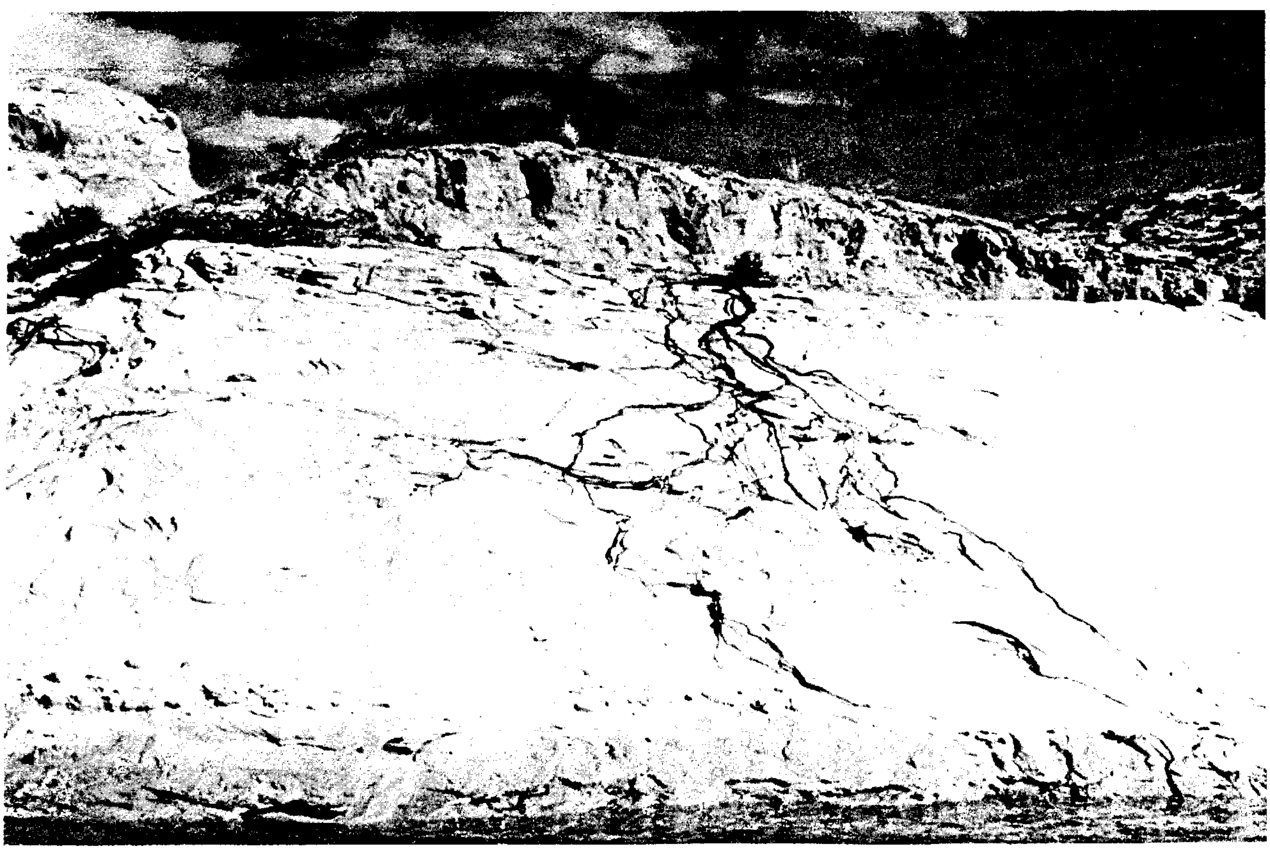


Figure 40. Removal of overlying sand mantle by high water level exposed root system spread out over rock surface.

Figure 41. Sharp edges of thin-bedded shelfy terrace have been rounded by submergence and reexposure in the draw-down zone.

Hope Bay to Trachyte Canyon extensive areas of talus slopes were affected. In some places they slumped downward as much as 20 feet, remaining intact but leaving a wide white band along the cliff wall indicating their previous level (Figure 42). Deep cracks developed and ran laterally through the talus slopes for hundreds of feet. Often a series of slump cracks developed up the slope. Some talus slopes, here and elsewhere, completely disappeared into the bottom sediments due to massive slumping (Figure 43). Obviously, some areas which were mapped as being talus shoreline material are now, or may become, greatly reduced or non-existent, leaving only a scar on the cliff wall as evidence.

Throughout the lakeshore, wherever previous upwarping results in the Chinle being at the water level, softening has occurred and the overlying blocky Wingate sandstone and the fragmented terraces of Kayenta are subject to tumbling downslope. These areas often form massive rockslides (Figure 44). The more common pattern of talus slumping throughout the shoreline is that of talus slopes composed of a mixture of boulders, cobbles, gravel, and sand. The removal of the silt and sand by rising and lowering water levels leaves a rubble of coarse material.

Along shorelines previously covered with Pleistocene alluvium over old river terraces the submergence also results in a change in texture (Figure 45). Here a gently sloping beach of mixed texture previously provided a favorable beach for mooring a boat and for camping. The exposed area of the drawdown zone has been subject to wave action and removal by suspension of

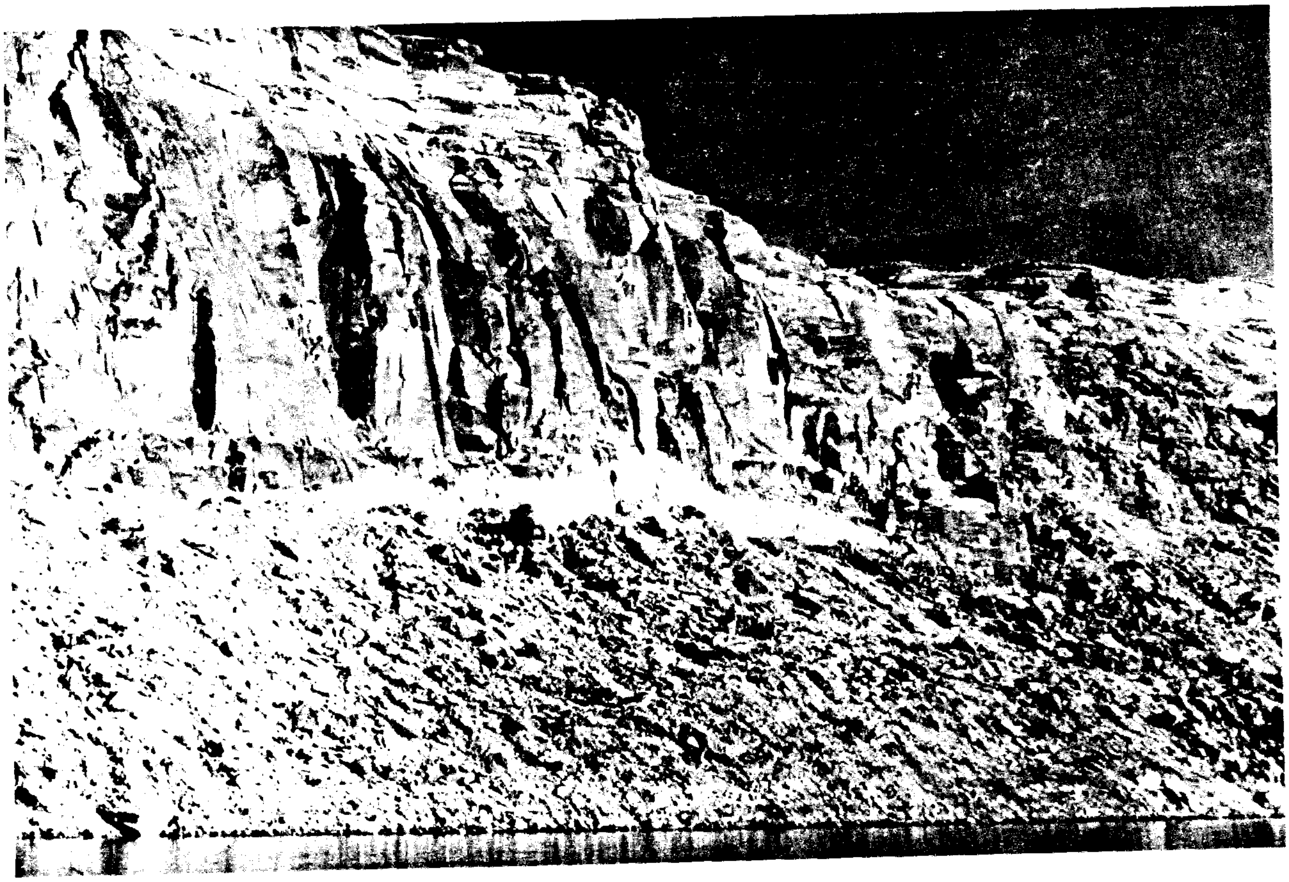


Figure 42. Vertical slump of talus slopes leaving a white band of cliff wall exposed.

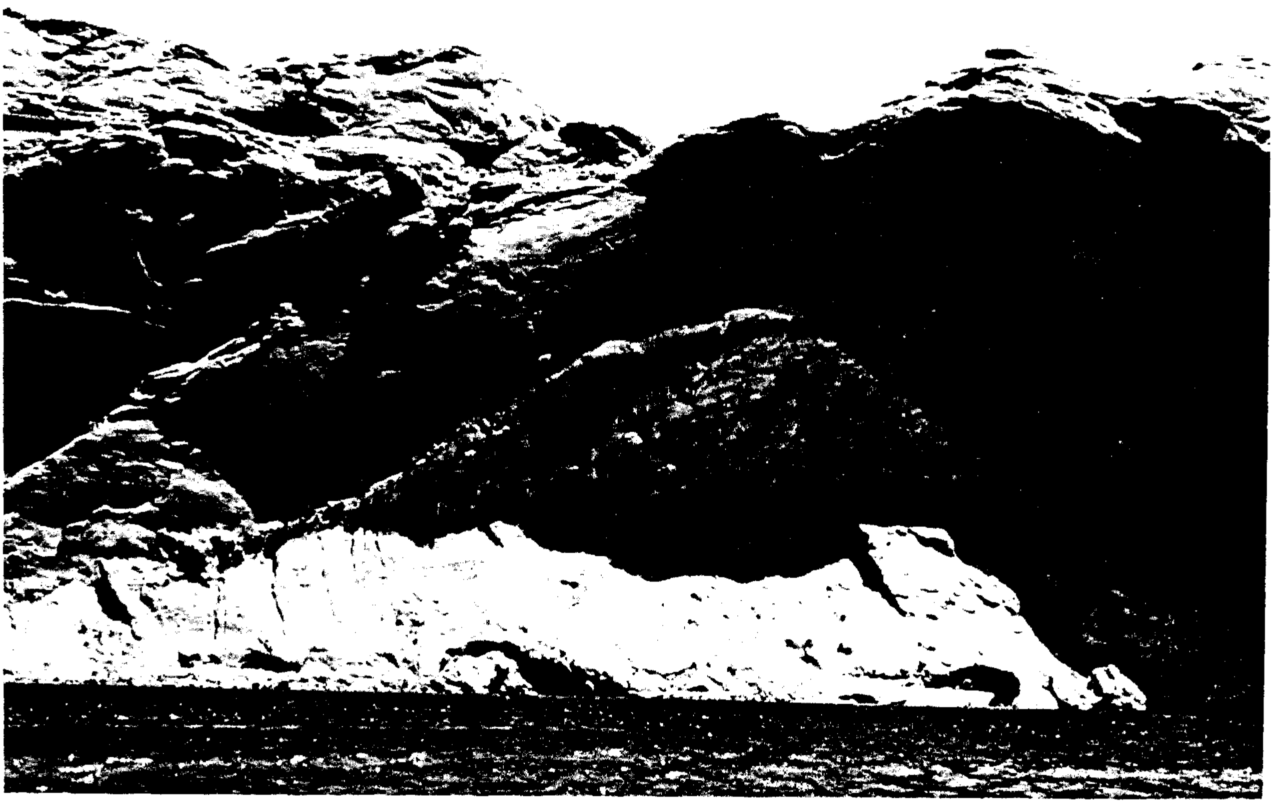


Figure 43. Loss of entire talus slope which slumped into the sediments of Lake Powell.

Figure 44. Rockslide of Wingate sandstone overlying weak, softened Chinle formation.

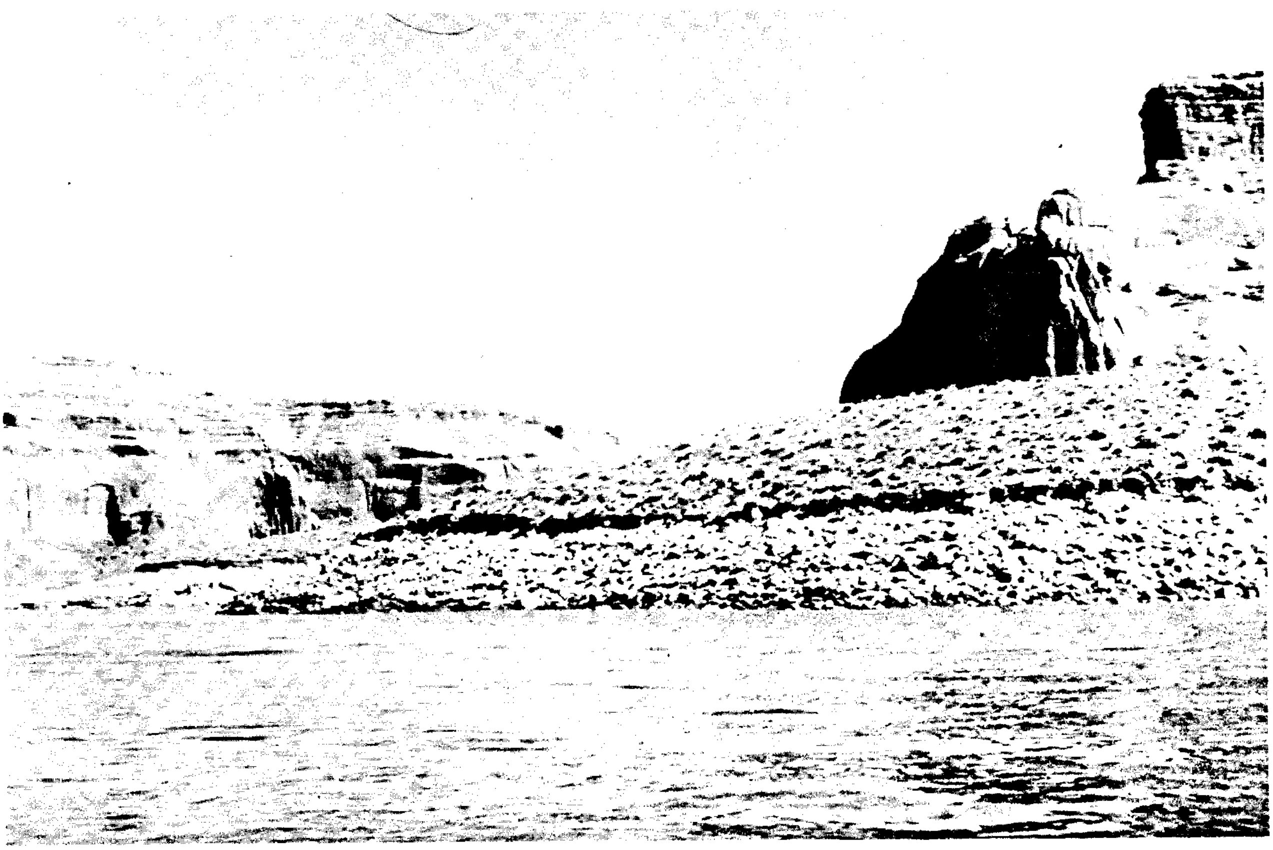


Figure 45. Mantle of Pleistocene alluvium from which the sand and silt have been removed leaving a less desirable cobblestone beach in the drawdown zone.

fine-textured material of sand and silt which has left a coarse boulder field as a shoreline--a much less desirable place for recreational use.

Shoreline areas consisting of several feet of dune sand are subject to slumping in a manner similar to talus slopes. Where the dune sand is a thinner mantle it is usually washed off the underlying rock by wave action and the action of undertow. The contour of sloping sandy shores is influenced by the intensity of wave action during the lowering of water level. The general lack of high winds during the fall season usually results in an uncut sloping beach, but periods of winter frontal storms and the common strong winds in the spring that produce high waves may result in wave-cut beach lines (Figure 46). These are eroded into the sand which is even less securely held than before submergence because of the killing of the dune vegetation and the loss of the soil-binding properties of its root systems except for occasional dead taprooted shrubs. Often a series of minor terracettes may be formed on these shorelines.

