Geomorphology of the Hanging Gardens of the Colorado Plateau

Cathleen L. May[1]

Department of Integrative Biology
Museum of Paleontology
University of California
Berkeley, California 94720

James F. Fowler and Nancy L. Stanton

Department of Zoology and Physiology
University of Wyoming
Laramie, Wyoming 82071

Abstract. A roughly J-shaped archipelago of island habitats is distributed within the drainage system of the Colorado Plateau from the Zion area at the southwest to the canyons of the Green and Yampa rivers in the northeast. This is the hanging garden habitat. Hanging gardens are isolated mesophytic communities physically and biologically distinct from surrounding xerophytic or riparian communities. Geologic and hydrologic parameters control the existence, distribution, and physical attributes of the hanging-garden habitat. Attributes vary with the sedimentologic type of the different aquifer-bearing geologic formations in which gardens develop. Within a given formation, garden habitat attributes are relatively consistent. This observation allows a simple, informative, and predictive model of garden geomorphology to be applied across the geographic range of the system. The sandstone aquifers of the Colorado Plateau provide the necessary condition for hanging garden development—a perennial, seep-delivered water supply and an absence of significant fluvial processes. An erosional process called groundwater sapping yields protective geomorphology that shields the habitat from the aridity of the region as well as extrinsic erosional processes. Discharge rate and the lithology of the seep-supplying geologic formation determine the size, shape, distribution, and abundance of microhabitats within a hanging garden. Colonization of microhabitats is determined by the ecological requirements and by the biogeographic and evolutionary history of individual species making up the hanging-garden community. Diversion of the seep supply and erosion of colluvial soil by human foot traffic and livestock use affect garden ecology negatively. Hanging gardens should be protected

---

[1]Present address: U.S. Forest Service, 740 Simms, Golden, Colorado 80401.

from both activities. Local and regional alteration of patterns of aquifer flow may affect the hanging-garden ecosystem.

Key words: Biogeography, ecology, groundwater sapping, hydrology, mesophytic community.

The Colorado Plateau physiographic province of North America is characterized by areally extensive sedimentary rocks of Paleozoic through Recent ages that are generally flat-lying and are dissected by the Colorado River drainage system. Several transmissive sandstone formations on the plateau, underlain by relatively impermeable strata, are effective aquifers (Taylor and Hood 1988). Large-scale geologic structures (e.g., the Waterpocket Fold monocline and San Rafael Swell upwarp) yield broad dip planes and extensive joint systems within sedimentary strata and control groundwater movement at local and regional scales (Heath 1988). Subject to structural flow controls, groundwater exits from perched aquifers as seeps and springs on the walls of the incised plateau drainage system.

Groundwater erosional processes are land-shaping agents on the arid Colorado Plateau where bedrock is frequently exposed and soil cover is minimal over large areas. For example, the familiar theatre-headed canyons with steep side walls, arch-roofed alcoves, and hanging valleys found in plateau sandstones are the result of a process called sapping (Laity and Malin 1985). Sapping occurs where groundwater flow is concentrated and exits as a seep, eroding rock in that zone and removing the basal support of overlying rock (Dunne 1990). Canyons both widen and lengthen when the unsupported rock collapses. Until this collapse, however, cliffward erosion at the seep zone produces a concave-inward geometry that provides protection from sun and from surface erosion. The hanging gardens of the Colorado Plateau are found in such concavities with active seeps.

The geographic distribution of aquifer sandstones and the drainages that expose seeps control the distribution of the hanging-garden ecosystem. The lithologic and structural character of the aquifer formation, flow dynamics at the seep zone (Kochel et al. 1985), and extent of headward erosion determine which of three basic microhabitats are present and the geomorphology of the whole garden habitat. Our purpose in delimiting the fundamental parameters of garden habitat development is to provide a context for ecological and biogeographic research that distinguishes physical variability from biological variability in the hanging-garden ecosystem. This distinction will constrain that research to best estimates of biological process and pattern.

Stanton et al. (1991*[2], 1992a*, 1992b*) present preliminary results of the community ecology research done on this system. Fowler (1995) discusses endemism in the Zion-area and Glen Canyon hanging-garden communities. We limit the following discussion to the physical character of the habitat of hanging gardens for the purpose described above.

Literature Review

Welsh (1989) and Welsh and Toft (1972) list geologic formations in which hanging gardens are found and classify garden types. Although descriptive and internally consistent, their typing of gardens centers largely on an ontogenetic description of garden development through time. Of course, a temporal component to the geomorphic processes involved exists; however, we find the change is almost entirely one of size. Size is related to the composition of the garden community only by the addition of microhabitat types. Basic microhabitat types are limited to three. Those that characterize a particular geomorphology are determined very early in the erosional sequence; thereafter, size alone does not significantly influence community composition or diversity (Stanton et al. 1992a*, 1992b*). Welsh and Toft (1972) also include both physical and taxonomic criteria in their classification scheme. This does not suit our purpose, because biogeographic and ecologic research require a distinction between geomorphic and biological processes. Where relevant in the following discussion, we correct some geological misinterpretations and misidentifications found in Welsh (1989) and Welsh and Toft (1972).

Little information dealing explicitly with geomorphic processes relating to this unique habitat exists in the literature, though the work of Laity and Malin (1985) describes canyon growth by groundwater sapping. Hamilton (1992) describes geologic processes in the Zion area thoroughly and with strong emphasis on the geomorphology of hanging gardens.

The senior author reviewed pertinent geological literature including stratigraphy, tectonics, sedimentology, geomorphology, and groundwater hydrology to

[2]Asterisk indicates unpublished material.

provide a regional and site-specific context for the field study of the hanging-garden system (e.g., Cooley 1965; Untermann and Untermann 1965; Huntoon 1982; Doelling 1985; Laity and Malin 1985; Nations 1986; Billingsley et al. 1987; Hamilton 1987; Hintze 1988; Taylor and Hood 1988; Blakey 1989; Bromley 1991; Marzolf 1991; Patton et al. 1991; and others).

Field Methods

In addition to relating the distribution of the hanging-garden ecosystem to the regional geology of the plateau, field study included three levels of analysis. The most inclusive level comprised the geology surrounding that portion of the drainage system containing gardens studied in each of the national parks involved in the project. The intermediate level consisted of observations within individual drainages—both those containing gardens and those where the appropriate geomorphology does not exist—to determine where and how garden development occurs. The most detailed level comprised on-site characterization of the particular geomorphology and lithologic and structural geology at each of the 75 hanging-garden sites that were used for the data base on community ecology. Information gathered and used to derive the following conclusions included location relative to local geological structure, relative location within the drainage, identification of aquifer and aquitard formations or intraformational facies, characterization of the contact between the two, relative estimation of seep discharge, characterization of weathering processes at the seep face and colluvial sedimentation below, and determination of the lateral control on groundwater seepage. Measured parameters included length of primary seep line and number of secondary seeps, dip of slope beneath seep zone, size of microhabitats (i.e., size of vegetation patches used in analysis of canopy coverage), and aspect of the axis perpendicular to the strike of the seep. The information most pertinent to the community ecology and biogeography of the system is in the 1993 annual report to the National Park Service and will also be in future publications.

The following discussion, prospectus, and conclusions resulted from 9 months of field work on the hanging-garden system in 1991, 1992, and 1993 in Zion National Park, Glen Canyon National Recreation Area, Capitol Reef National Park, Natural Bridges National Monument, Arches National Park, Canyonlands National Park, and Dinosaur National Monument.

Discussion

We define the hanging-garden community by its assemblage of mesophytic vascular plants—characterization is made at the community level (Stanton et al. 1991*, 1992a*, 1992b*). Whereas the garden habitat may support some xerophytic and riparian species, the converse is less likely for most garden species—that is, the garden community occupies a distinct habitat and, as a whole, may not survive in either xeric or riparian conditions. We define this habitat by the extent of the primary seep and seep-moistened colluvial soil as described below. The garden habitat is the product of groundwater seepage. Seeps provide perennial, drought-resistant localized water supplies. The associated sapping process creates the protective geometry that allows for colluvial soil development and shields the habitat from the general aridity of the region.

The seep is the necessary—though not sufficient—condition for hanging garden development. Additional primary conditions include the absence of significant fluvial processes and protection from excessive sun and wind in the driest parts of the plateau. These few critical physical parameters determine whether appropriate habitat develops and whether colonization by garden species will be successful. The biogeographic history and dispersal and colonization characteristics of garden species determine the community composition of individual hanging gardens.

Groundwater Sapping and Garden Geomorphology

Sapping occurs where groundwater exits as a seep—not as a spring or point source. At the seep line, water that has moved through the aquifer formation encounters an impermeable layer that prevents its continued downward movement. The impermeable layer, or aquitard, may be the contact with the underlying formation or a stratigraphic facies of lower permeability within the aquifer formation or simply a lense or lamina of lower permeability within the aquifer. A seep zone develops above the aquitard; the rock at the cliff face is virtually water-saturated in this zone, and groundwater exits at a regular rate. Chemical weathering of the aquifer rock occurs in the seep zone, dissolving the cement that consolidates the material. Mechanical weathering—such as expansion by ice formation in colder areas and the precipitation of salt crystals whose growth further deconsolidates aquifer rock—also occurs in the seep zone. The loosened material falls away from the weathering face. The cliffward erosion of rock at the seep line creates overhead protection for as long as the overhanging rock remains in place, and a concave-headward geometry develops on the strike axis of the seep. Gravity-deposited material, or colluvium, accumulates where slope beneath the seep line is less than the angle of repose of the colluvium and where it is sufficiently protected overhead from precipitation and erosion by fluvial processes.

Seep delivery ensures that water cycles through the garden habitat at a relatively slow rate. Discharge rate is a product of the hydraulic head or pressure of the groundwater at the air–rock interface, the number of seep lines in the seep zone, and the number of secondary seep lines at the site. Beyond a certain discharge rate—the fluvial threshold—water is lost to runoff and may support riparian habitat on alluvial soils beneath the garden.

The absence of significant fluvial processes means that most of the moisture available to garden vegetation moves to root systems laterally and upward by capillary action rather than downward by precipitation. Whereas precipitation and surface water flow are not themselves detrimental to vegetation, they erode the colluvial soil in which garden vegetation takes root.

Hanging-garden Microhabitats

We use *microhabitat* to distinguish specific kinds of places within gardens from the whole hanging-garden habitat. We identify three microhabitats that may exist singly or multiply within hanging gardens: seep-line, wet-wall, and colluvial-soil. The colluvial-soil microhabitat is further divided for increased precision into soil slope and soil ledge in measuring canopy coverage and describing the vascular community. We do not, however, employ the distinction in this paper.

Seep-line Microhabitat

The seep line is the fundamental microhabitat of a hanging garden—seep occupied by garden species is defined as a garden, regardless of size or the presence of other microhabitats. Drainages where groundwater sapping is the primary agent of erosion may contain a large number of individual seep-line gardens. Where these are stacked vertically at one site, we identify one garden with a primary seep and one or more secondary seeps. Where the seep-line microhabitat exists without the other microhabitats, discharge is relatively low, colluvium does not support garden vegetation, and there is insufficient water to maintain a wet-wall microhabitat. Vascular plants root directly in the seep zone. Vegetation uses all water

that is not lost to evaporation. Garden species that can tolerate the driest conditions—*Petrophytum caespitosum*, for example—tend to occupy seep-line gardens with low discharge.

Where discharge rates are higher, the seep-line is but one of the two or three microhabitats present. In these instances, garden species that are also found on colluvial soil and the wet wall occupy the seep-line microhabitat, and the transition into the colluvial-soil microhabitat can be continuous and without a distinct edge.