The maximal period of shoreline use for camping occurs from May to September. It should be noted that in the normal yearly cycle of fluctuating water levels (Figure 20) the times when (1) water levels are at the upper or maximal heights and (2) the previous drawdown zone has either been just submerged or a new one not yet exposed, correspond to this period of maximal use. Although visitor use for fishing remains relatively stable from April to October, recreational shoreline use is more summer-oriented. During the reservoir's filling stages when

Figure 46. Wave-cut shoreline in sandy drawdown zone.

the yearly peak normally exceeds that of the year before, the most-used shorelines during the summer season are the sandy beaches where the new water level comes up into native vegetation. During this period there is no evidence of either previously submerged, dead, partially decomposed vegetation or the result of successional invaders into the sandy areas of the drawdown zone. From the viewpoint of maintaining a natural appearance of the summer aspect of the reservoir's shoreline and of avoiding the apparent intrusion of exotic successional invaders, this period of reservoir life is the "honeymoon" period.

Growth Effects of Peak Water Levels

The vegetation of those areas submerged by rising waters is soon killed. Most plants succumb upon complete submergence--it is biologically unreasonable to expect a desert-adapted species to quickly be successful as a submerged aquatic. As the water level rises into the native vegetation there is an increase of available soil moisture along the new shoreline. The distance and rate of lateral movement of moisture is dependent upon the soil texture of the shoreline, being faster in dune sand than in silt and clay. Moisture availability above the shoreline is aided by wave action and capillary rise. In areas of silt and clay banks the lateral zone of growth stimulation is only a few feet wide. Here, species such as shadscale and blackbrush show increased twig growth, leaves become more succulent, and flowering is increased. In a variety of soils the common mustard (*Streptanthella longirostris*) is stimulated into prolific growth and seed production and by June has completely matured. Annual bromes (Bromus spp.) also increase.

The most pronounced stimulation of growth occurs along sandy shorelines. Here a beneficial effect frequently occurs for a distance of 10 to 20 feet upslope. The dominant species such as Indian ricegrass, Mormon tea, goldenweed, and sand sagebrush (Artemisia filifolia) show an increase in vegetative growth. Even the slow-growing, hard, woody blackbrush shows more twig elongation and the next year has a great increase in flower production which is otherwise very sparse. Most outstanding is the lush development of Indian ricegrass which becomes tall and dense with fruiting stalks. In Figure 47 the light-colored, bushy grass dense with fruiting stalks to the right, on the lower unflooded slope, is Indian ricegrass. The larger size of the bushes on the right is the result of increased available moisture for sand sagebrush and four-wing saltbush. The coverage of this stimulated zone is to be contrasted to that of the higher portion of the unflooded bank to the upper right and to the dense stand of tamarisk which has developed in the upper part of the drawdown zone shown in the lower left.

Vegetational Succession of Drawdown Zone

During the investigation of the lakeshore ecology the opportunity was provided to see the effects of a year when the peak water level did not reach or exceed that of a previous year. In July 1971 the water reached a level of 3622 feet. The ensuing drawdown to 3607 feet in April 1972 exposed a previously

Figure 47. Stimulation of vegetational growth along line of maximum water level. Dark shrubby growth to the left is tamarisk of the upper drawdown zone. The light-colored dense, tall grass is the growth stimulation of Indian ricegrass (Oryzopsis hymenoides).

submerged zone of 15 vertical feet. The peak level reached in 1972 was only 3620 feet, 2 vertical feet lower than in the previous year. As previously mentioned, the shoreline areas supporting the greatest biomass of vegetation are the sandy shores. As the water level retreats in these areas, there is left a moist, sandy seedbed ideal for germination of seeds and the development of roots of seedlings of species the migrules of which are either blown by wind or are water-dispersed and left along the shore. In the above situation the successional vegetation of the uppermost 2 feet of the previous year's drawdown zone was not eliminated by submergence but was allowed to develop and mature for a second year before submergence in May 1973.

Now for the first time in the history of the reservoir there was in many areas the development of a shoreline band of a vegetational pioneer stage of exotic invaders which quickly matured and were able to provide an immediate seed source--much in the manner of the established dense stands of similar species occupying the upper terraces along the Colorado River. Most importantly this provided an opportunity to see what would happen when the reservoir reached a maximal level and, on the basis of even the 1 year's growth and reproduction, to predict the successional events which would occur to provide the vegetation of the sandy shoreline in the future.

The dominant plant of these stands was tamarisk. This introduced Eurasian exotic has been successful in spreading throughout the Southwest, being found along the channels of most rivers, and at the headwaters of most tributaries. Its light, air-borne seeds, also capable of water transport, have allowed it to develop a discontinuous distribution. It may be found in widely separated, locally moist pockets in areas of seeps, spring water, or surface catchment basins. Its establishment is favored by a moist, sandy seedbed. It is tolerant of alkaline conditions common in the Southwest. It has all the attributes common to an invader of sandbars and sand dunes. It flowers and matures seed over a long period, its seeds are quick to germinate after dispersal, and the seedling root system consists of a rapidly growing taproot which allows it to penetrate deeply and to keep ahead of the surface drying of sandy soils. When sandy soils of dune sand texture dry from the surface downward, a sand mulch effect results which breaks the capillary rise of moisture and tends to protect and conserve the moisture supply below about 10 centimeters. During seedling development there is a favorable root:shoot ratio which provides for maximal water absorption and reduced loss by transpiration. Seedlings with shoots 1 to 2 centimeters high may have taproots 30 to 38 centimeters long. As lateral roots develop, shoot growth increases elongation of stems, basal buds produce a bushy growth form, absorptive power of roots is increased, and the roots become capable of adding to vegetative proliferation by producing root sprouts, thus avoiding the more susceptible seedling stage. After germination in July to September, the seedlings grow slowly during the winter and do not become deciduous. They reach a height of 1 to 2 meters by May and start to flower by May or June. If allowed to grow through the summer growing season, they mature and continue to flower the first year and reach heights of over 2 meters by September. Thus the species has all the attributes needed for competitive invasion and rapid, dense establishment. And, it succeeds in reproducing itself both vegetatively by root sprouts and by dispersing seeds within the first year of establishment. During the winter months when the water table is lowered because of reservoir drawdown, tamarisk has the advantage after the first year of being deciduous and losing its transpiring leaves.

Occasional reseeding of grasses may occur in the upper part of the drawdown zone and includes Indian ricegrass, sand dropseed, mesa dropseed (*Sporobolus flexuosus*), and galleta (*Hilaria jamesii*). In the very upper part of the zone, common invading forbs are sandverbenas (*Abronia* spp.) and evening primroses (*Oenothera* spp.). At the uppermost part of the drawdown zone there is often a luxuriant growth of plants of jimsonweed which produces a prolific crop of showy white flowers. Occasionally there develop a few seedlings of Fremont cottonwood dispersed from native trees of alcoves or from the heads of tributaries.

As the water level is lowered after its peak in early July, those areas having a sandy shoreline are receptive seed beds for seeds which are dispersed by water and are washed up on the shore. Germination occurs and the seedlings are repeatedly moistened for several weeks by occasional waves washing ashore, even though water levels are lowered. In a few weeks, rows of tamarisk seedlings appear on contour lines. Meanwhile those at the maximal water levels have been growing (as seen in Figure 48) just below the wave-cut terrace representing the peak water level. The net result of one fall season of invasion and growth in the drawdown zone is a series of contour rows of seedlings and a gradient in height (Figure 49).

If the vegetation of the drawdown zone is not completely submerged by the rising reservoir levels the next year, as in 1972 when the peak was 2 feet lower than the 1971 maximum, a belt of tamarisk remains along the shoreline, is already mature, and provides a local source of seeds to reinvade the drawdown zone. With the abundance of nearby seed supply, the density of seedling establishment increases. And where there is a gently sloping sandy shoreline, as on the west side of Warm Creek Bay, vast meadows of tamarisk seedlings may develop. Figure 50 shows the 21-month-old belt of tamarisk between 3620 and 3622 feet elevation and a vast green meadow extending for hundreds of acres down to the retreating waterline in the distance as seen in May 1973. On steeper shorelines, the drawdown area is less extensive. The lower part of the drawdown zone exposed in late fall and early winter is either barren of vegetation or is invaded by bugseed (Corispermum nitidum)--a common weed naturalized from Europe, or by Russian thistle--a common invader of the West and naturalized from Eurasia. So, the drawdown zone becomes dominated by three exotic pioneer species--quite in contrast to the native vegetation.

The study of standing biomass of typical vegetational types in June 1972 included an analysis of the upper part of several

Figure 48. Row of young tamarisk along contour line left by retreating lake level.

Figure 49. Rows of tamarisk seedlings occupying the upper draw-down zone of sandy shorelines.

Figure 50. In the foreground is a second-year stand of tamarisk not flooded by second-year peak water levels; in the background is a vast meadow of 6-month-old tamarisk seedlings.

sandy drawdown areas, in contrast to the undisturbed dune sand vegetation above. After denudation by flooding and wave action, the upper part of the drawdown zone recovered to nearly the same foliage cover as the undisturbed vegetation above, and the 10-month accumulation of biomass was one-eighth that of the long established sandy vegetation above. While the unflooded areas were dominated by blackbrush, Indian ricegrass, and Mormon tea, the drawdown zone was dominated by tamarisk and evening primrose. Details have been discussed in the section on biomass.

In the fall of 1972 and the winter and spring of 1973, studies were conducted on the correlation to elevational levels of number and biomass of tamarisk seedlings. The tamarisk seedlings are principally located along contour lines, the elevations of which occurred at known dates as obtained from the daily water level records of the Bureau of Reclamation. It is recognized that there is not a perfect correlation because of the disruptive action of waves which results in washing the seeds farther upslope. However, high winds are not usual to the time of the year in question and the resulting contour alignment of the seedlings is in itself the best evidence.

In Figure 51 is a summary of the number and distribution of tamarisk seedlings as they relate to shoreline elevations and dates of water elevations. In the zone between 3622 and 3620 feet, the tamarisk belt established in the previous year was found and had not been inundated in 1972; it was a principal source of seeds. However, the number of seedlings within this belt of tamarisk grown to 1 or 2 meters in height was very small. Here,

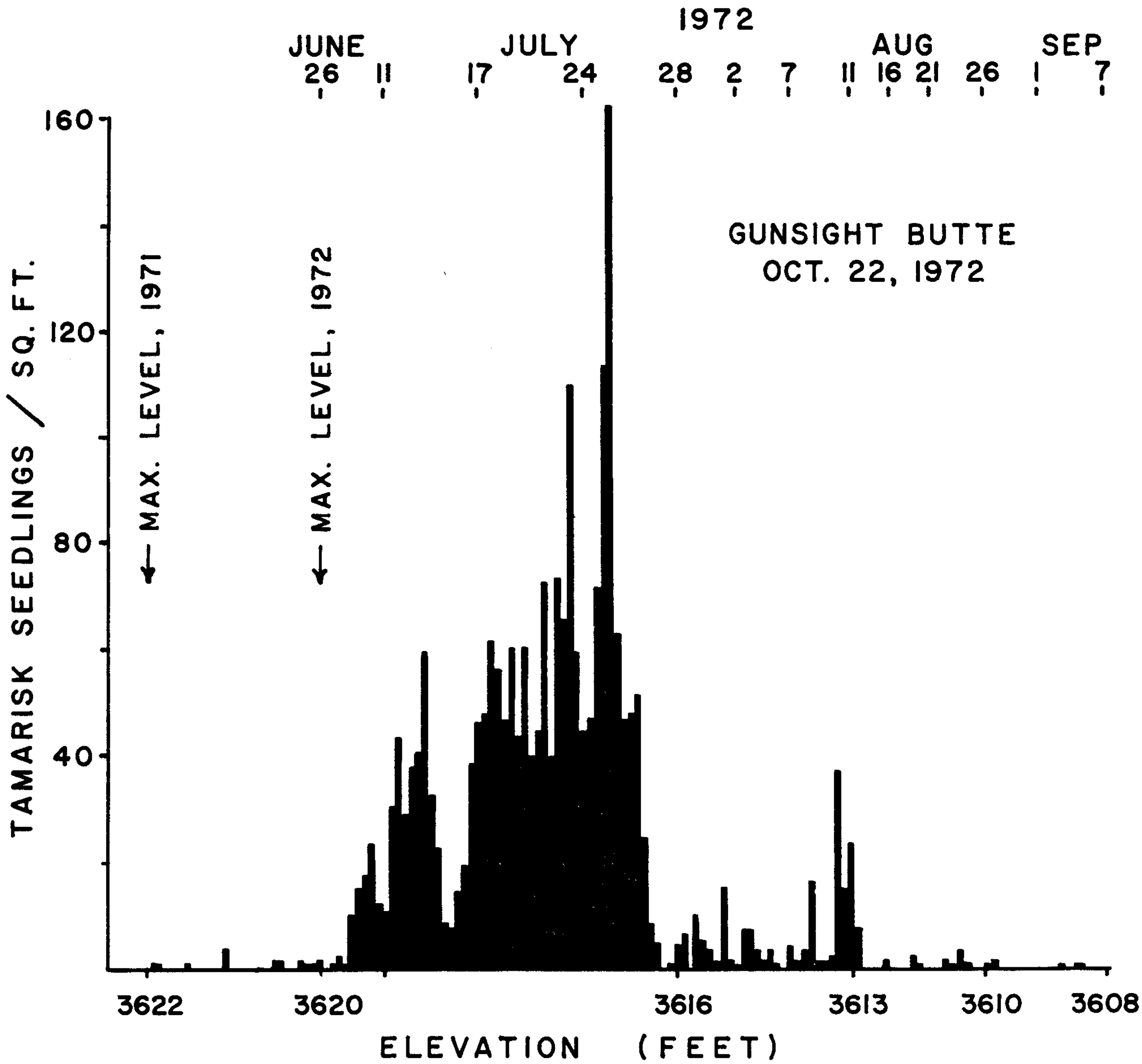


Figure 51. The number of tamarisk seedlings of sandy drawdown zone correlated to time of beach exposure and contour level.

most of the reproduction was from root sprouts. After reaching the maximum level of 3620 feet in late June the water level receded. During July there was an increasing number of seedlings developed, reaching a maximum density at the water level attained about July 25. Irregular germination occurred at decreasing water levels until the second week in August after which only occasional seedlings developed. Beyond the first week in September practically no seedlings were found. Thus, the upper vertical 7 feet of the drawdown zone exposed from the end of June until the second week in August contained nearly all the seedlings of tamarisk. The lower 9 vertical feet were nearly barren.

The accumulated drawdown biomass which had developed by January and April or May of 1973 is illustrated in Figures 52A and 52B for Gunsight Butte and West Canyon, respectively. The first set of data represents the total accumulated biomass of tamarisk developed at the 3622-foot level since July 1971, a period of about 21 to 22 months. Of interest is the proportionately large biomass accumulated at the 3619- and 3617.5-foot levels after only the fall and winter exposure and without the advantage of a summer period of vegetative growth except as seedlings the previous late summer. The lower productivity of the 3619-foot level at Gunsight Butte was probably due to the steep slope and the result of wave action into the bank at that site.

The rapid filling of the reservoir from 3590 to 3646 feet in the period from May to August and then additional increase,

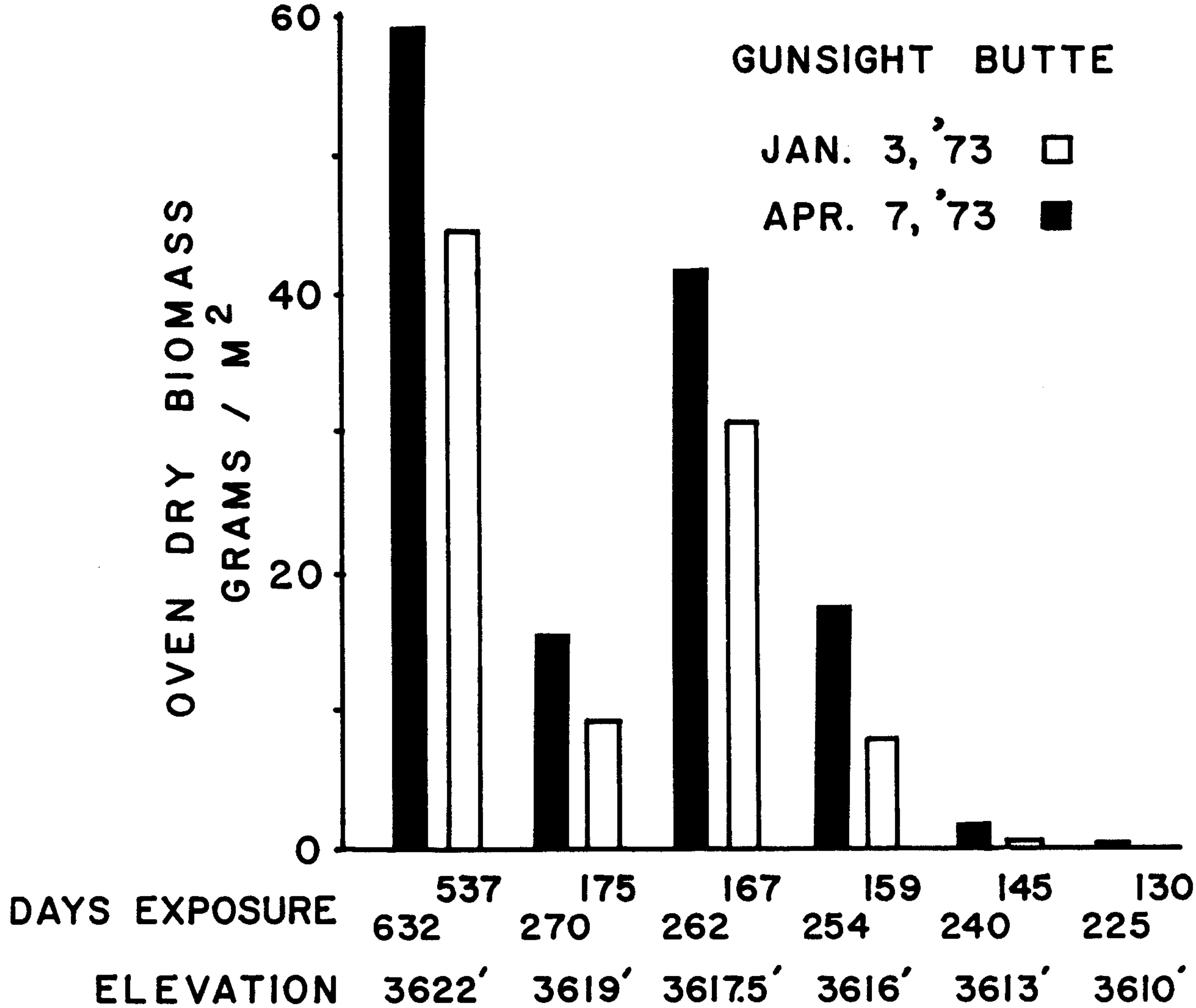


Figure 52A. The biomass, principally tamarisk, accumulated in the sandy drawdown zone near Gunsight Butte, from July 1972 to January and April 1973.

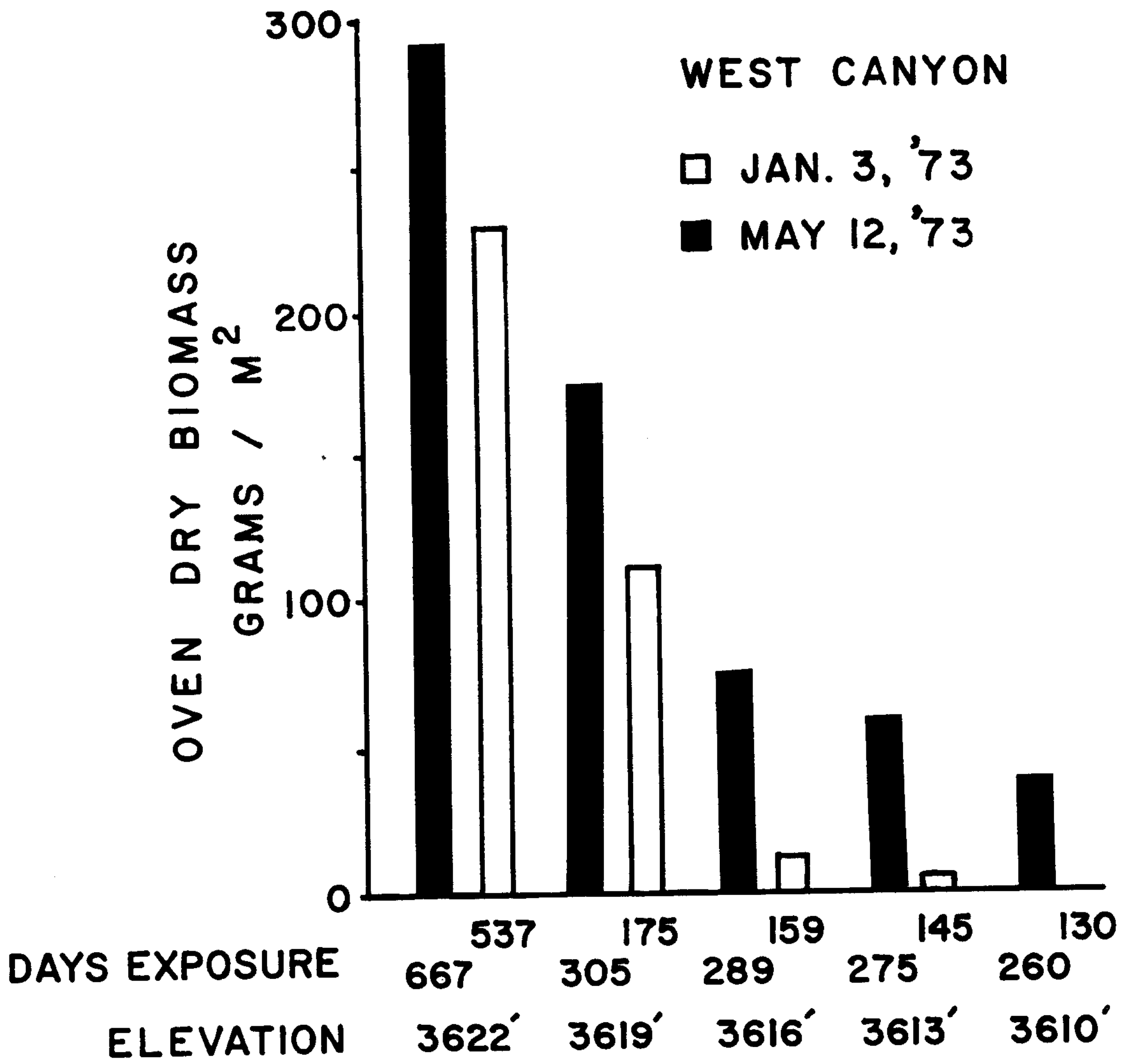


Figure 52B. The biomass of principally tamarisk accumulated in the sandy drawdown zone near the mouth of West Canyon from July 1972 to January and May 1973.

with no summer drawdown, to 3650 feet produced what appeared to be a major change in the successional picture of tamarisk. All lake shoreline stands were completely submerged and killed by the depth and duration of submergence; the increased reservoir level submerged many of the alluvial terraces to be found part way up many tributaries; and as the water level rose into the upper reaches of many tributaries, the canyon walls closed in and the stands of tamarisk became fewer. Contrastingly, in some areas the higher reservoir levels spread out onto large, expansive, former river terraces where tamarisk stands had long existed. As long as any part of the foliage remained above the water level, the tamarisk plants survived, flowered, and disseminated seeds into the water (Figure 53). With each major increase in water level the shoreline invasion of tamarisk was retarded. But, how long would it take for the reinvasion of the main lakeshore from the headwaters of tributaries and some isolated pockets of tamarisk in side bays?

Following the peak level of 3667 feet in the summer of 1974, the drawdown zone of sandy shorelines was again examined for tamarisk succession. Tamarisk invasion of areas of the main channel, most remote from tributaries, was nil. However, for distances of several miles down from flooded tributaries and in the vicinity of isolated stands of tamarisk in moist recesses, there appeared a repetition of the previously described succession. However, because of the greater distance from the seed source, the dispersal period was more irregular and the density of seedlings much less. While some contours had as many as 160

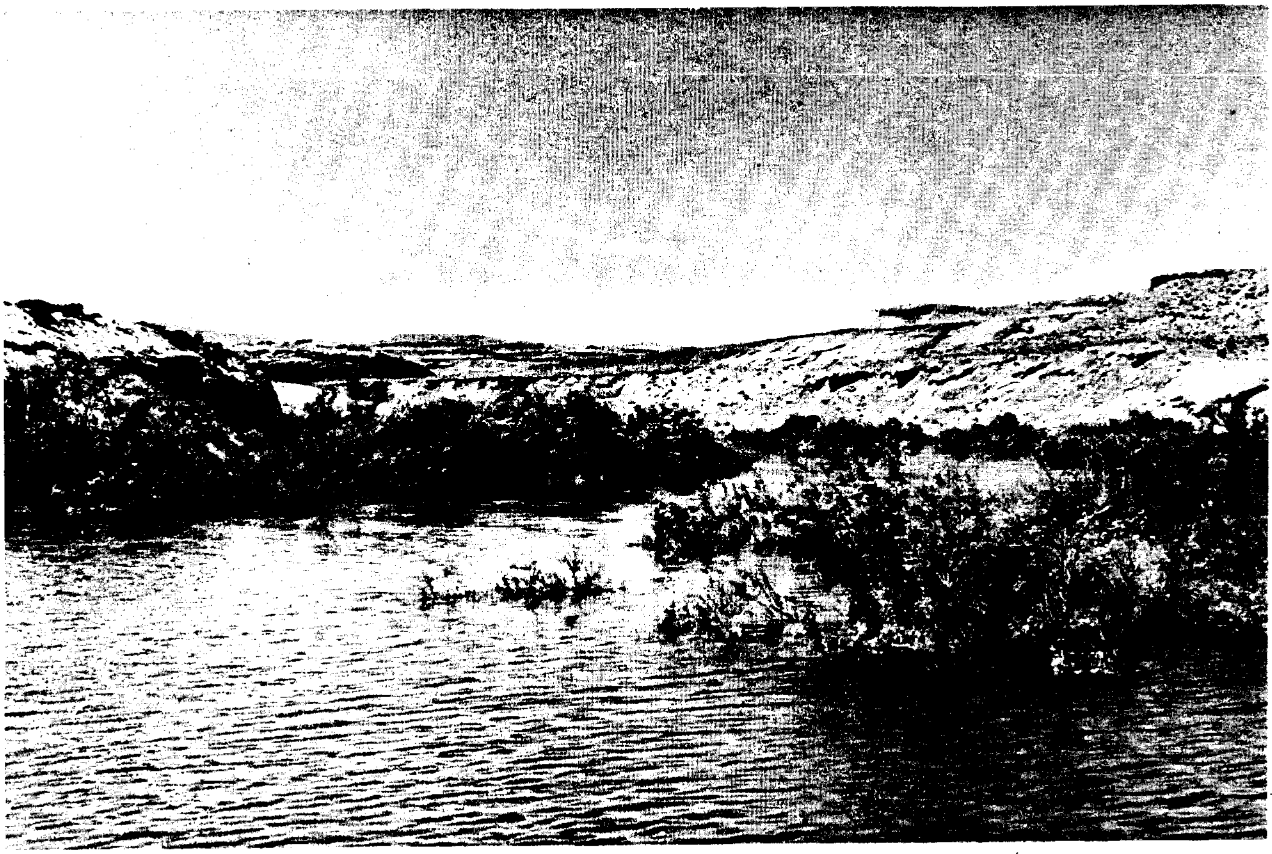


Figure 53. Principal source of tamarisk seed is from stands of tamarisk along flooded tributaries and embayments.

seedlings per square foot at Gunsight Butte in 1973, the maximum was about 30 in 1974. However, as before, those levels exposed after the first week in September were without tamarisk reproduction, and most of the reproduction occurred in the top 7 to 11 feet of the drawdown zone.

The above pattern of reproduction during July and August suggests a possible method of control with proper water level manipulation. If a narrow zone were exposed during this time of seedling establishment and then the water level were raised sufficiently to completely submerge the seedlings and held for an adequate period to cause their death (assisted by the abrasive effect of wave action), the water level could then be lowered and the exposed zone not be suspect to tamarisk invasion. Plans were made to determine experimentally the limitations and susceptibility of tamarisk seedlings to this method of control.

SUBMERGENCE EFFECTS

Breakdown and Decomposition of Flooded Vegetation

The rising water of the reservoir which floods vegetation, organic litter, and in some areas soil with organic matter has effects which are both detrimental and beneficial. The decomposition of all organic matter provides a source of increased nutrients and organic acids into the reservoir which are added to the continued influx of nutrients washed in from the tributary canyons and the Colorado River. The rate of physical breakdown and biological decomposition of different species varies with their anatomical structure and with the chemical composition of tissues, e.g., the degree of lignification. Some underwater studies at intervals of time after submergence have provided an insight into the relative rates of breakdown.

Among the trees common to the area, the more resistant include singleleaf ash, Gambel oak, and netleaf hackberry. Less resistant to decay are western redbud, squawberry, Fremont cottonwood, and species of willow.

Among the common shrubs, the most prevalent--blackbrush--is also the most resistant to decay. It is followed in resistance by species of Mormon tea whose photosynthetic stems, which are heavily cutinized and lignified, remain intact. Of the two species of *Atriplex*, shadscale is more resistant because of its indurate, thorny, lignified stems than is four-wing saltbush. Finer branched and more easily decomposed are goldenweed, sand sagebrush, hairworm snakeweed, and indigo bush.

Figure 54 shows representative shrubs which were killed by submergence in April to June and then were exposed with the lowering of water level in September. The deep, woody taproots of several species resist removal by wave action and the surface erosion by undertow during periods of stormy weather. Many of the dead plants become pedestalled and around some plants pockets of sand have been removed by the activity of fish. Species of cacti rapidly decompose after submergence due to their high percentage of soft, succulent tissue.

Unique is the breakdown of the leaves of narrow-leaved species of Spanish bayonet (Yucca spp.). Yuccas have been an important resource of the Indians of the Southwest. Buds, flowers, and the succulent emerging flower stalks are eaten raw or boiled. Fleshy fruits are eaten raw or boiled, are dried for winter use, or are used for a fermented beverage. The roots, known as amole, are used as a soap or laxative. The fibers from the leaves are used for rope, mats, sandals, baskets, and cloth. A typical plant is shown in Figure 55. The plant remains green and intact for several weeks after submergence, and plants have been seen which continued flowering when only the flowering stalk was emergent above the water. The stiff leaves are resistant to mechanical breakage by the waves. However, after several weeks of submergence, microbial action begins the process of decomposition of the soft tissues of the leaves, leaving only the long strands of thick-walled, lignified cells of the fibro-vascular bundles--the result of the process of retting. Figure 56 shows the change in a rosette of Spanish bayonet leaves which was

Figure 54. Dead blackbrush, resistant to decomposition during one season of submergence, remain intact on pedestalled, woody taproots in drawdown zone.