The seep-line microhabitat is linear. Some overhead protection, if only centimeters deep, is associated with headward erosion by sapping. Orientation of primary seep lines is generally horizontal, though they may exist at any angle—including the vertical—when water movement through joints of the aquifer sandstone is slow (i.e., not greater than the fluvial threshold). In eolian sandstone aquifers like the Navajo and Entrada formations, the high-angle cross-bedding of ancient dunes creates planes of differential permeability that can perch water long enough for its exit as a seep. In these situations, garden vegetation occupies seeps whose geometry mimics the slip-face angle of the original sand dune.

Wet-wall Microhabitat

Where there is sufficient discharge, water flows slowly across bare rock at slopes too steep for the accumulation of colluvium. This is the wet-wall microhabitat, best exemplified by the giant weeping walls in Zion Canyon. The wet-wall microhabitat supports the clinging vascular plants commonly associated with the name and notion of a hanging garden as well as algal and bacterial colonies and bryophytes. Vegetation roots directly in rock fractures or on small clumps of colluvium that accumulate on the irregular wet-wall face.

The wet wall is a zone of active weathering of parent aquifer rock and, because it is sparsely colonized, the erosional process of sapping is most visible here. Wet walls exhibit a continuum of the weathering cycle from well indurated rock (i.e., fresh shear surfaces) to unconsolidated sand that is saturated to depths of several centimeters. Unconsolidated material is held at the face of the wet wall by a gelatinous slime of colonial cyanobacteria. This mass eventually sloughs off with increased weight and becomes part of the colluvial sediment below the seep zone, leaving a fresh shear face on the wet wall. Mineral precipitates and evaporites are common at the air–rock interface of the wet wall, especially on gardens whose aquifer recharge area includes overlying limestones. Groundwater picks up additional mineral compounds that are not degraded before reaching the rock–air interface. Much of what Welsh (1989) describes as *tufa* precipitates, however, are neither chemical precipitates nor evaporites. Rather, they are a dried crust made up of the sand–cyanobacterial combination described above. These crusts can be quite extensive on some gardens, especially in Zion where the wet-wall microhabitat is common. Broken apart, the alternating substrate and bacterial laminae give the appearance of stromatolite. This crust is abrasive when dry, as is travertine. Though this is a property of its sand content, it probably partly led to the misinterpretation that it is a precipitate.

Wet walls are usually close to vertical in orientation and frequently are super-vertical with either parallel concave or convex geometry relative to the cliff face as a function of site-specific structure. Clinging species are able to take root even on the underside of a garden roof, providing the seep zone continues overhead. Wet-wall microhabitat may also exist at substantially lower slopes though, when approaching the horizontal, water tends to flow faster, and fewer plants are able to take root. This microhabitat is subject to perturbation by ice shear in some areas.

Colluvial-soil Microhabitat

The colluvial-soil microhabitat supports both the greatest abundance and the greatest diversity of hanging-garden vascular species (Stanton et al. 1992a). Soil development on colluvium results from direct weathering of parent material. Colluvial soils in the protective geometry of hanging gardens are moistened by lateral and upward wicking of seep-delivered water. A drip line from overhanging rock is a slow, steady supply in most instances and does not result in significant erosion.

Species found on the seep line and wet wall also colonize the colluvial-soil microhabitat, with the exception of the least mesophytic (e.g., *P. caespitosum*). Additional forbs, grasses, sedges, and woody species colonize colluvial soil and increase the diversity of gardens with this microhabitat. Those xerophytic and riparian species that are able to colonize hanging gardens usually do so at the corresponding edges of colluvial-soil vegetation patches. Edges with transitional species are defined at either the point at which colluvium is no longer moist (in the instance of a xeric edge) or where alluvial sediments begin and colluvial sediments end (in the instance of a riparian edge).

The geometry of the colluvial-soil microhabitat may be triangular or tabular (i.e., quadrilateral), depending on the structure of the aquifer formation. Gardens

that form in eolian sandstones generally have triangular colluvial slopes, with the broad edge high and extending the length of the primary seep line and tapering inward downslope with the movement of water through the soil. Triangular shape is associated with a concave-inward geometry on the axis perpendicular to the strike of the seep. This is especially true for obvious reasons at the drainage head, even in noneolian aquifer formations. Welsh and Toft's (1972) classic alcoves exhibit this geometry. Tabular shape is associated with near-shore marine and fluvially deposited sandstones with strong horizontal bedding. The soil extends downslope at relatively equal depths all along the lateral extent of the primary seep. These slopes may also be concave-inward parallel to strike but not perpendicularly, and they do not taper downslope.

Unlike the other two microhabitats, the colluvial-soil slope is located almost entirely below the seep zone, developing largely in the aquitard formation or facies. Aquitard facies are finer-grained sandstones, siltstones, or mudstones of fluvial or lacustrine origin—hence their lower transmissivity and water-perching ability. They are horizontally bedded and so weather into alternating slopes and ledges above which colluvial sediments can accumulate. The colluvial soil that develops on the aquitard is thus composed not only of weathered sandstone but also has a component of the aquitard petrology as the result of in situ weathering of that parent material. The higher the mudstone percentage composition of the aquitard, the higher the clay content of colluvial soils that develop on it.

Colluvial soils on hanging gardens tend to be water saturated. Slopes are frequently greater than 65°. Neither unconsolidated sand nor suspended clay is particularly stable at steep slopes, so this microhabitat is exceptionally sensitive to disturbance and may be easily eroded.

Hanging-garden Classification

Hanging gardens may be described in terms of their shape and geometry and the microhabitats present. This specifies relative discharge rate of the seeps and implies the overall geomorphology of the habitat and its sedimentological origin. A classification built on microhabitats is descriptive and predictive, yet it serves to minimize physical variability that does not relate to biological variation. This is an important distinction for ecological research.