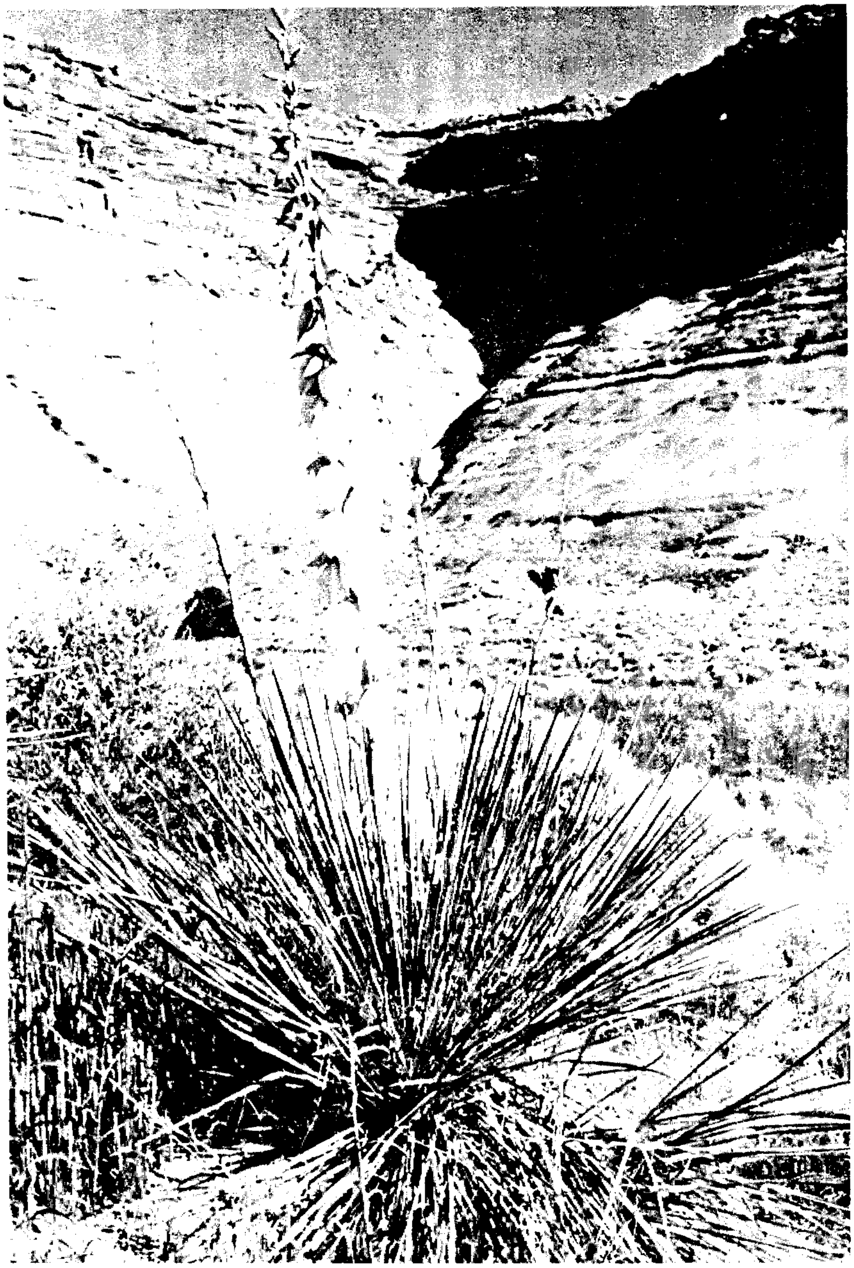


Figure 55. Typical growth form of a narrow-leaved species of Spanish bayonet (*Yucca angustissima*).

Figure 56. Decomposition, or retting, of Spanish bayonet leaves while submerged leaving a "tangled wig" of fibrous strands.

submerged for a period of about 5 months and was subjected to retting and wave action. The mass of fibers, bleached to a golden color upon reexposure, has the appearance of an unkempt blond wig left on the beach. With continued submergence, the fibrous mass breaks away from the erect, thickened rootstalk leaving a woody cylindrical stump sticking up from the bottom.

Most broad-leaved herbs (forbs) are quickly decomposed after submergence and none remain photosynthetically active for more than a few days or weeks. Wave action along the shore at the time of submergence uproots, or undercuts, many of the shallow, fibrous-rooted species. Many are bent and broken by wave action even before they are completely submerged. Grass leaves quickly become limp strands of fibrous tissue.

The destinies of the fragmented and variously decomposed organic materials are several. Some of the fine leaf and stem material from plants and litter form floating mats of straw-like chaff. These may be commonly found in waters flooding organic-rich tributaries. Floating mats of this organic debris occasionally drift into the main channel and have the appearance of an oil slick. These mats are areas of active microbial activity, and studies of mercury accumulation (Potter, Kidd, and Standiford, 1975) have indicated an enrichment of mercury concentration in this debris. Where woody vegetation is flooded, logs and branches may be added to the floating organic debris. As the reservoir reaches maximum level this phenomenon will be less common. The rising water level into wooded alcoves and tributaries has caused a new problem for beaver who for centuries have cut down streamside trees to feed on the bark and to construct dams to retain the water from upstream. With the rising water during reservoir filling, the water has been coming from the "downstream" side. A number of beaver still exist but as bank dwellers in the alcoves and without dams. Eventually all of the woody material becomes waterlogged and settles to the bottom to become part of the organic enrichment of the bottom sediments. Secondly, the fragmented, flooded organic matter may quickly settle to the bottom where it is subject to movement by the undertow of wave action and is aligned in furrows associated with the bottom ripple patterns or trapped against any obstacle of the bottom. This material soon becomes incorporated into the bottom sediment. Thirdly, chemical and biological decomposition of the submerged vegetation occurs and is important in adding to the enrichment of nitrates and phosphates of the reservoir. These compounds are important in determining the rate of eutrophication of the reservoir and are being studied by limnologists. Other breakdown products such as tannic acids and a variety of soluble organic carbon compounds may have complex interacting effects on such things as salt precipitation rates, an interaction being investigated by Dr. Robert Reynolds of Dartmouth College. Finally, the submerged vegetation provides a substrate for the growth of periphyton and invertebrate organisms. These organisms include macro- and micro-invertebrates, diatoms, green and blue-green algae, and bacteria. During the spring rise of water level, submerged vegetation may quickly develop a coating of periphyton within several days, appearing as a misty shroud of greenish, gelatinous, and filamentous growth. The entire surface of shrubs and even grass plants may become covered (Figure 57). With the accumulation of the algal coating, the population of invertebrates increases. These are important as a basic food supply to the fish populations and are thus an important aspect of fishery management. Simultaneous with the development of periphyton is the development of benthic (bottom) organisms on the sand, silt, and rock substrate of the bottom. In Figure 57 are shown initial clumps of algae on a sandy bottom within a week after submergence.

Benthic Development

Before discussing studies of vegetational decomposition, nutrient release, and periphyton development, mention should be made of the general nature of the benthic development. In 1973 and 1974, as the water level rose in the spring and summer onto previously unflooded beach areas, there was a dramatic rapid development of a green chlorophyllous layer on the submerged sandy bottoms. Within 2 to 7 days a perceptible green color developed simultaneously with the development of periphyton on submerged plants. Large areas of bubbles resulted on the bottom where algal development occurred. Throughout the extent of the reservoir in the littoral zone, where light reaches the bottom, there was often development of a layer up to a half-inch thick of a highly flocculated, granular complex of silt and organisms of olive-green color. This layer provided a mantle over slickrock more commonly than over sand. Aggregates were

Figure 57. Bottom vegetation submerged 1 to 2 weeks and quickly covered with strands of green algae. Clumps of benthic algae have developed on the sandy bottom.

commonly up to 0.5 centimeter in diameter. When stirred up from the bottom the aggregates maintained their entity and slowly settled again to the bottom. The nature of the material is illustrated in Figure 58, and the material literally was scraped off the bottom by the handful. Microscopic examination of these bottom granules revealed them to be a very complex aggregation of silt grains enmeshed in the gelatinous coatings and strands produced by a highly diverse taxonomic collection of diatoms and blue-green and green algae.

While scuba diving in conjunction with other research, a benthic algal cover has been observed as a greenish, photosynthetic layer to depths of about 10 meters, beyond which it usually turns into a darkened mass. In July 1974 a survey of the algal coverage on the bottom of a gently sloping sandy beach near Gunsight Butte (which is subject to considerable wave action and off-shore turbulence) revealed the following average coverages along three underwater transects:

Depth (meters)	Coverage %	Submergence (weeks)
1	0-5	4
2	20	6
3	22	7
4	23	8
5	80	15
6	83	21
7	95	48
8	95	50
9	95	51
10	95	53

Using scuba gear, samples of the benthic material were collected at several times of the year from rocky underwater substrates. A known area of 1 square foot was delineated on

Figure 58. Flocculated aggregates of silt and algae enmeshed in a gelatinous matrix, olive-green in color, and common as a benthic layer on the bottom.

the bottom by a square metal frame with 2-inch-high sides. The benthic material was vacuumed up with a flexible rubber hose attached to the intake of a bilge pump which was taken to the lake bottom. A long hose led from the outlet of the pump to the boat where the suspended material was filtered through a plankton net. The benthic material was transferred to plastic bags, kept near freezing in the dark, and taken to the laboratory for examination for organic matter and chlorophyll content.

Microscopic examination of the samples indicated that the organic matter was made up almost entirely of a complex mixture of diatoms and blue-green and green algae enmeshed in a gelatinous mass causing the aggregation of clay and silt into globules. Representative samples of this benthic material obtained at two locations and at depths ranging from 3.3 to 5.9 meters resulted in values for oven-dry weight of organic material averaging 2.14 grams per square meter (a range of 1.57 to 2.62).

In October 1975 samples of the aggregated benthic material were collected from a rocky bottom in Labyrinth Canyon at a variety of depths for chlorophyll analyses. Preliminary results are given in Table 8 and are based on three replicates per sample. Variation between depths was significant at the P.05 level but was not significant among replicates. The average concentration at all levels was 352 milligrams per square meter of bottom surface. Following are some general comparisons with concentrations of chlorophyll of phytoplankton material contained in a 1-meter-square column of water and the depth from the surface down through the photic zone:

Table 8. Chlorophyll concentration of benthic organic matter, Labyrinth Canyon, October 1975.

Depth (meters)	Total Chlorophyll Concentration (milligrams per square meter)[a] Rep.1	Rep.2	Rep.3	Aver.
1	314	288	-	301
2	409	409	383	400
3	332	340	418	363
6	344	340	353	346

[a]In this case the milligram concentration of chlorophyll is equivalent to a square meter of bottom surface and could be compared to the chlorophyll concentration of a column of water through the euphotic zone which was a square meter in area.

Milligrams/ square meter	Location
3	Silver Spring, Florida (Duffer and Dorris 1966)
4	Blue River, Oklahoma "
30-80	ordinary eutrophic lake (Kobayasi 1961)
100-200	extremely eutrophic lake "
33	Lake Powell (Steve Gloss, personal communication)

In Lake Powell the littoral zone--that area of the lake where light penetrates to the bottom--is about 10% of the lake area. Using chlorophyll concentration as a rough estimation of productivity, the chlorophyll concentration of benthic material in the photic zone was about ten times that of the average concentration in plankton, or approximately equal in total value for the entire lake. This zone would appear to warrant considerable attention.

When the water level is lowered, the flocculated silt, clay, and algae are left to dry on cliff walls and shores of rock and sand. On the cliffs a thin layer of whitish, crusty material forms part of the whitening referred to as the "bathtub" ring. On sloping shorelines the benthic material, which may wash into depressions, dries into a light-weight, porous, foam-like material greenish-gray in color (Figure 59).

Particularly dense and vividly colored mats of algal growth have been observed on sloping rock surfaces several months after submergence of a new rocky shoreline. These greenish mats persist until the depth of water exceeds about 10 meters, at which depth the degradation products of the pigments start to turn the color to brown and finally black. It was observed that the brilliantly colored mats tapered to an upper focal point, frequently leading to a crevice in the rocks. These crevices,

Figure 59. Flocculated clay, silt, and algae of benthic mass dried into foam-like material in drawdown zone.

especially common in the area of shelfy terraces, are the sites of nests of wood or pack rats, mice, lizards, or birds (Figure 60). It is hypothesized that centuries of accumulation of nitrogenous organic matter in these sites, which had been constantly dry, is the local source upon flooding of a rich nutrient supply. Brilliantly pigmented algal growths may extend 5 to 7 meters downslope, be as much as 1 to 2 meters wide, and form a felt-like mat a centimeter thick. Where there are crevices in the cross-bedding sloping away from the nutrient source, the intensity of color of the algae indicates a downslope movement of the nutrients along the cracks. On reaching a basin depression the pigment-enriched lines branch out in a fashion comparable to a dendritic drainage pattern. In contrast to the normal yellowish, olive-green-colored benthic algae, the mats underwater appear to be almost irridescent green. After storage in a refrigerator, the water-soluble pigments are an intense purplish color of extremely high concentration. The pigmentation is probably high in phycocyanins in addition to the enriched concentration of carotenes and chlorophylls. The water-soluble pigments which are bluish-purple by transmitted light fluoresce as blood-red by reflected light.

In December 1974, samples were taken from several positions within the above mats and from the benthic material just outside the mats from about 6 meters depth of water. They were analyzed in the laboratory for the percentage of total nitrogen based on the oven-dry weight of the algal sample. The results are given in Table 9. The total nitrogen is about four times

Figure 60. Pack rat nest in rock crevice with a long-time accumulation of organic matter and fecal material. On flooding, these sites provide focal points of increased nutrients.

Table 9. The percentage of total nitrogen of nutrient-enriched algal mats, based on oven-dry weight of organic material.

	Total Nitrogen Concentration (%)	
Sample Location	Replicates	Average
Densest area	3.88-2.34-2.27	2.83
Lateral edge	1.55-0.93-0.48	0.99
Outside the mat	0.71	0.71

higher in concentration within the mat than it is in the average surrounding benthic material.

The benthic organic mat, surprisingly dense in coverage and high in organic matter, is, as indicated above, a major source of organic material available for reduction as it becomes mixed with and covered by a layer of silt. Surprisingly, the water depth does not have to become deep, nor the water deoxygenated, for the process of reduction to occur within the bottom substrate. Where pockets of silt and organic matter occur under shallow water of only several feet in depth and even aerated by wave action, the bottom may become anaerobic and the chemical process of reduction may occur. This is evidenced by digging into the bottom sediments, or even sandy shorelines, where a black layer of reduction is observed just below the surface. Commonly, when water levels retreat and leave pockets of silt exposed, even after a few months' submergence, a black layer 0.5 to 7 centimeters thick has developed which is additionally evidenced by the odor of hydrogen sulphide until the deposit is completely dried.

Nutrient-Weight Relations of Submerged Tamarisk and Attached Organisms

Because tamarisk is the dominant species invading the draw-down zone and is then flooded by the rising waters in the spring, a submergence experiment was performed with this species. On May 11, 1973, cuttings were made of 120 1-year-old tamarisk shoots of as uniform size and shape as possible. Each was labelled and measured as to length and green weight. They averaged 82 centimeters high. Based on data from 20 shoots taken to the laboratory where the oven-dry weight and average percentage moisture contents were determined, they had an average moisture content of 57.6%. The base of each shoot was attached to a short length of dowel which was embedded in sand-filled fiber-glass pans. Two plants were placed in each pan. Using scuba equipment, the 100 plants were placed in 4 meters of water along a sloping sandy shore of Lake Powell near Gunsight Butte. At intervals of 1, 2, 4, 6, and 10 weeks five plants were recovered for analysis. Recovery was accomplished by diving with a supply of plastic bags large enough to slip over the shoots without disturbing the attached periphyton. The plant was then pulled out of the sand, the dowel wiped off, and the entire plant pushed up into the bag to which was then added some exhaled air from the diving mouthpiece. The opening of the bag was sealed by folding it over and fastening it with several wraps of strong rubber bands. The bags then were allowed to float to the surface from whence they were taken to shore. Each bag was opened, the dowel removed, and the tamarisk plant vigorously shaken in the water of the bag to remove the periphyton and silt. These were then separated from the water by filtering through a plankton net of #20 mesh nylon, 173 threads per inch and aperture size of 76 microns. It is recognized that this mesh does not retain the very small-sized algae and invertebrates, but because of the mass of total material the use of finer bolting cloth was impractical. The tamarisk plants were air-dried and the plastic bags of peri-phyton, to which preservative was added, were refrigerated for transport to the laboratory.

Plants were dried at 85°C for at least 48 hours before oven-dry weights were determined. Each shoot was separately ground in a Wiley mill with a 40-mesh screen and kept dried in plastic bags for analysis of organic content, total nitrogen, and phosphorus content. The attached material which had been filtered was floated in a pan to allow removal of fragments of tamarisk which were dried and added to the tamarisk weight. The sand portion was separated by centrifugation and separately dried. The finer silt cannot readily be separated from the periphyton and was combined for oven-dry weight measurements. Oven-dried aliquots of each sample (plant and periphyton plus silt) were weighed, subjected to combustion at 500°C in a muffle furnace for 4 hours, and the percentage of ash and organic matter determined.

Total nitrogen concentration was determined on 0.1 gram of oven-dried material digested in micro Kjeldahl flasks and distilled in a Kjeldahl still following the Kjeldahl method for total nitrogen determination.

The total phosphorus analysis was done on samples of ash digested with nitric acid using the molybdate blue colorimetric determination method of Truog-Meyer (Chapman and Pratt 1961).

The spring-summer experiment was performed after an initial trial experiment done in a similar manner in mid-winter, from December 3, 1972, until February 3, 1973. During this period the water depth was about 1.5 to 3 meters and during these months the water reaches its lowest temperature but its greatest clarity. Table 10 summarizes the results of the winter experiment. There was a

Table 10. Analyses of organic matter, ash, nitrogen, and phosphorus of submerged tamarisk plants and attached periphyton (winter).

		1 month*		2 month	
		Aver.	S.E.	Aver.	S.E.
WEIGHTS:**					
Plant	O.D. wt(g)	8.3	0.67	10.4	1.27
	wt loss(%)	10.1	3.53	21.9	9.33
Periphyton and Silt	O.D. wt(g)	5.07	.99	27.5	7.77
	Ash Free O.M.(g)	.60		3.8	
ASH: ORGANIC MATTER:					
Plant	Ash (%)	13.14	2.00	14.8	2.59
	O.M.(%)	86.86	2.00	85.2	2.60
Periphyton and Silt	Ash (%)	88.21	1.24	86.0	.790
	O.M.(%)	11.79	1.24	14.0	.797
NITROGEN (%):					
Plant	O.D. wt	0.84	0.06	.90	.056
	Ash Free O.M.	0.97	0.08	1.08	.083
Periphyton and Silt	O.D. wt	0.75	0.08	.56	.042
	Ash Free O.M.	6.65	0.86	4.04	.342
PHOSPHORUS(%):					
Plant	O.D. wt	.096	.009	.090	.005
	Ash Free O.M.	.111	.012	.107	.003
	N:P Ratio	8.7:1		10.1:1	
Periphyton and Silt	O.D. wt	.097	.014	.050	.002
	Ash Free O.M.	.726	.035	.336	.011
	N:P Ratio	9.2:1		12.0:1	

*Tamarisk plants submerged December 3, 1972, in 3 meters of water

**O.D. wt(g) represents the oven-dry weight in grams after 24 hours at 85°C. O.M. represents organic matter. All data are based on five replicate plants.

definite loss of weight in the tamarisk plants. The ash-free organic matter of the periphyton increased six-fold between the first and second month. At this time of the year there are developed masses of periphyton encasing the substrate in golden globs of gelatinous material, often 3 centimeters in diameter, around slender stems. There was also a slight increase in the organic matter percentage in the second month. However, the percentage concentration of both nitrogen and phosphorus in the periphyton decreased in the second month, phosphorus being reduced to about one-half the percentage concentration. The nitrogen:phosphorus ratios at 1 and 2 months were 8.7:1 and 10.1:1 for the tamarisk and 9.2:1 and 12.0:1 for the periphyton. This preliminary study led to the more detailed investigation during the period of rapidly rising water level.

In Table 11 are summarized the results of the spring-summer tamarisk submergence study showing the changes in ash:organic matter relationship; total nitrogen; and total phosphorus of both tamarisk plants and the attached silt, periphyton, and invertebrates. The time periods represent duration of submergence after May 11, 1973. The water depths are those at the time of removal, having been originally placed at a depth of 4 meters. Because of the rapidly rising water, on May 25 a group of plants were moved in their containers along the bottom to a 2-meter depth. The first set of plants collected at 6 weeks and at an 8-meter depth represents those plants which were moved in contrast to the second set at that date which were recovered from a 17-meter depth. The 10-week samples were also taken from

Table 11. Analyses of organic matter, ash, nitrogen, and phosphorus of submerged tamarisk plants and attached periphyton (spring-summer).

		Time and Depth of Submergence											
		1 Week 6 Meters		2 Week 8 Meters		4 Week 12 Meters		6 Week* 8 Meters		6 Week 17 Meters		10 Week 11 Meters	
		Aver.	S.E.	Aver.	S.E.	Aver.	S.E.	Aver.	S.E.	Aver.	S.E.	Aver.	S.E.
WEIGHTS:													
Plant	O.D.**wt(g)	15.00	4.39	12.3	2.18	11.2	1.66	8.52	1.74	12.86	2.50	8.47	1.97
	wt. loss (%)	6.34		13.0		7.4		17.5		10.5		22.5	
Periphyton	O.D. wt(g)	2.3	1.17	2.8	.82	9.2	2.49	2.9	.65	2.4	.59	.85	.23
and Silt	Ash Free O.M.(g)	.29		.32		1.25		.45		.35		.22	
ASH: ORGANIC MATTER													
Plant	Ash (%)	7.14	.46	7.36	.66	7.70	.87	8.73	1.13	5.95	.39	6.41	1.42
	O.M. (%)	92.86	.47	92.64	.65	92.30	.87	91.26	1.13	94.04	.39	93.58	1.42
Periphyton	Ash (%)	87.44	1.48	88.58	1.38	86.42	.50	84.62	1.42	85.25	1.07	74.12	4.38
and Silt	O.M. (%)	12.56	1.48	11.42	1.38	13.57	.50	15.37	1.42	14.74	1.07	25.92	4.29
NITROGEN (%):													
Plant	O.D. wt+	1.28	.09	13.5	.22	0.84	.09	1.13	.14	1.12	.08	0.85	.20
	Ash Free O.M.	1.37	.11	1.46	.24	0.91	.11	1.24	.17	1.19	.08	0.91	.22
Periphyton	O.D. wt	0.64	.14	0.51	.06	0.59	.07	0.57	.08	0.47	.04	0.73	.07
and Silt	Ash Free O.M.	5.18	.96	4.54	.16	4.39	.68	3.61	.67	3.19	.16	2.89	.20
PHOSPHORUS (%):													
Plant	O.D. wt++	0.18	.01	0.19	.02	0.12	.02	0.12	.01	0.12	.01	0.12	.01
	Ash Free O.M.	0.19	.01	0.20	.02	0.13	.02	0.13	.01	0.13	.01	0.13	.01
Periphyton	O.D. wt	0.10	.02	0.09	.01	0.09	.02	0.07	.01	0.10	.01	0.13	.01
and Silt	Ash Free O.M.	0.84	.16	0.84	.15	0.67	.18	0.46	.04	0.68	.07	0.53	.06

*Collection from plants which had been moved after 2 weeks to shallower depth.

**O.D. wt represents the oven-dry weight after 24 hours at 85°C. All data based on five replicate plants.

+Total nitrogen concentration of tamarisk before submergence(May 11, 1973): leaves 1.60%, stems 0.539%, whole shoots 0.92%, based on oven-dry weight.

++Total phosphorus concentration of tamarisk before submergence(May 11, 1973): leaves 0.232%, stems 0.117%, whole shoots 0.170%.

the group moved to shallower water. Although the plants were moved through the water with the least agitation possible, some periphyton was observed falling off. However, as can be seen by comparing the two sets of 6-week samples the amount of periphyton was not less than on those left undisturbed at the greater depth.

The loss in weight of the tamarisk plants, expressed as a percentage of the original oven-dry weight, is based on a calculated value for oven-dry weight at the time of submergence derived from the known green weight of each cutting less the average moisture content of 57.6% which was determined for 20 of the 120 cuttings. There is indication of decreased weight with time. Some of this may be due to the foraging of fish, especially bluegills and carp, rather than to decomposition.

The weight of periphyton and silt combined seems to increase up to a month and then decrease. There is a reasonable carrying load of the substrate provided by the slender tamarisk shoots and once there is an accumulation it apparently stimulates the foraging by fish. The ash:organic matter ratio of the tamarisk plants was rather consistent. However, there appears to be an increase in the relative percentage of organic matter in the attached material. It is to be expected that the amount of silting would be greatest when initially submerged at the 4-meter depth because wave action near the shore stirs up the bottom. As the water level increased the plants were at increasing depths and at greater distances from the shore.

Representative tamarisk shoots sampled for total nitrogen

(N) and for total phosphorus (P) contained the following percentage concentrations before submergence:

	% Total Nitrogen	% Total Phosphorus	N:P Ratio
Leaves	1.60	0.232	6.9:1.0
Stems	0.53	0.117	4.5:1.0
Whole Shoots	0.92	0.170	5.4:1.0

The low values obtained for both nitrogen and phosphorus and the low N:P ratio might be expected from a terrestrial plant growing in the relatively sterile dune sand. The percentages of nitrogen in the plants did not consistently decrease with time of submergence. The percentages of phosphorus, however, apparently declined and then remained at 0.13% of the oven-dry plant weight. Current studies in the nitrogen:phosphorus relations of terrestrial litter decomposition (Gosz, personal communication) suggest that if higher-than-usual concentrations of either are present, they are released until a balanced ratio is obtained which is then maintained through continuing stages of decomposition. Or, if concentrations are low to begin with, decomposition does not drastically change the ratio. In comparing the N:P ratios of the submerged plants there was a shift from the 5.4:1.0 ratio before submergence to a ratio of 7.1:1.0 by the first week and an average ratio of 7.8:1.0 for the period of 1 to 10 weeks, indicating a greater release of phosphorus than nitrogen from the tamarisk.

The nitrogen and phosphorus percentages of the attached material are expressed both on the basis of the total oven-dry weight, which would include both the silt and the organic matter, and on the basis of the ash-free organic matter, which would exclude the silt portion. The nitrogen percentage of the organic matter decreased with time and with increased depth. The latter relationship would be expected, as previous studies by Hansmann, Kidd, and Gilbert (1974) have shown that maximum photosynthetic activity occurs at depths of 2 to 3 meters (6.5 to 9.8 feet) and then drops rapidly to 8 meters (26.2 feet). Observations while diving at all seasons of the year have indicated that below 8 to 10 meters the benthic algae and the attached periphyton have a much lower chlorophyll content and the dark olive-brown and black colors of decomposition products become more pronounced. As the photosynthetically active tissues decrease so too would the concentration of nitrogenous protoplasm; this was clearly indicated in this study where the total nitrogen decreased from 5 to 3%. The decrease in phosphorus content of the periphyton also occurs with time and increased depth but was somewhat less. The average ratio of N:P for the periphyton was 6:1.

Composition of Attached Organisms in Relation to Season and Depth

The preliminary trials using tamarisk shoots in submergence studies in the winter and again in spring and summer indicated variations in the accumulation of periphyton at different seasons of the year in response to temperature changes and clarity of the water and to different depths of water. To eliminate the variable surface area presented by tamarisk shoots, plastic trees 57 cm. high, sold as Christmas decorations, were substituted. These are very uniform in construction, have a surface area of about 1 square meter, and apparently have served as a substrate in the same manner as tamarisk.

From July 7, 1973, until October 26, 1974, samples were collected and trees repositioned underwater so that triplicate samples were available which had been submerged for 1 month and for 3 months and at depths of 1, 2, 3, 4.5, 6, 8, and 10 meters. The samples were obtained and treated in the same manner as previously discussed, except that they are being examined for total dry weight; dry weight of various fractions (e.g., silt, macroinvertebrates, microinvertebrates, and algae); and taxonomic composition and numbers of macroinvertebrates and diatoms. Slides have also been prepared from which other algal composition could be determined. These analyses are currently underway by Ellen Louderbough and will be reported in a separate bulletin.

Impact of Submergence on Tamarisk Seedlings

Because most of the invading tamarisk seedlings become established from the time of peak water level in July until the first part of September, an experiment was designed to test the possible control of the seedlings by submergence in late September of tamarisk plants 1, 2, and 3 months old.

The older seedlings were grown in a sandy loam soil in crocks 21 centimeters in diameter and 23 centimeters deep to allow for deeper root growth than provided by the 10-centimeter-high fiberglass pans used for the 1-month-old seedlings. Both types of containers were provided with drainage holes. The plants were grown in the greenhouse with periodic subirrigation.

At the time of submergence in the field on September 26, 1975, all plants looked healthy and corresponded closely to equivalent-aged tamarisk seedlings along the sandy beach. The 1-, 2-, and 3-month-old seedlings averaged respective heights of 2, 6, and 9 centimeters.

After the number of seedlings in each container was counted, they were placed off a sandy shoreline in Wahweap Bay so that the soil level was covered by about 50 centimeters of water and all plants remained under water at all times. Several times during the 24-day experimental submergence the plants were moved farther offshore to maintain the depth of submergence during this period when the lake level was being lowered. At appropriate intervals, containers of plants of each age were removed and partially buried in the sandy shore just above the waterline to allow them to receive some moisture from below and for the soil to become drained to field capacity. Several days after removal from the water the live plants were counted. Figure 61 is based upon the data obtained from these measurements. It is obvious that a few days of submergence is not an effective control measure for any age of seedlings, there being a 50% mortality after 3 days for 1-month-old seedlings, a degree of elimination not reached until about 6 days for 2-month-old and not until more than 24 days for 3-month-old seedlings. About 95% mortality was attained for 1-month-old seedlings at 12 days and 100% elimination for both 1- and 2-month-old seedlings after 24 days. At that time, however, only 40% of the 3-month-old seedlings had succumbed.

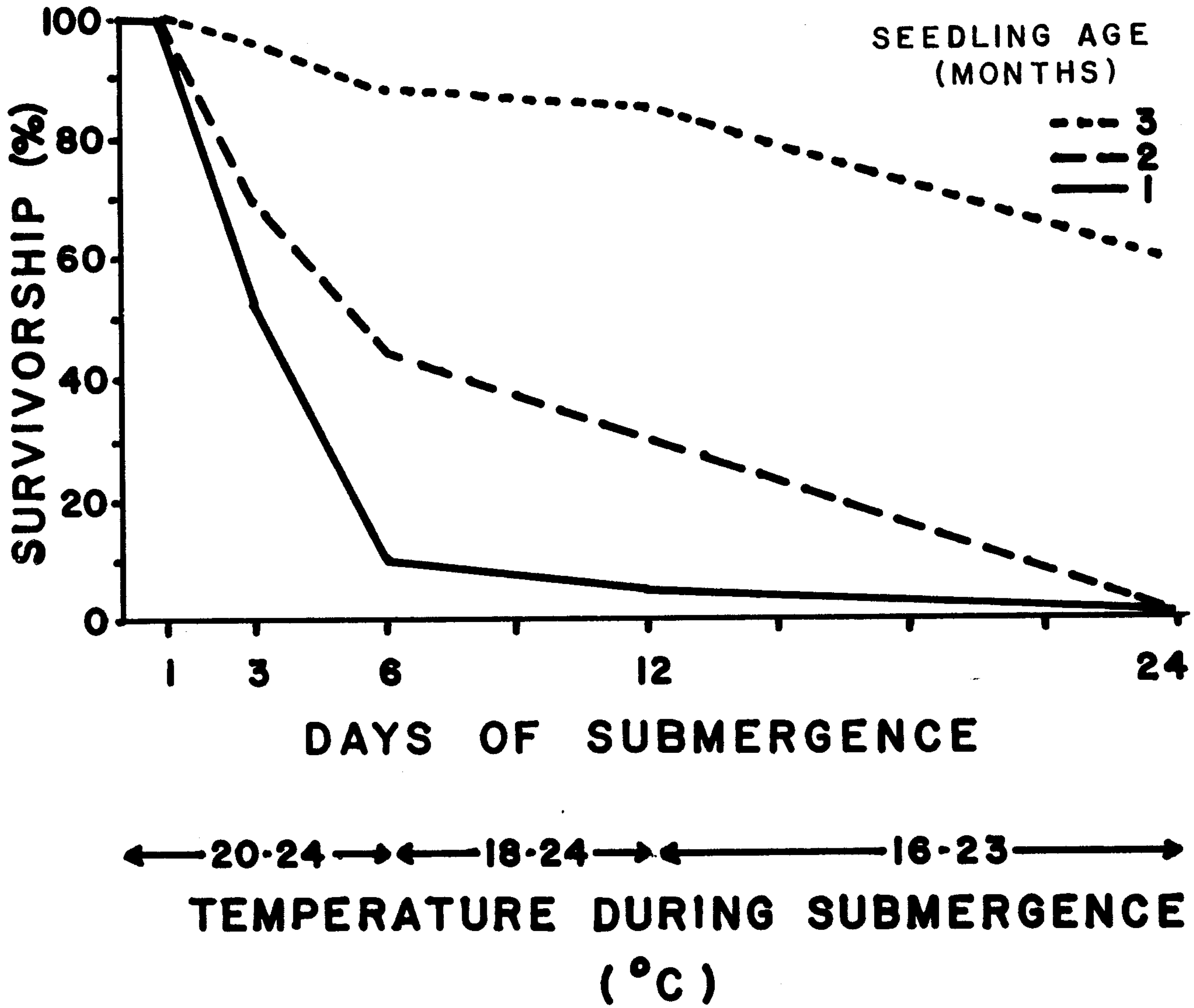


Figure 61. The effect on tamarisk seedlings of submergence under natural conditions in Lake Powell, September 26-October 20, 1975. (The number of 1-, 2-, and 3-month-old seedlings at the beginning of each submergence trial averaged 1099, 263, and 33, respectively.)