Gardens are either simple or complex; that is, they consist of either the seep-line microhabitat alone or that microhabitat plus either or both the wet-wall and colluvial-soil microhabitats.

The overall shape and geometry of complex gardens is strongly associated with the sedimentologic type of the aquifer formation. Those that are triangular and strongly concave-inward perpendicular to strike are associated eolian sandstones such as the Navajo Sandstone (Ss). We refer to gardens with this overall geometry as *Navajo-type* complexes. These generally exhibit strong lateral control on the seep zone by either jointing or structural concentration of groundwater flow. When headward erosion has undercut overlying rock that is still in place, these gardens are roofed and correspond with Welsh's classic alcove (Welsh and Toft 1972.)

Tabular-shaped gardens are associated with sandstones that are strongly horizontally bedded, like the Cedar Mesa Ss. The Cedar Mesa is of near-shore marine and fluvial origin, with alternating facies of differential permeability. Lateral control on the seep line is weak—groundwater is translated horizontally for long distances above aquitard facies. Colluvial-soil slopes are long and shallow with slight strike-parallel concave-inward geometry, except at drainage headwalls. We refer to gardens with this geometry as *Cedar Mesa-type* complexes.

Thus we describe gardens as one of four possible combinations of microhabitats in one of three categories as follows:

Simple (linear)	**Navajo-type complex** (triangular)	**Cedar Mesa-type complex** (tabular)
(1) seep-line	(2) seep-line + wet-wall	
	(3) seep-line + colluvial-soil	
	(4) seep-line + colluvial-soil + wet-wall	

Diversity of the garden community does not increase substantially with the addition of the wet-wall microhabitat. The presence of the colluvial-soil microhabitat does correlate, however, with increased diversity (Stanton et al. 1991*, 1992a*, 1992b*). Multiple instances of different microhabitats within a single garden, though a measure of increased physical complexity, do not correlate significantly with diversity trends in the vegetative community (contra Welsh and Toft 1972).

We do not distinguish gardens associated with plunge pools from those that are not. Vegetation surrounding such pools is normally riparian and is not counted in the garden community unless it is obviously on colluvial soil rather than alluvial. Plunge pools are the geomorphic results of intense, periodic surface runoff. Though both surface and groundwater tend to concentrate at the heads of drainages (indeed, the topographic concentration creates the drainage), hanging gardens and plunge pools at headwalls are coincidentally linked by location. Seeps are a groundwater process—plunge pools are the product of surface flow.

Hanging Gardens in Colorado Plateau National Parks

The following is a general physical characterization of hanging gardens in each of the seven national park jurisdictions included for research in this study. Gardens in each are treated collectively. (Please see reports to the National Park Service [Stanton et al. 1991*, 1992a*, 1992b*] for descriptions of individual garden morphology and community ecology.)

Zion National Park

We studied hanging gardens in Zion National Park in 1991 and 1992. Pine Creek Hanging Garden is developed in the Springdale Sandstone Member (Mbr) of the Early Jurassic Moenave Formation, above the clay-rich mudstone of the Whitmore Point Mbr. It is a complex Cedar Mesa-type hanging garden, with a tabular colluvial-soil slope. The small wet-wall microhabitat is saturated up to 3 cm cliffward. Precipitates, evaporites, and dried cyanobacterial crust are prevalent at this garden and elsewhere at seep zones in Pine Creek.

All other gardens studied in Zion are developed in the Jurassic Navajo Ss. The Navajo Ss reaches its greatest stratigraphic thickness here (more than 600 m) and contains a large volume of groundwater. Gardens in Zion Canyon have surplus discharge that runs off the garden and is frequently held in plunge pools below (e.g., Upper Emerald Pool) before discharging into perennial tributaries to the Virgin River. Amphitheatre-shaped bowls at the heads of these tributaries support well developed hanging gardens. These are complexes of all three microhabitats, which frequently exist in multiple. Gardens that develop on the sidewalls of Zion Canyon and tributaries tend to have extensive wet walls. This is due partly to the hydraulic head of groundwater in this thickest section of the Navajo Ss, which results in large seep zones with high discharge rates. Frequently, however, a joint in the Navajo Ss lies in a plane parallel to the canyon wall so that groundwater exiting high simply flows over the edge of the joint onto the cliff face (e.g., Weeping Rock Hanging Garden). Eventually the outer slab of suspended rock spalls away from the face, exposing even more wet wall.

The base of the Navajo Ss is exposed throughout much of Zion Canyon, and it is at this basal [gradational] contact with the underlying Kayenta Formation (Fm) siltstones–mudstones that most primary seep microhabitats are located. The wet-wall microhabitat above develops in the Navajo Ss and is supplied by higher secondary seeps. The colluvial-soil microhabitat occupies slopes and ledges in the Kayenta Fm below. The Emerald Pools in Heap's Canyon are a curiosity in which two Navajo–Kayenta couplets are vertically stacked. The Navajo and Kayenta formations intertongue extensively in the southwest portion of the Colorado Plateau (Blakey 1989). In this locality, a tongue of Navajo Ss separates the Kayenta siltstone–mudstone into upper and lower aquitards (Hamilton 1992). The hanging gardens above Upper and Lower Emerald pools develop at the base of the main body and the tongue of the Navajo, respectively (contra Welsh 1989; the Springdale Mbr of the Moenave Fm is not exposed in this portion of the canyon). Welsh describes a *boulder* [hanging] *garden* between Upper and Lower Emerald pools; we identify this habitat as riparian with colonization by some garden species and do not recognize a Middle Emerald hanging garden.

Garden habitat along the Narrows Trail in Zion National Park is also a complex of the three microhabitats. In this locality, the basal Navajo seep line extends laterally for several hundred meters, and multiple patches of wet-wall and colluvial-soil microhabitat are distributed where the seep follows an inward curve of the canyon wall.

We also studied gardens found high up-section in the Navajo Ss on the Overlook Trail at the east end of the highway tunnel. Seeps here are perched on an intraformational horizontal bedding plane. Less groundwater is available this high in the section—these gardens have lower relative discharge rates than stratigraphically lower gardens. Interestingly, these drier gardens have higher species-to-area ratios than the large, wet gardens in Zion Canyon and were our first evidence for the inverse relation between overall wetness and diversity on hanging gardens.

Glen Canyon National Recreation Area

We studied gardens on the Colorado River and on tributaries to the San Juan and Escalante rivers of Glen Canyon in 1991 and 1992. These 27 gardens are all developed within the Navajo Ss, at its base, or within the 12–21-m-thick transitional zone that exists between it and the underlying Kayenta Fm in some areas of Glen Canyon (Cooley 1965). The Navajo Ss is between 120 and 245 m thick in the Glen Canyon area and is largely flat-lying and exposed at its surface with little soil development or vegetative cover. The contrast between the surrounding slickrock and the hanging-garden community is striking in Glen Canyon. This area is the hottest and most arid of those in this study, and protection from both sun and drying wind is a critical geomorphic parameter. The shade line at midday in July virtually prescribes the edge of the garden community. Gardens on sidewalls are frequently developed in distinct, relatively compact alcoves with deep roofs—a very protective geomorphology. Simple seep-line gardens of low diversity are ubiquitous on those drainages growing by groundwater sapping. These exist anywhere on canyon walls along cross-bed laminae and horizontal bedding planes. Many are monospecific—inhabited only by *Petrophytum caespitosum*.

Gardens located in drainage headwalls exhibit the typical complex of three microhabitats, concave-inward geometry on both axes, and triangular colluvial-soil slopes. Secondary seep lines above the primary seep zone are common. The wet-wall microhabitat in Glen Canyon is generally small relative to total garden size and moist rather than covered with sheet flow. Plunge pools are common below the garden. Their formation by periodic intense surface runoff from the canyon rim above the garden is obvious here in the slickrock.

Although the thickness of the Navajo Ss here is half of that in Zion, it has greater surface exposure to recharge. Runoff of excess water is common here as well, extending seasonal persistence of intermittent streams below and providing reproductive habitat for several amphibian species. *Bufo punctatus*, *B. woodhousei*, *Hyla arenicolor*, and *Rana pipiens* utilize the plunge pool habitat below gardens at a number of our Glen Canyon sites. Water loss to evaporation, however, is high at all points in the cycle from seep to runoff and probably masks the true discharge volume.

Capitol Reef National Park

Hall's Creek and the east side of Waterpocket Fold were surveyed for gardens in the 1992 and 1993 field seasons. This monoclinal structure largely precludes the geomorphology necessary for hanging garden development. The Navajo Ss dips at so strong an angle over the east side of Waterpocket Fold that there is almost no low-angle exposure to charge the interstitial space of the sandstone. Water entering the sandstone at its upper exposure is quickly shunted downward through the joints and fractures associated with the strong monocline. Surface water flowing over the sandstone simply runs right over the slickrock fold. During intense summer storms, this runoff shoots outward off the fold to free fall almost 245 m into Hall's Creek—a powerful sight from the bottom of the drainage. Furthermore, the contact with the Kayenta aquitard is buried at the bottom of the fold so that what groundwater does move through the sandstone does not encounter an impermeable layer while exposed.

Nevertheless, some hanging garden development exists in Capitol Reef National Park. At the bottom of the fold, in the Hall's Creek Narrows, seep lines just above the riparian zone support low-diversity gardens primarily composed of *Adiantum capillus-veneris*. The seeps are intraformational on horizontal bedding planes and cross-bed laminae within the Navajo Ss. The recharge is probably the upstream water table of Hall's Creek. One low garden, Sidewall Hanging Garden, seems to be supplied by water moving down an extensive vertical joint and charging laminar seeps above the garden.

We found two gardens higher in the Navajo Ss formed at intraformational seep lines. These are small (long axis <10 m) with little colluvial soil development and low discharge rates. The diversity-to-area ratio is high for one of these gardens. This habitat also supported one canyon treefrog (*H. arenicolor*) far from any other source of permanent moisture. The scarcity of hanging gardens in Capitol Reef National Park makes those that are developed a rare and important resource.

Natural Bridges National Monument

White Canyon and its tributary drainages cut through the Permian Cedar Mesa Formation in Natural Bridges. The Cedar Mesa Fm consists of fluvial and nearshore marine dune sands interbedded with less permeable finer-grained interdunal, lacustrine, and overbank facies. The sandstone facies are up to 10 m thick, and the silty facies are usually less than 3 m thick in the outcrop area studied. Low-angle cross-bedding and significant horizontal bedding characterize the sandy facies, and horizontal structure is primary in the silty facies. This sedimentology yields a different geomorphology than that seen in the eolian sandstones of the plateau. Eolian sandstones are characterized by high-angle cross-bedding, little horizontal structure, and relatively homogeneous, amorphous lithology. When undercut, eolian rock masses spall off along curved planes that frequently correspond to the angle of repose of the slip face of the original dune. This angle is

harmoniously repeated all over the slickrock country of the plateau in alcoves, arches, and other nonlinear landforms. Noneolian sandstones like the Cedar Mesa do not exhibit this weathering pattern. The Cedar Mesa Fm is strongly structured horizontally, is more heterogeneous in lithology, and weathers into steplike, linear, laterally extensive geometries by both fluvial and groundwater processes.

The gardens that form in the Cedar Mesa Fm are long laterally and short vertically. We estimated that one garden in Tuwa Canyon, while not included in this study, extended laterally more than 500 m, but its width never exceeded about 10 m. Gardens are concentrated in the upper third of the Cedar Mesa section; most groundwater volume is translated laterally before reaching the lower two-thirds of the section.