Although the plants in the experimental pots were subject to some stresses (such as wave action and coating with silt and algal growth) other than the physiological ones of submergence, they probably were not as exposed to physical forces as seedlings would be along a natural shoreline. In the latter case, the wave action and backtow of shallow submergence would produce a physical deterioration caused by the surge of sand back and forth across the bottom. Seedlings under completely natural conditions would also be more suspect to both undercutting and burial.

This preliminary experiment showed a definite increased resistance to flooding with increase in age of the seedlings from 1 to 3 months. The submergence study was done in the fall of the year at the time when it would be necessary to use water level regulation as a possible control of tamarisk invasion of the drawdown zone. This management practice would require lowering the water after the peak level to expose a narrow zone for tamarisk seedling establishment, then in mid-September raising the water sufficiently to submerge the newly established seedlings. From the data presented above, this procedure would be quite successful to control 1- to 2-month-old seedlings if they were submerged for a period of about 3 weeks.

Tomanek and Ziegler (1961) reported that when 1-foot-high tamarisk plants were submerged for 3 weeks they were seemingly killed, but that when reexposed to air they produced lateral and basal buds. Complete submergence for a year resulted in death of tamarisk. A stand of tamarisk on a sandy shore in Wahweap Bay became established in July to September 1974 and plants were 1 to 2 meters tall by the time the bases were flooded on June 26, 1975. The water rose to a new maximum level in 1975 and completely covered the tops of 2-meter-tall tamarisk plants for a period of 34 days. During this period of submergence many twigs and some leaves stayed alive; adventitious roots were developed from the submerged stems and functioned as aquatic absorptive roots. Upon emergence with the drawdown from August 17 to October 9, 1975, many shoots showed increased chlorophyll in surviving leaves and others produced new shoots. Within a month's time after exposure of the upper twigs some plants were in flower and even fruit. Figure 62 illustrates the apparent health of a tamarisk stand completely submerged for over a month. Note the adventitious roots on the lower stems. As the water retreated to the ground level, the adventitious stem roots (now aerial) became non-functional and survival was dependent on the activity of the original root system growing in the sand base. During submergence this sandy substratum had become surprisingly low in oxygen, as was evidenced by the development of a layer 7 centimeters thick just below the surface which was jet black as a result of chemical reduction (Figure 63). Upon exposure, this layer emitted fumes of hydrogen sulphide. As this layer became reduced, the root system in that zone suffered from lack of oxygen, root respiration was prevented, growth was prevented, and the lateral roots were lost. Below the zone the roots remained alive and, upon soil drainage with lowered water level, continued growth (Figure 63).

Figure 62. Survival and recovery of a stand of 1-year-old tamarisk completely submerged 34 days and then exposed.

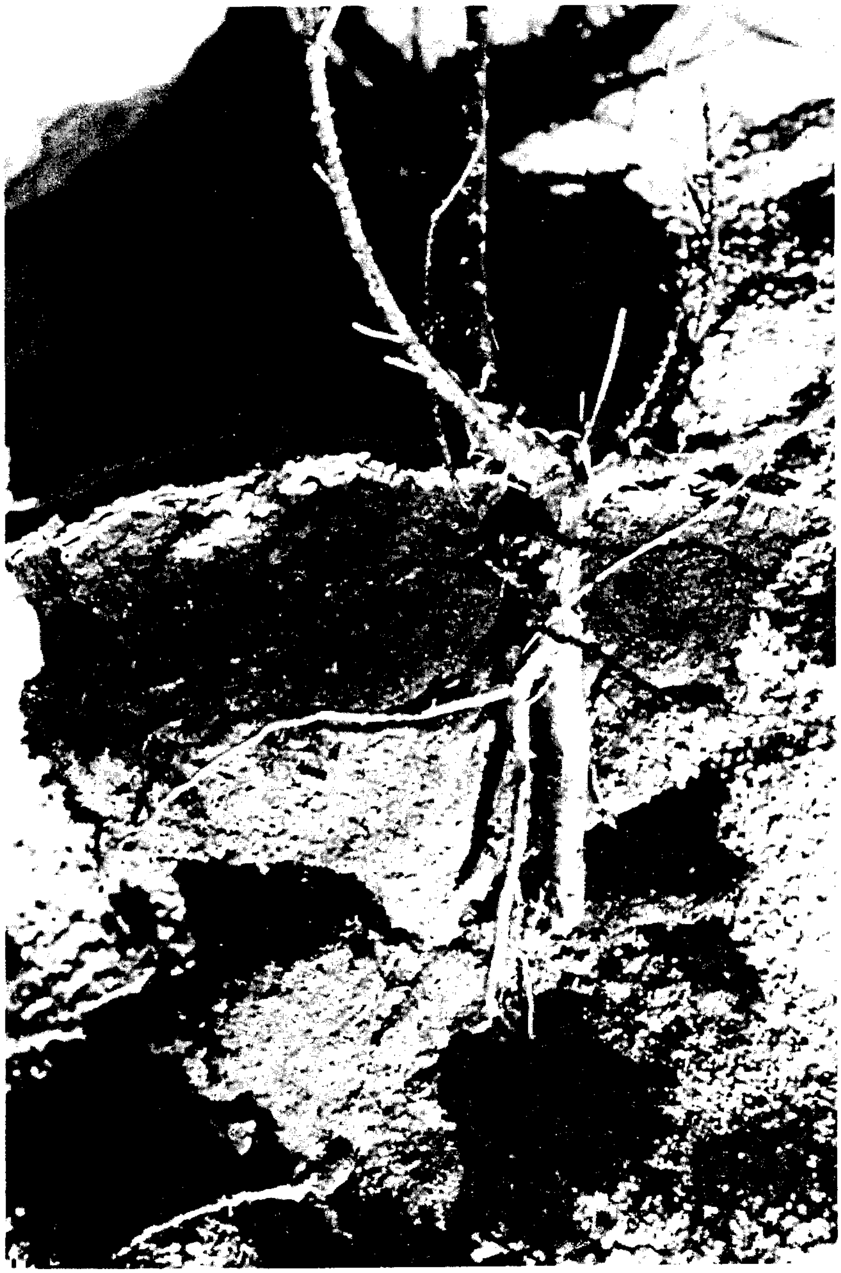


Figure 63. Block of soil from sandy shore with 7-centimeter-thick black zone of reduction. Tamarisk showing white adventitious roots from the stem, no roots in zone of reduction, and healthy roots below.

The tremendous adaptability of this riparian species to flooding once plants reach several months of age is obvious and is further evidenced by its mechanisms for rapid recovery on exposure. These mechanisms include the habit of proliferation by producing basal shoots and new stems by root sprouts from lateral roots. Simultaneously, most of the herbs which had invaded the area before flooding were killed by the submergence, removing them from interspecific competition. The moist sand left by the retreating water also provides an ideal seed bed for the seeds of tamarisk produced by the recovered plants.

SHORELINE PREDICTIONS AND WATER LEVEL MANAGEMENT

At the time of writing (in the early spring of 1976), the predictions are that, with normal runoff and water use, the water level will reach 3700 feet in a period of 2 to 3 years. There is also a generally accepted opinion that after several years, with increased water demand of a variety of projects, the operating level will be lowered to somewhere around 3660 feet. A normal seasonal drawdown of 15 to 20 feet can be anticipated. Based on these predictions, it is felt advisable to indicate the likely sequence of events which will occur after a reexposure of 40 vertical feet along the shoreline.

The shoreline least affected will be the cliff walls which occupy about 54% of the shoreline (Table 2). The principal change will be superficial but very visual. Even 1 year of submergence and then exposure with lowering of water level results in a distinct white "bathtub ring." This will be a broad vertical band remaining from 3700 feet down to the operating level of the lake. Because many of the vertical cliff walls are protected from weathering, after an initial sloughing off of encrusted material the "whitewash" appearance can be expected to remain for several decades. On cliff faces subject to streaking by patina formation the horizontal bands of whitening will become streaked.

Also slightly affected, but in a different way, will be the 21% of domed terrace shoreline. About one-third of this area had a thin mantle of talus, sand, or alluvium covering the rounded surface of sandstone. Some of this mantle will have been removed by submergence and wave action. Some will have washed into deeper sediments; some will be redeposited in hollows within the domed terrace and its content of silt and organic matter will be increased. It is likely that a black zone of reduction will be left just below the surface. Upon exposure and aeration these pockets will be reinvaded by vegetation and will slowly tend to develop toward the rich isolated flora which was there previously. Many, however, may be occupied by tamarisk during the period of lowering the water level. The depth of sediment and its moisture capacity may then be a selective factor in the survival of tamarisk. The longer it survives, the longer it will take, if ever, for a succession to take place back to a flora composed principally of native species.

Areas of shelfy terrace are minor, about 2%. The sharp, jagged contours will be somewhat softened and will be more favorable for beaching a boat. Deposits of sediments in hollows will be similar to those of domed terraces, but growth conditions for shrubs such as tamarisk will be somewhat more favorable because of root growth in the more porous cross-bedding.

Talus slopes and rock slides occupying, respectively, 19 and 1% of the shoreline before flooding will be changed. Considerable slumping will be part of the bottom sediment, leaving only a scar on the cliff wall. Others will be changed in texture by removal of the silt and sand, leaving cobbles and boulders. Shoreline use of these types will not change, as most were too steeply sloping and unsafe for camping before the flooding occurred. Vegetational succession, principally by shrubs, will not drastically change their appearance.

The sand and alluvium shorelines, each 3% at the 3660-foot contour, will in some areas be smoothed out into gently sloping shores. In deep deposits, wave-cut steps may be left along the shoreline. The surfaces of both types will have an increased percentage of silt and organic matter. This 6% of the shoreline at the 3660-foot contour represents the area which receives almost all of the impact of shoreline use for recreation. These areas are level or gently sloping; they are safe shores on which to land a boat; they provide a means of easily tying up a boat; it is possible to pitch a tent by using stakes in the soil; areas can be found level enough on which to sleep; and for those not using portable toilets these areas are most frequently used for toiletry. Swimming and other water sports most commonly demand a sloping sandy shoreline, especially for children, and finally there is a common attitude that a lake vacation means camping on a sandy shore. The minority--those who sleep on boats, swim only in deep water, or prefer the cleanliness of slickrock surfaces--is recognized.

The 6% of the shoreline occupied by sand and alluvium which is the focal point of shoreline recreational use and impact is the same shoreline which is most susceptible to the greatest change by vegetational succession upon its exposure after flooding. The principal concern is the invasion of tamarisk. This process and the potential density of thickets which may develop have been previously discussed. The perpetuation of shoreline stands of tamarisk around the lake is partially dependent on the rate of filling. The faster the increase in water level, the less is the opportunity for stands of tamarisk to become established and survive to reseed additional areas. Past examples, e.g., 1971-1972, have illustrated that slight increases, or the lack of exceeding the previous year's peak level, have resulted in vast acreages of meadows of tamarisk seedlings. In 1975 these were later eliminated from that area of shoreline by rapid rise of water level and continued deep submergence. However, increases of only 8 feet in the maximal level in 1975 over that of 1974 did not eliminate many established stands of tamarisk. At the projected rate of filling, it can be anticipated that local stands of tamarisk will be found on sandy shorelines, especially in protected bays and inlets, around the lake when the 3700-foot level is attained. Each year that the level is held at that contour, with the usual seasonal drawdown, the extent of tamarisk establishment along the shoreline will increase. Also, one can expect a vertical growth of 3 to 6 feet per year and an increase in density of the stands into impenetrable thickets by the production of shoot sprouts from the horizontal roots. A visual impression of the potential thickets which can develop along the sandy-alluvial shoreline can be seen by both pre- and post-dam terrace stands below Glen Canyon Dam. Not only will tamarisk become established along and above the high water mark, but during drawdown periods it will become established in the upper part of the zone and will endure flooding the next summer. Unlike seasonal stands along a river channel, which are subject to scouring action, these lakeshore stands are not deleteriously affected and, as illustrated by shoreline stands in 1975, start to grow, flower, and produce seeds a few weeks after emerging from the summer high water. Each time the thickets are flooded the woody plants become covered with a coating of attached algae. Because the principal shoreline recreational use coincides with the period of high water level, there will be offshore submerged and partially submerged woody vegetation. The accumulation of organic matter and silt will soon change the nature of the formerly clean, sandy bottom. These undesirable conditions have not developed in the past because of the continuing rise of water to new high levels. The "honeymoon" period of "virgin" beaches will soon be over. Bringing a boat to shore through a tamarisk thicket, swimming in the submerged stands, and camping in a tamarisk thicket with the resulting populations of insects that soon develop will not be an enriching, aesthetically pleasing experience.

As the water level is decreased to lower operational levels one can expect tamarisk to advance downslope as long as sandy or alluvial surfaces are available. The continued survival of stands of tamarisk established at the high levels will depend on the depth of soil, allowing for progressive root penetration as the water table drops. With its deep taproot, it is reasonable to predict a successful adjustment of this highly adapted phreatophyte species. Where there is a thin mantle over bedrock, upper stands may become weakened or die. However, the well-developed lateral root system and sprouting habit of tamarisk will be important in maintaining upslope members. It is entirely feasible that stands of tamarisk may occupy the entire exposed shoreline slope from 3700 feet down to the operational level.

The shoreline surface materials of principal concern as sites of tamarisk development are those of sand, alluvium, and domed terrace with a mantle of sand or of alluvium. These types represent the following percentages of the linear shoreline at the 3660-foot contour: 3, 3, 1, and 11%, totalling 18% of the shoreline. These percentages represent linear distances of 49, 49, 16, and 180 miles, respectively. The acreages of the above types were determined for the shore between the 3660- and 3700-foot levels by use of an electronic planimeter and the computer at Dartmouth College. These areas are given in Table 12 by shoreline type and for each tributary containing the types. Tributaries with extensive areas suspect to tamarisk invasion are Wahweap, Bullfrog, Warm Creek, Main Channel, San Juan, and Hall's Creek. The total area of domed terrace with alluvial mantle (6941 acres) may be reduced somewhat after erosional removal resulting from flooding, but the decreased area will be somewhat compensated for by other depressions in both domed and shelfy terraces that are enriched with silt. The total potential area which could likely be invaded by tamarisk is 10,414 acres which is equivalent to over 16 square miles.

There is general agreement that tamarisk does not provide desirable shade or campsite vegetation because of the density of the thickets and the concentration of noxious insects which soon develop. In addition, the role which tamarisk thickets play in the loss of water by evapotranspiration is worthy of consideration. Most of the loss occurs during the period of foliage, from April to December. Studies at Safford, Arizona (Gatewood et al. 1950) indicated losses of 72 inches per year. Work by Turner and Halpenny (1941) indicated water losses of 48 inches when the water table was 4 feet below the surface, and 61 inches when 2 feet below. The lack of correlation of water loss to density of tamarisk stand was indicated by the experimental work reported by Van Hylckama (1970) where thinning of stands by 50% resulted in a reduction of only 15% in water loss compared to unthinned plots. Using the conservative figure of 4 feet of water lost from stands of tamarisk, the potential loss from the 10,400 acres in Table 12 would represent a 41,600 acre-foot loss per year.

Replacement of tamarisk with another vegetation would not result in complete reduction of water lost by evapotranspiration but substantial reductions could be attained. Even substitution of a grass sod, as has been reported for Bermuda grass in central Arizona (Decker, Gaylor, and Cole 1962) reduced losses by 50%.

Because of the importance of the limited sandy shoreline for recreational use in the Glen Canyon National Recreation Area, it is recommended that control measures for tamarisk be instigated as soon as the maximum water level is reached. The cost is least and the effectiveness greatest when control is started with seedling or young-aged stands. As the stands mature, the increased woody biomass, the increased extensive root system, and the increased capability of root sprout development make control very difficult.

It should be recognized that there is no way to eliminate tamarisk from a reservoir and that control, like maintenance, is a continuing process. A priority ranking of sandy shoreline areas with consideration to their limited availability in certain tributaries and the demand for public use should provide a basis for selection of areas to manage. A good illustration of the decreased use of a shoreline containing submerged, partially emergent, and emergent tamarisk was provided in 1975-1976 by the tamarisk stand (Figure 62) below the lodge at Wahweap Bay. This strip, in contrast to the barren shoreline on either side, was very rarely used as a landing for boats or for any shoreline recreation. If the stand were to persist for several years, its undesirability would increase further.