The wet-wall microhabitat is not common on Cedar Mesa gardens. Bicarbonate is an abundant evaporite on colluvium. Except at drainage heads, the colluvial-soil microhabitat is generally tabular shaped with slight, concave-inward geometry parallel to strike. Overhanging ledges protect colluvial soils from erosion by precipitation. These are higher-elevation gardens than those in Zion and Glen Canyon, and shade seems to be less important to the garden community (determined by the correlation between aspect and vascular community attributes). Gardens are concentrated on the east side of White Canyon because groundwater follows the shallow west dip of the formation until it exits at the canyon intersection.

Arches and Canyonlands National Parks

Gardens in these parks, studied in the 1993 field season, are treated collectively here because there is no significant geomorphic difference between them. The Jurassic Wingate, Navajo, and Entrada sandstones (the Glen Canyon group) are all well exposed in this area. All are considered to be primarily eolian dune deposits, though this interpretation for the Navajo further west has been debated (e.g., Marzolf 1976). All are characterized by high-angle cross-stratification and the weathering pattern described above. While the Wingate is a potential aquifer, it is largely overlain by the Kayenta Fm and is seldom exposed to recharge at the surface. May surveyed the top of the Chinle Fm (i.e., the base of the Wingate) in 1993 in the Upheaval Dome area of the Island in the Sky district and identified no hanging gardens. The large alcove supporting garden species off the first switchback of the Schafer Trail reported by Welsh (1989) as forming in the Wingate is actually in the Navajo Ss.

The Navajo Ss is the primary garden-forming aquifer in this region. At Island in the Sky in Canyonlands National Park, seeps on the Neck Springs Trail form at the base of the Navajo (contra Welsh 1989) above a fairly distinct contact with the underlying Kayenta Fm. The Navajo Ss is less than 100 m thick here, and the recharge area at Island in the Sky is restricted, so seeps here are probably more subject to seasonal fluctuations in discharge rate. Nevertheless, there is sufficient flow through the aquifer to support gardens of moderate to large size with excess runoff. These are typical Navajo-type gardens, much like those found in Glen Canyon.

Navajo-type hanging gardens develop in the eolian Entrada Ss in Arches National Park as well. We sampled gardens developed on south-facing walls on the north side of the Salt Valley in the Delicate Arch vicinity. Vertical displacement on a more or less west–east trending fault creates two slickrock benches that expose the contact between the Moab Tongue Mbr above and the Slickrock Mbr (below) of the Entrada Fm. The seep line runs much of the length of this contact on both benches. Navajo-type gardens form in the drainage nickpoints of a series of joints that run perpendicular to the fault line. The seep line in between these larger gardens supports laterally extensive gardens that grade outward from complex to simple.

Dinosaur National Monument

We studied gardens on the Green and Yampa rivers and tributary canyons in the 1993 field season. The primary garden-forming aquifer in this region is the Pennsylvanian–Permian Weber Ss. The Weber exhibits variable facies lithologies. Gardens high in the section (e.g., up Bull, Johnson, and Red Rock canyons and up Ely Creek) are of the Cedar Mesa-type geomorphology. Signature Cave hanging garden, however, developed at the base of the Weber Ss beneath a deep classic alcove. It is a Navajo-type garden with a triangular colluvial-soil slope and pronounced strike-perpendicular concave-inward geometry. The seep seems to exit from the base of the Weber at its contact with the underlying Morgan Fm, though the seep line itself is largely obscured by colluvium. This far north on the plateau, and at this elevation, shade becomes relatively unimportant.

An anomalous situation exists at Limestone Hanging Garden up Limestone Draw on the Green River. Groundwater moves down through about 245 m of Morgan Fm and Round Valley Limestone and is slowed at the top of the Mississippian Doughnut shale. It exits and flows over the sloping Doughnut Fm and the sandier Humbug Fm. The groundwater exit at this site is laterally small, yet a large volume of water is discharged onto a narrow, deep, vegetated slope. Close to the seep line, the garden is typically concave-inward, with a wet-wall microhabitat, secondary seeps, and a protected triangular colluvial-soil slope. Below the seep zone, however, are several vegetated slopes that are fully exposed to fluvial processes. These slopes support hanging-garden species, though a channel through the larger slope contains running water and supports riparian species. In this instance only, the authors disagree on how to delimit the garden. One of us (J.F.F.) defines the anomalous slopes as in-garden based on the presence of the hanging-garden plant community. The senior author (C.L.M.) cannot distinguish a sedimentologic difference between these slopes and the surrounding talus slopes with which they are continuous (other than their colonization by garden vegetation) and would limit this garden to the edge of typical fine-grained, well sorted colluvial sedimentation and protective geomorphology. This site includes point–source flow in addition to seepage and accompanying alluvial sedimentation on the talus beneath the colluvial slope.

Aquifers on the Colorado Plateau and the Age of the Hanging-garden Ecosystem

The sandstones of the Colorado Plateau are the region's major aquifers. The Early Jurassic Glen Canyon group in particular is both laterally and stratigraphically extensive. In fact, the Navajo Sandstone is the largest eolian unit of the Earth's rock record. These aquifers hold an immense volume of water. However, due to fine grain size, alteration of mineralogy during diagenesis, overburden loading, and secondary infilling of joints and fractures, the primary permeability of these sandstones is minimal (Hood and Patterson 1984; Taylor and Hood 1988). Furthermore, the Colorado Plateau–Wyoming Basins hydrologic region has the lowest recharge rate on the North American continent (Heath 1988). Considering, then, that these formations are not easily charged with groundwater, how is it that they are such effective aquifers? Logically, if recharge is slow, then a significant amount of time is required to account for the present volume of water stored in these sandstones. Likewise, the rate of discharge must not have significantly exceeded recharge rate during the time elapsed since downcutting exposed perched aquifers.

Downcutting on the Colorado Plateau began with its initial uplift as early as the middle Eocene (+43 million years ago [m.y.a.]). The Colorado River and its tributaries seem to have evolved separately in individual areas and at slightly different times (Patton et al. 1991). The modern Colorado drainage was established between 11 and 5 m.y.a. (Larson et al. 1975a, 1975b; Lucchitta and Young 1986; Lucchitta 1990). Given the Recent arid climate regime on the Colorado Plateau, it seems likely that aquifers exposed to surface recharge during Pleistocene wet cycles were fully charged at that time and that recharge has more or less kept up with discharge to maintain the current volume for about 1.8 million years.

The age of the hanging-garden ecosystem is not known. We may parsimoniously assume that as soon as downcutting exposed perched aquifers, the processes that develop garden geomorphology could proceed. Based on estimated ages of paleodrainages, it is conceivable that appropriate garden geomorphology has existed in some areas for as long as 15 million years. A safer assumption, based on the estimated age of the modern drainage system, would allow garden geomorphology since about 5 m.y.a. Certainly the process of groundwater sapping on the Colorado Plateau was well under way by the early Pleistocene (~1.8 m.y.a.). Quaternary paleontologists and paleoecologists use fossil data collected in dry alcoves and caves formed by this geomorphic process to reconstruct post-Pleistocene climate and ecosystem history.

The presence of the appropriate geomorphology, however, does not necessarily imply the historical presence of hanging gardens. A strong possibility exists that discharge rates from perched aquifers before the current arid regime were too high to allow colluvial sediments to accumulate. The garden community is supported by slow-delivery seeps—not by springs. Furthermore, we do not know whether the early vegetation that occupied this geomorphic habitat was similar to the modern assemblages. Direct evidence is unavailable because the saturated soils of the garden habitat do not preserve plant megafossils. Palynomorph analysis of sediments from dry alcoves or fossil evidence from packrat (*Neotoma* spp.) middens can tell us what the vegetation of the region was like at a particular time, but that does not necessarily inform us of the community composition of a hanging garden from the same stratigraphic horizon. Certainly the modern garden community is dissimilar from its surrounding flora. Also, alcoves and caves in the canyon system of the plateau are formed by fluvial processes as well as groundwater processes. As downcutting proceeds, channel widening performs the same removal of basal support as the seep does on a canyon wall or headwall. So even evidence from dry alcoves at the same stratigraphic level does not assure the historical presence of a hanging garden (contra Welsh 1989; gardens are consequent on their geomorphology, not the converse).

We may deduce only that the distinct ecosystem we identify as hanging gardens on the basis of the vegetative community is maximally as old as charged aquifers exposed by downcutting and likely no older than the current arid climate regime (i.e., the system probably dates from the Pleistocene). The senior author further postulates that a significant portion of the current plateau aquifer volume is Pleistocene in age and that post-Pleistocene aridity and the low recharge rate of these aquifers combine to make this groundwater system extremely susceptible to permanent draw down. The hanging-garden ecosystem is necessarily equally susceptible to degradation.

Prospectus

Whether the modern garden community is a relict of a previously widespread flora or the product of dispersal from other source areas—or both—is a central question currently being addressed by the authors. The hanging-garden system naturally lends itself to longitudinal ecological investigation; indeed, monitoring the status of its endemics requires continued research. Additional primary research should include a comprehensive soil analysis with sufficient geographic distribution to ensure sampling the variability. The Grand Canyon section of the Colorado drainage system should be surveyed for hanging gardens.

Conclusions

The importance of groundwater geomorphology to the hanging-garden ecosystem cannot be overstated. The first condition for both habitat development and initial colonization is the seep. Habitat and community evolution are linked to seep-controlled geomorphic processes. A fluctuation-resistant water delivery system with no fluvial component is critical to the persistence and stability of the garden ecosystem.

Aridity is a primary feature of the Colorado Plateau, affecting geomorphic and biologic processes in both ecological and evolutionary time. The aquifers of the plateau mitigate aridity constraints for the hanging gardens. These aquifers are likely older than the current climatic regime and recharge at a very slow rate. Long-term persistence of the hanging gardens depends on maintenance of aquifer volumes.

The physical attributes of hanging gardens are a product of the sedimentology, lithology, and structure of the geological formations in which they develop and the corresponding geomorphology produced by groundwater sapping. Similar sedimentologies yield gardens that are geomorphically similar. Community similarity or difference is a function of the biogeographic and evolutionary history of component species.

Management of the hanging-garden ecosystem should include preventing the erosional effects of humans and livestock, preventing or removing local seep diversions, and consideration of the potential long-term effects of both drawdown and reservoirs on aquifer flow patterns.

Acknowledgments

We thank J. Hak for his participation in the 1991 and 1992 grant years. We appreciate the insight, information, and assistance provided in this research by National Park Service staff at each jurisdiction of the Colorado Plateau, especially J. Belknap, R. Harris, N. Henderson, S. Petersburg, and V. Viera. The participants in the 1993 River Conference on Hanging Gardens and Global Change were particularly inspiring. C. Bell and T. Fiorillo read and commented on the manuscript. This research was supported by NPS-32752 to Stanton.

Cited Literature[3]

Billingsley, G. H., P. W. Huntoon, and W. J. Breed. 1987. Geologic map of Capitol Reef National Park and vicinity, Utah. Utah Geological and Mineral Survey, Salt Lake City.

Blakey, R. C. 1989. Triassic and Jurassic geology of the southern Colorado Plateau. Pages 369–396 *in* J. P. Jenney and S. J. Reynolds, editors. Geologic evolution of Arizona. Arizona Geological Society Digest 17, Tucson.

Bromley, M. H. 1991. Architectural features of the Kayenta Formation (Lower Jurassic), Colorado Plateau, USA: relationship to salt tectonics in the Paradox basin. Sedimentary Geology 73:77–99.