Among the species invading the upper drawdown zone have been found seedlings of the native Fremont cottonwood. Occasional mature trees and groves dominated by this species have been desired and heavily used as shoreline campsites. The species offers ideal shade and camping conditions. There is some evidence that its shade provides competition against tamarisk. Both cottonwood and Russian-olive (Elaeagnus angustifolia) can be easily rooted and transplanted. It is suggested that these species be transplanted along selected shorelines of deep sand when the reservoir reaches maximum level. Also, plantings should be made at the summer peak levels during the period of time when the water levels are decreased to lower operational levels. It is suggested that plantings be made in dispersed clumps along the shore. Such plantings would, of course, negate the possibility of widespread herbicide control of tamarisk unless an herbicide is developed which is specific to tamarisk.

SUMMARY

Because of the close correlation in this arid region of geological formations with erosion, sedimentation, and vegetational development, the shoreline surface materials were classified, mapped, and summarized according to tributary and main channel location. The 54% of cliff provides much of the scenic value of Lake Powell and is least affected by fluctuating water levels; the 21% of domed terrace provides for possible rock-type campsites; the 19% of talus slope is a source of slumping and sedimentation, and is of no value for campsites; shelfy terraces at 2% are of limited value for shoreline recreation; the 2 and 1% of sand and alluvium are much affected by fluctuating water levels and are the prime areas used for shoreline recreation; and the 1% of rockslide area is dangerous and unstable. Variations in shoreline surface materials in each tributary determine the recreational use, e.g., sightseeing, camping, swimming, or fishing.

Species composition and development of vegetation is closely correlated to the geological surface material. Unweathered, fractured rock favors woody, taprooted shrubby species. Maximal coverage and biomass occur in deep sands, and the most rapid recovery of both biomass and foliar coverage after submergence and exposure occurs in areas of deep sand. A unique calciphilous vegetation develops in the seeps which contain calcium-carbonate-enriched water coming from the limestone layers within the sandstone. The most mesic vegetation, with species equivalent to a moist eastern deciduous forest site, occurs in large splash pools of occasional overhead drainage or in protected areas receiving seepage water, as below alcoves at the heads of canyons. Here densely forested groves are in contrast to the mixture of Painted Desert and Great Basin flora of the surrounding uplands.

Fluctuating water levels, common to the annual drawdown period, leave a whitish "bathtub" ring on cliff walls, change the texture of shorelines toward coarser gravel and boulders, cause slumping of talus slopes, and leave wave-cut terraces in sandy and alluvial shorelines. Vegetation just above the maximum water level shows a stimulation of growth due to increased soil moisture availability.

With rising water levels and submergence, trees decompose at different rates--the most resistant ones being singleleaf ash, Gambel oak, and netleaf hackberry. The most common shrub, blackbrush, is also most resistant to decomposition, followed by species of Mormon tea and saltbush. Grasses and forbs decompose rapidly after submergence. Shortly after submergence, both sandy and rocky shores develop a mantle of benthic organisms, often as flocculated granules of silt and clay embedded in a gelatinous matrix of algae. Local brilliantly colored mats of algae develop downslope from point sources of nutrients, e.g., rat middens and bird roosts in rock crevices. These algal mats are especially enriched in nitrates.

Tamarisk plants submerged and subject to decomposition show a greater loss of phosphorus than of nitrogen, with an average shift of the nitrogen:phosphorus ratio for whole shoots ranging from 5.4:1.0 to 7.1:1.0 after several weeks. With increasing depth of submergence, attached periphyton loses more nitrogen than phosphorus content.

Vegetational succession into the drawdown zone occurs primarily on sandy and alluvial shorelines, the same shorelines used principally by recreationists. The upper portion, normally exposed from July to September, is invaded by salt cedar or tamarisk, the lower portion later by Russian thistle. Growth of the taproot of tamarisk is rapid, keeping apace of the lowering water table. Tamarisk plants are not deciduous the first winter and by spring may be 3 to 6 feet tall. Upon submergence plants soon become covered with silt and a mantle of algae. During the period of filling the reservoir, increased peak water levels each year were generally successful in eliminating the yearly established stands. However, when the reservoir reaches a normal operational level the stands of tamarisk invading the drawdown zone will not be eliminated. Several month-old tamarisk plants endure the complete submergence of spring and early summer flooding, during which time they stay green and produce functional adventitious roots along their stems. Upon emergence when the water level is lowered the existing shoots soon increase in chlorophyll, new shoots quickly develop, terrestrial roots and sprouts increase, and flowers and fruits are produced within a few weeks. Not only will the shore above the high water line become occupied by a dense thicket of tamarisk, but the shallow off-shore waters will be occupied by a dense, partially submerged woody vegetation with an increased mass of organic matter and accumulated silt and algal growth, all causing soil reduction of a black subsurface soil layer and the emission of hydrogen sulphide gas. Noxious insect populations soon accumulate in the tamarisk stands.

The acreage between the 3660- and 3700-foot contours that consists of alluvium and sandy soils--on which tamarisk invasion can be expected to occur--amounts to about 10,400 acres. Unfortunately these shoreline areas are those most sought and used by the public for shoreline recreation, boat landing, camping, and swimming. The change will be from highly desirable to highly undesirable. If, as has been suggested, after reaching a water level of 3700 feet the reservoir is lowered in a few years to an operational level of about 3660 feet, the 10,400 acres suspect to tamarisk invasion could also be an important source of additional water loss. Using the conservative figure of 4 acre-feet of annual water loss from a stand of tamarisk would mean about 42,000 acre-feet lost per year.

Because of the multiple disadvantages of the development of tamarisk stands, a program of control in selected areas is recommended to be put into practice as soon as the water level reaches the maximum and to be continued yearly thereafter. The extent of possible control is indicated by the linear distances of shoreline suspect to tamarisk invasion at the 3660-foot contour level. This shoreline is composed of sand, alluvium, or mantles of sand or alluvium over domed terrace which are 49, 49, 16, and 180 miles, respectively--a total distance of 294 miles. This control should be supplemented by plantings, in selected sites, of easily transplanted, more desirable shade species such as cottonwood and Russian olive. The alternative is the impenetrable thicket-forest of tamarisk as exemplified by the sandy river terraces above and below the reservoir.

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APPENDIX

Appendix A-1. Vegetative cover and frequency indices, large sand dune, Gunsight Canyon.

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Sporobolus cryptandrus			10.4	19	18.7	30		
Ephedra viridis	18.5	28	15.3	31	11.0	27	10.6	78
Haplopappus gracilis					9.1	42		
Oryzopsis hymenoides	40.8	80	16.9	81	9.4	65	26.0	69
Brickellia sp.			3.2	87	7.0	27		
Erysimum capitatum					5.2	61	.5	15
Artemisia filifolia	2.4	4	6.1	4	5.1	48		
Cryptantha sp.					4.3	30		
Psoralea juncea			4.6	27	3.1	27	23.7	15
Abronia sp.			2.2	12	2.7	19		
Astragalus ensiformis	.1	40	.1	87	2.7	11		
Phacelia ivesiana			2.0	39	2.6	87		
Artemisia sp.					2.5	84	.4	77
Bromus rubens					2.4	11		
Sphaeralcea coccinea			2.4	15	2.3	19		
Gutierrezia microcephala			.6	50	1.8	8		
Opuntia sp.	2.9	80	2.2	12	1.6	11		
Poliomintha incana			1.1	48	1.6	4	23.5	23

Appendix A-1 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Tamarix pentandra			2.1	34	1.5	34		
Gilia sp.					1.1	23		
Erigeron sp.					1.1	27		
Streptanthella longirostris	1.0	28	11.2	46	.5	46		
Croton texensis			.2	12	.5	46	.1	87
Malacothrix sonchoides					.4	38		
Festuca octoflora					.4	19		
Salsola kali	.1	40			.4	15		
Phacelia sp.	.3	40	.3	87	.2	15		
Stanleya sp.			2.5	58	.1	8		
Ambrosia sp.			.1	8	.1	15		
Allium sp.					.1	11		
Helianthus petiolaris	.1	40	.6	48	.1	8		
Lepidium sp.					.1	4		
Erigeron oreophilus					.1	8		
Cymopterus sp.					.1	4		
Chaenactis stevicides					.1	8		
Lupinus sp.					.1	4		
Calochortus mariposa					.1	4		
Gilia multiflora					.1	4		

Appendix A-1 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Plantago sp.					.1	4		
Argemone sp.	.1	40						
Aster spinosa							1.3	7
Atriplex canescens			.1	48				
Chrysopsis villosa			2.6	4				
Cryptantha confertifolia							12.2	15
Euphorbia sp.			.1	4				
Grindelia aphanactis			6.0	15				
Haplopappus drummondii	14.8	36					1.5	39
Heliotrope sp.			.1	4				
Hymenopappus pauciflorus			.1	4				
Lappula sp.	.4	12						
Lithospermum sp.							.1	15
Malocothrix glabrata			.5	12				
Mentzelia albicaulis			6.2	42				
Nama hispidum			.3	4				
Oenothera pallida	.1	4	.6	4				
Petalostemum candidum			.2	4				
Unknown spp.	18.7	-	.1	4			.1	8
Total Foliage Cover	5.1		5.8		8.6		2.4	

Appendix A-2. Vegetative cover and frequency indices, partially stabilized low sand dunes, main channel opposite Navajo Canyon.

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Ephedra viridis	29.7	42	34.0	50	35.5	47	41.3	49
Astragalus ensiformis			.7	77	18.9	83	2.7	55
Malacothrix glabrata			2.8	70	10.3	97	.1	18
Oenothera pallida			.8	13	6.9	40	2.6	30
Oryzopsis hymenoides	58.3	90	15.6	83	5.3	53	10.0	76
Festuca octoflora					4.8	93		
Lygodesmia sp.	3.6	6	1.8	80	3.2	93	2.8	79
Lepidium sp.			1.0	7	2.8	10		
Atriplex canescens	.1	20	2.6	7	2.7	7		
Cryptantha ivesiana					2.5	37	.8	21
Sporobolus cryptandrus	.1	2	.9	37	.9	37	3.1	49
Aster abatus					.9	30	9.4	94
Abronia sp.			.5	27	.6	70	.1	18
Hymenopappus pauciflorus			.1	20	.6	30	1.8	21
Gilia multiflora			.2	17	.5	43	.2	18
Sphaeralcea coccinea			.1	17	.4	47	1.5	49
Eriogonum inflatum					.4	7	1.0	18
Artemisia filifolia			.4	17	.4	7	7.9	15

Appendix A-2 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Lupinus pusillus			.1	3	.2	10		
Chaenactis stevioides					.1	37		
Malacothrix sonchoides					.1	20		
Cymopterus fendleri			.1	3	.1	13		
Opuntia sp.	.1	2			.1	3		
Streptanthella longirostris	6.0	50	35.5	97	.1	17		
Psoralea juncea			.4	10	.1	67		
Eriogonum sp.			.1	7	.1	7		
Stipa comata					.1	3		
Gutierrezia microcephala			.7	10	.1	3	.3	30
Haplopappus drummondii	1.3	8			.1	3	11.6	27
Plantago purshii					.1	7		
Cryptantha confertifolia					.1	3		
Euphorbia sp.					.1	3	.1	6
Astragalus sp.							.1	3
Cryptantha jamesii							.1	3
Helianthus petiolaris							.5	61
Hilaria jamesii			.1	3				

Appendix A-2 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Lappula sp.	.1	4						
Mentzelia albicaulis			.1	3				
Yucca utahensis	1.3	6					2.0	9
Unknown spp.	.5	-	.5	-	.1	3		
Total Foliage Cover(%)	7.6		12.5		11.7		8.4	

Appendix A-3. Vegetative cover and frequency indices, well-stabilized low dune area, Friendship Cove.

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Oryzopsis hymenoides	38.1	100	20.1	11	14.8	100		
Ephedra viridis	17.0	50	10.8	43	12.7	40		
Lupinus sp.					11.2	97		
Festuca octoflora	.1	3			10.8	100		
Gutierrezia microcephala	3.8	13	4.6	23	5.8	53		
Sporobolus cryptandrus	19.1	97	27.6	100	5.5	73		
Astragalus ensiformis			.1	40	5.3	90		
Artemisia filifolia	5.7	17	6.7	10	5.0	13		
Sphaeralcea coccinea	.7	13	3.3	23	3.6	27		
Plantago purshii			.4	20	3.3	60		
Psoralea juncea	4.5	17	3.9	30	3.2	20		
Dalea fremontii	2.6	17	2.5	23	2.9	20		
Yucca utahensis	5.7	17	4.0	17	2.8	17		
Haplopappus gracilis					2.6	67		
Gilia multiflora			4.0	67	2.4	87		
Abronia elliptica			2.7	27	1.7	40		
Atriplex canescens	.9	10	.8	7	1.6	10		

Appendix A-3 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Cymopterus sp.					1.0	57		
Streptanthella longirostris	.9	7	1.0	40	.8	90		
Bromus rubens	.1	3			.7	60		
Tamarix pentandra			2.4	3	.7	3		
Opuntia sp.	.3	7	.7	13	.5	10		
Lygodesmia grandiflora					.2	20		
Cryptantha sp.					.1	30		
Phacelia ivesiana			.1	3	.1	10		
Erigeron sp.					.1	27		
Chaenactis stevioides					.1	17		
Helianthus petiolaris			1.0	7	.1	13		
Happlopappus drummondii					.1	3		
Lepidium sp.	.4	10			.1	3		
Malacothrix glabrata					.1	7		
Calochortus mariposa					.1	3		
Ambrosia sp.					.1	3		
Aristida sp.			.2	27				
Aster arenosus			.4	7				
Aster bigelovii			1.2	60				

Appendix A-3 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Astragalus sp.	.1	3						
Coleogyne ramosissima	.1	3						
Grindelia aphanactis			.3	3				
Hymenopappus pauciflorus			.8	53				
Lygodesmia exigua			.1	3				
Unknown spp.	.1	3			.9	-		
Total Foliage Cover(%)	16.0		17.4		24.1			

Appendix A-4. Vegetative cover and frequency indices, mantle of dune sand, island south of Gunsight Butte.

Species	1971		1972		1973		1974	
	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %
Ephedra viridis	23.9	22	21.9	[illegible]	[illegible]	30	40.2	27
Coleogyne ramosissima	19.1	28	30.1	[illegible]	29.9	43	9.7	10
Malacothix glabrata			1.1	43	[illegible]	[illegible]	.2	2
Oryzopsis hymenoides	40.0	93	20.5	83	7.8	73	28.6	80
Gilia longiflora					6.0	85		
Streptanthella longirostris			8.6	93	4.0	75		
Gilia multiflora			.3	25	2.4	53		
Festuca octoflora	1.4	12	.1	3	2.3	68	.2	13
Lygodesmia exigua			1.1	48	2.1	65	.6	13
Sporobolus cryptandrus	.2	7	1.9	23	1.3	18	2.4	27
Hilaria jamesii			1.1	20	1.0	28	4.3	33
Brickellia longifolia					.6	3		
Artemisia filifolia	1.0	2	.4	3	.6	3	1.3	20
Mentzelia albicaulis			.1	3	.6	10		
Cryptantha sp.					.5	3		
Cymopterus sp.					.4	28		
Astragalus ensiformis	.1	2	.2	43	.3	55	.1	10
Erigeron sp.					.3	50		

Appendix A-4 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Lupinus pusillus			.1	13	.2	20		
Gutierrezia microcephala	.4	3	.3	50	.2	50	1.1	20
Abronia sp.			.1	5	.2	15	.4	30
Haplopappus gracilis					.1	13		
Oenothera pallida			.1	8	.1	10		
Yucca utahensis	2.4	7	.5	3	.1	3	2.2	7
Malacothrix sonchoides					.1	10	.1	3
Sphaeralcea coccinea	.1	5	.2	5	.1	13	.5	27
Chaenactis stevioides					.1	8		
Phacelia ivesiana			.4	30	.1	5	1.9	47
Bromus rubens					.1	3		
Calochortus mariposa					.1	5		
Aster arenosus			.1	3	.1	3		
Artemisia sp.	7.8	5						
Chrysopsis villosa			.4	3				
Cryptantha confertifolia							1.5	10
Cryptantha jamesii							.2	10
Eriogonum sp.							.1	3

Appendix A-4 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Erysimum capitatum							.1	13
Grindelia aphanactis			.6	5				
Haplopappus drummondii	.4	3	.1	3			1.1	7
Helianthus petiolaris							.1	33
Hymenopappus pauciflorus			.1	3				
Lappula redowski			.1	18				
Lepidium sp.	2.3	43						
Oenothera albicaulis							.6	37
Petalostemum candidum							.1	7
Psoralea juncea							2.7	7
Stephanomeria exigua	1.0	7						
Unknown spp.	.1	2	.1	3				
Total Foliage Cover (%)	9.5		7.9		10.7		9.4	

Appendix A-5. Vegetative cover and frequency indices, alluvium on rolling hills, Warm Creek.

Species	1971		1972		1973		1974	
	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %
Astragalus ensiformis			1.1	58	18.3	85	9.6	66
Atriplex canescens	3.9	12	33.3	12	18.0	18		
Salsola kali	.1	33	7.0	91	10.1	100	39.1	100
Sphaeralcea coccinea			6.2	9	9.4	9	3.6	33
Ephedra viridis	48.6	33	24.0	33	8.5	36	25.7	50
Cryptantha spp					6.7	94	.3	33
Tamarix pentandra			2.8	3	4.8	3		
Malacothrix sonchoides					3.2	55		
Lupinus pusillus			.1	15	3.0	55		
Abronia sp			.7	12	2.4	12		
Sporobolus cryptandrus			.8	9	2.0	30	2.3	50
Aster tenacetifolius					1.9	90	3.0	33
Croton texensis			.2	12	1.7	97	.1	17
Mentzelia albicaulis			.1	12	1.6	30		
Hymenopappus pauciflorus			.1	6	1.0	88	4.3	83
Gilia multiflora			.5	15	1.0	70		
Phacelia ivesiana			.1	3	1.0	27		
Oryzopsis hymenoides	43.0	100	9.7	88	.8	76	4.7	100

Appendix A-5 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Erigeron sp.					.6	30		
Bromus rubens					.6	6		
Streptanthella longirostris			10.3	64	.5	58		
Festuca octoflora					.4	33	.4	17
Eriogonum inflatum	2.2	12	.7	3	.3	6	1.3	17
Descurainia sp.					.3	24		
Cymopterus sp.					.2	15		
Lygodesmia exigua					.2	9	.3	17
Plantago purshii			.1	3	.2	27		
Eriogonum sp.			.1	2	.2	24	.4	17
Lepidium sp.	1.1	3			.1	3		
Coldenia hispidissima					.1	3	1.5	17
Androsace sp.					.1	12		
Chaenactis stevioides					.1	6		
Haplopappus gracilis					.1	3		
Calochortus mariposa					.1	3		
Euphorbia sp.					.1	3		
Helianthus petiolaris					.1	3		
Astragalus sp.							3.3	17

Appendix A-5 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Dalea fremontii	.1	3						
Gutierrezia microcephala	.1	3						
Malacothrix glabrata			.3	12				
Phacelia sp.			2.5	3				
Unknown spp.			.2	-	.1	9.1		
Total Foliage Cover(%)	2.4		4.0		7.9		4.6	

Appendix A-6. Vegetative cover and frequency indices, talus slope, Last Chance Bay.

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Haplopappus drummondii	30.7	77	33.6	80	32.8	90	34.3	100
Oryzopsis hymenoides	50.2	100	42.7	90	25.7	93	47.7	100
Atriplex canescens	2.4	13	10.4	[illegible]	7.2	17		
Ephedra viridis	6.4	23	5.2	37	6.6	30	4.4	13
Atriplex semibaccata					4.0	20	3.7	6
Streptanthella longirostris	1.0	10	.1	3	[illegible]	100		
Sphaeralcea coccinea	2.4	40	2.4	27	2.7	37	2.6	20
Festuca octoflora					2.7	73		
Cryptantha sp.					2.4	50		
Phacelia ivesiana			.3	3	2.1	30		
Tamarix pentandra					1.8	3		
Lepidium sp.			1.0	17	1.5	27	.1	6
Gilia longiflora					1.0	46		
Aster bigelovii					1.0	20		
Hilaria jamesii			1.1	17	.9	23	2.4	19
Lupinus sp.					.9	33		
Astragalus sp.					.7	50		
Gila multiflora			.1	3	.5	46		

Appendix A-6 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Eriogonum sp.					.4	13		
Lygodesmia exigua			.1	3	.4	13		
Eurotia lanata	.1	3	.5	7	.4	7		
Coldenia hispidissima			.2	7	.4	7	.5	6
Thelypodium lasiocarpa					.3	26		
Eriogonum inflatum	.4	13	.3	7	.3	17		
Sporobolus cryptandrus					.1	3		
Chaenactis stevioides					.1	30		
Malacothrix glabrata					.1	20		
Descurainia sp.					.1	3	.1	6
Nama hispidum	.6	7			.1	7		
Lappula sp.					.1	3		
Gutierrezia microcephala					.1	3		
Abronia sp.							.1	6
Bahia dissecta	1.0	10						
Brickellia longifolia			1.1	10			4.1	50
Coleogyne ramosissima	4.7	13						
Erigeron sp.	.1	6						
Erysimum capitatum	.1	6						

Appendix A-6 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Tamarix pentandra			1.3	[illegible]				
Unknown spp.			[illegible]	-	.1	3		
Total Foliage Cover(%)	12.8		[illegible]		15.3		10.2	

Appendix A-7. Vegetative cover and frequency indices, talus slope, Rock Creek.

Species	1971		1972		1973		1974	
	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %
Bromus rubens					42.5	100	15.8	90
Haplopappus drummondii	26.0	50	2.1	15	12.8	60	27.7	70
Sporobolus cryptandrus	31.4	90	26.3	80	9.5	55	.1	10
Oryzopsis hymenoides	5.2	20	6.7	3	5.3	25		
Ephedra viridis	8.6	15	9.3	20	4.3	15	24.0	20
Dalea fremontii			3.5	15	4.1	20	1.6	40
Aster abatus					2.4	15		
Astragalus ensiformis			.1	5	2.[illegible]	80	.3	20
Coleogyne ramosissima	7.9	15	3.8	5	2.2	10	10.4	30
Atriplex canescens	.2	5	4.2	20	2.2	20		
Brickellia longifolia	2.2	25	1.2	5	1.4	5		
Festuca octoflora	9.4	80	20.9	75	1.4	50		
Atriplex semibaccata	7.0	30	4.2	20	1.2	25	5.5	10
Aster bigelovii			.3	25	1.1	20		
Haplopappus gracilis					1.1	35		
Phacelia crenulata			.1	5	1.0	50		
Eurotia lanata	1.1	5	1.0	5	.6	5		
Lepidium sp.			.1	10	.6	35		

Appendix A-7 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Gilia multiflora					.5	60		
Eriogonum inflatum	.2	10			.5	20	2.5	20
Tamarix pentandra			.3	5	.3	5		
Cryptantha sp.					.3	25		
Streptanthella longirostris			.1	5	.3	35		
Thelypodium lasiophylum					.3	35		
Lappula sp.					.2	40		
Oenothera caespitosa					.1	10		
Nama hispidum	.3	5			.1	10		
Chaenactis fremontii					.1	25		
Croton texensis					.1	25		
Sphaeralcea coccinea					.1	10		
Calochortus mariposa			.1	15	.1	15		
Hilaria jamesii					.1	5	.2	10
Cymopterus sp.					.1	10		
Plantago sp.					.1	5		
Phacelia ivesiana					.1	10		
Malacothrix glabrata			.1	5	.1	10		
Chaenactis stevioides					.1	5		

Appendix A-7 (continued)

Species	1971 Relative Cover %	1971 Frequency Index %	1972 Relative Cover %	1972 Frequency Index %	1973 Relative Cover %	1973 Frequency Index %	1974 Relative Cover %	1974 Frequency Index %
Gutierrezia microcephala			11.1	30	.1	5	4.9	40
Lithospermum sp.					.1	5		
Mentzelia albicaulis			.1	5	.1	5	.4	10
Abronia sp.			.1	5				
Bouteloua barbata			.1	5				
Eriogonum sp.			.2	5				
Poa sp.			.1	5				
Salsola kali	.1	10	2.5	15				
Tridens pulchellus	.4	15	.1	20				
Unknown spp.			1.4	10	.1	-	6.6	50
Total Foliage Cover (%)	5.6		5.8		14.1		6.0	

Appendix A-8. Vegetative cover and frequency indices, domed terrace, main channel east of Warm Creek.

Species	1971		1972		1973		1974	
	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %
Ephedra torreyana	37.8	10			25.7	13		
Gutierrezia microcephala	21.9	7			21.8	13		
Aristida sp.					14.6	7		
Thamnosma montana	17.1	7			12.3	7		
Oryzopsis hymenoides	4.9	7			6.0	7		
Astragalus sp.					5.9	7		
Festuca octoflora					3.8	10		
Tridens pulchellus	.4	3			2.4	3		
Opuntia sp.	.1	3			1.4	3		
Brickellia scabra	8.2	3			1.3	3		
Streptanthella longirostris					.7	17		
Cryptantha sp.					.7	10		
Erigeron sp.					.4	3		
Bromus rubens					.2	7		
Malacothrix sonchoides					.2	3		
Phacelia ivesiana					.2	3		
Plantago purshii					.2	7		
Sporobolus sp.					.1	3		

Appendix A-8 (continued)

Species	1971		1972		1973		1974	
	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %	Relative Cover %	Frequency Index %
Linum sp.					.1	3		
Malacothrix glabrata					.1	2		
Stipa sp.					.1	3		
Mentzelia albicaulis					.1	3		
Aristida sp.	8.7	7						
Unknown sp.					.9	10		
Total Foliage Cover(%)	.79				1.3			

GLOSSARY

adventitious	arising in abnormal position; of roots developing from part of the plant other than the roots
algae (blue-green and green)	chiefly aquatic, non-vascular plants with chlorophyll
aliquot	a selected portion of a solution
alluvium	detrital deposits resulting from operations of recent streams, including sediments of riverbeds, flood plains, lakes, fans at canyon mouths, and estuaries
anticline	a fold that is convex upward
bed	the floor or bottom on which a body of water rests, or a deposit parallel to the stratification
benthic	referring to those plants and animals living on the bottom of the lake

biomass	the total weight of matter incorporated into (living and dead) organisms
block slump	the downward slipping of a mass of rock moving as a unit
butte	a conspicuous isolated hill, especially one with steep sides; a mesa
calciphilous	refers to "calcium-loving," as those organisms especially adapted to areas or waters rich in lime or calcium carbonate
caprock	a comparatively impervious stratum immediately overlying a more porous stratum
cavation; cavate	to carve out or cut back into a cliff face to form a cave
cfs	cubic feet per second
conglomerate	rounded waterworn fragments of rock or pebbles, cemented

	together by another mineral substance
cross-bedding	the arrangement of laminations of strata transverse or oblique to the main planes of stratification of the strata concerned
cutinized	cell walls which have been impregnated with cutin, a waxy substance common to epidermal cells
desert varnish	a surface stain or crust of manganese or iron oxide, of brown or black color and usually with a glistening luster, which characterizes many exposed rock surfaces in the desert
desiccate	to dry up
detrital	referring to loose material (as rock fragments or organic particles) that result directly from disintegration

dip slope	a slope of the land surface which conforms approximately to the dip of the underlying rocks
dome	a roughly symmetrical upfold, the beds dipping in all directions more or less equally
drawdown zone	the shoreline area exposed as the water level of the reservoir is lowered
eluviation	movement of soil material from one place to another within the soil in solution or in suspension and either downward or sidewise
epidermal	referring to the thin outer surface layer
eutrophication	the process of enrichment, as of dissolved nutrients in a lake
evapotranspiration	the combined water loss of evaporation from moist or wet surfaces and the water loss from living plant tissue by the physiological process of transpiration

exfoliation	the breaking or peeling off of scales or layers from bare rock surfaces by physical or chemical forces
filamentous	said of a single-thread, elongated flexible structure
flocculated	combined or aggregated into a mass from fine suspended parts
flood plain	the portion of a river valley covered by water during flood stages and built of sediments
fluvial	pertaining to rivers; growing in streams or ponds; produced by river action
fold	a bend in strata
forb	a broad-leaved herbaceous plant
formation	the primary unit in stratigraphy consisting of a succession of related strata, subdivided into members

fossiliferous	containing organic remains
fracture lines	linear breaks in rocks due to intense folding or faulting
frequency index	a measure of randomness of distribution expressed as a percentage of the sampling plots in which the species or taxon occurred
friable	easily crumbled, as rock which is poorly cemented
group	an association, as of two or more formations, based upon some feature of similarity
gypsiferous	containing gypsum
gypsum	a common mineral of evaporites, $CaSO_4 \cdot 2H_2O$
hydrophilic	having strong affinity for water

importance percentage	a summary measure used in plant community analysis which combines relative density, relative coverage, and relative frequency
interbed	interstratified, occurring between beds
laccolithic	structure resulting from a concordant, intrusive body that has domed up the overlying rocks
lacustrine	pertaining to, formed, or growing in lakes
lateral transport	movement of materials in solution in a horizontal direction
lignification	impregnation of cell walls with lignin which gives strength and rigidity to cells such as fibers and other woody cells
limestone	a bedded sedimentary deposit consisting chiefly of calcium carbonate

littoral	the shoreward region of a body of water in which light penetrates to the bottom; in lakes or ponds from shoreline to the lakeward limit of rooted aquatic plants
mesa	a tableland; a flat-topped mountain or other elevation with steep side or sides
mesic	characterized or pertaining to conditions of favorable moisture supply
microclimate	the detailed climate of a very small area
migrules	any portion of a plant capable of either sexual or vegetative reproduction and dispersal from the parent body, thus not restricted to seeds
Miocene	the fourth of five epochs into which the Tertiary period is divided

montane	relating to the biogeographic zone of relatively moist cool upland slopes characterized by large evergreen trees
morphology	relating to form and structure
$P < 0.5$ level	the probability is less than 5 percent that the difference occurred by chance
patina	thin, light-colored outer layer produced by weathering
periphyton	community of organisms usually small but densely set, closely attached to stems and leaves of rooted aquatic plants or other surfaces projecting above the bottom
Permian	the last period of the Paleozoic era
photic zone	the region of aquatic environments in which the intensity of light is sufficient for photosynthesis

physiography	the study of the origin and evolution of land forms
plateau	a relatively elevated area of comparatively flat land, commonly with at least one side having an abrupt descent
ppm	parts per million
reduction (chemical process)	process of removing oxygen; decrease in positive valence or increase in negative valence; addition of electrons
relative foliage cover	the percentage of the total foliage cover occupied by a species or taxon
replicate	one of several identical experiments, procedures, or samples
retting	the soaking or exposing to moisture, usually with fibrous materials where microbial decomposition removes soft tissues and leaves resistant fibers

riparian	pertaining to living on the bank of a river or a lake
salinity	measure of the quantity of total dissolved solids in water
sandstone	a cemented or compacted detrital sediment of predominantly quartz grains of sand size
seepage line	a fissure from which water oozes or trickles
shale	laminated sediment in which the particles are predominantly of clay size
siltstone	very fine-grained consolidated elastic rock composed predominantly of silt particles
spall	commonly curved and sharp-edged piece of rock produced by exfoliation, as from a vertical cliff

stratum; strata	section or sections of a formation that consists throughout of approximately the same kind of rock material
stripped plain	a plain composed of flat-lying or gently tilted sedimentary rocks from which sediments have been removed down to some resistant bed
sub-alpine	the region of mountain slopes below the alpine tundra
successional vegetation	the series of stages of vegetational communities leading from bare areas to climax vegetation
terrace	benches of relatively flat, horizontal surfaces, usually bounded by steeper ascending slopes on one side and descending on the other
terracette	ledges of earth on steep hillsides, relatively narrow, formed

	as a result of slippage planes and slumping
Tertiary	earlier of two geologic periods of the Cenozoic era
tongue	part of a formation known to wedge out laterally, between sediments of different character
topography	the physical features of a region
total foliage cover	the percentage of the ground surface which is covered by a vertical projection of the foliage canopy
travertine	calcium carbonate of light color, usually concretionary and compact, and deposited from solution in ground and surface waters
Triassic	earliest of three geologic periods of the Mesozoic era

true soil profile	stratified soil horizons resulting from stabilization and the influence of vegetation
turbidity	the state, condition, or quality of opaqueness, or reduced clarity of a fluid, due to the presence of suspended matter
uplift	elevation of any extensive part of the earth's surface relative to some other parts
upthrust	an upheaval of rock; said preferably of a violent upheaval
upwarp	an area that has been uplifted, generally used for broad anticlines
understory vegetation	small trees, shrubs, and herbs under a forest canopy

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