[3]Asterisk indicates unpublished material.

Cooley, M. E. 1965. Stratigraphic sections and records of springs in the Glen Canyon region. Museum of Northern Arizona Technical Series 6: Glen Canyon Series. Northern Arizona Society of Science and Art, Flagstaff. 140 pp.

Doelling, H. H. 1985. Geologic map of Arches National Park and vicinity, Grand County, Utah. Utah Geological and Mineral Survey, Salt Lake City.

Dunne, T. 1990. Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow. Geological Society of America Special Paper 252:1–28.

Fowler, J. F., N. L. Stanton, R. Hartman, and C. L. May. 1995. Level of endemism in hanging gardens of the Colorado Plateau. Pages 215–224 *in* C. van Riper III, editor. Proceedings of the Second Biennial Conference on Research in Colorado Plateau National Parks. 25–28 October 1993. National Park Service Transactions and Proceedings Series NPS/NRNAU/NRTP-95/11.

Hamilton, W. H. 1987. Geological map of Zion National Park, Utah. Zion Natural History Association, Springdale, Utah.

Hamilton, W. H. 1992. The sculpturing of Zion. Zion Natural History Association, Springdale. 132 pp.

Heath, R. C. 1988. Hydrogeologic setting of regions. Pages 15–23 *in* W. Back, J. S. Rosenshein, and P. R. Seaber, editors. Hydrogeology. DNAG O-2. Geological Society of America, Boulder, Colo.

Hintze, L. F., editor. 1988. Geologic history of Utah. Brigham Young University Geology Studies Special Publication 7. Provo, Utah. 203 pp.

Hood, J. W., and D. J. Patterson. 1984. Bedrock aquifers in the northern San Rafael Swell area, Utah, with special emphasis on the Navajo Sandstone. Utah Department of Natural Resources Technical Publication 78:1–28.

Huntoon, P. W., G. H. Billingsley, and W. J. Breed. 1982. Geological map of Canyonlands National Park and vicinity, Utah. Canyonlands Natural History Association, Moab, Utah.

Kochel, R. C., A. D. Howard, and C. F. McLane. 1985. Channel networks developed by groundwater sapping in fine-grained sediments; analogs to some Martian valleys. Pages 313–341 *in* M. J. Woldenber, editor. Models in geomorphology. Allen and Unwin, Boston, Mass.

Laity, J. E., and M. C. Malin. 1985. Sapping processes and the development of theater-headed valley networks on the Colorado Plateau. Geological Society of America Bulletin 96:203–217.

Larson, E. E., W. C. Bradley, and M. Ozima. 1975a. Development of the Colorado River system in northwestern Colorado during the late Cenozoic. Pages 97–102 *in* J. Fassett, editor. Canyonlands country: Four Corners Geological Society 8th field conference guidebook.

Larson, E. E., M. Ozima, and W. C. Bradley. 1975b. Late Cenozoic volcanism in northwestern Colorado and its implications concerning tectonism and the origin of the Colorado River system. Pages 155–178 *in* B. M. Curtis, editor. Cenozoic history of the southern Rocky Mountains. Geological Society of America Memoir 144.

Lucchitta, L. 1990. History of the Grand Canyon and of the Colorado River in Arizona. *In* J. Jenny and S. J. Reynolds, editors. Geological evolution of Arizona. Arizona Geological Society, Tucson.

Lucchitta, L., and R. A. Young. 1986. Structure and geomorphic character of western Colorado Plateau in the Grand Canyon–Lake Mead region. Pages 159–176 *in* J. D.

Nations, C. M. Conway, and G. A. Swann, editors. Geology of central and northern Arizona. Geological Society of America Rocky Mountain Section field trip guidebook, Flagstaff, Ariz.

Marzolf, J. E. 1976. Sand grain frosting and quartz overgrowth examined by scanning electron microscopy; the Navajo Sandstone (Jurassic(?)), Utah. Journal of Sedimentary Petrology 46:906–912.

Marzolf, J. E. 1991. Lower Jurassic unconformity (J-0) from the Colorado Plateau to the eastern Mojave Desert: evidence of a major tectonic event at the close of the Triassic. Geology 19:320–323.

Nations, J. D., C. M. Conway, and G. A. Swann, editors. 1986. Geology of central and northern Arizona. Geological Society of America Rocky Mountain Section field trip guidebook, Flagstaff, Ariz. 176 pp.

Patton, P. C., N. Biggar, C. D. Condit, M. L. Gillam, D. W. Love, M. N. Machette, L. Mayer, R. B. Morrison, and J. N. Rosholt. 1991. Quaternary geology of the Colorado Plateau. Pages 373–406 *in* R. B. Morrison, editor. Quaternary nonglacial geology; conterminous U.S. DNAG K-2. Geological Society of America, Boulder, Colo.

Peters, F., and G. N. Pipiringos. 1979. Stratigraphic relationships of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona. U.S. Geological Survey Professional Paper 1035-B:1–43.

*Stanton, N. L., S. J. Buskirk, and J. F. Fowler. 1991. Semiannual report for biogeography of invertebrates and plants in hanging gardens of the Colorado Plateau. University of Wyoming, Cooperative Park Studies Unit, Laramie. UW-NPS-32752.

*Stanton, N. L., S. J. Buskirk, and J. F. Fowler. 1992a. Annual report for biogeography of invertebrates and plants in hanging gardens of the Colorado Plateau. University of Wyoming, Cooperative Park Studies Unit, Laramie. UW-NPS-32752.

*Stanton, N. L., S. J. Buskirk, and J. F. Fowler. 1992b. Semiannual report for biogeography of invertebrates and plants in hanging gardens of the Colorado Plateau. University of Wyoming, Cooperative Park Studies Unit, Laramie. UW-NPS-32752.

Taylor, O. J., and J. W. Hood. 1988. Region 3, Colorado Plateau and Wyoming basins. Pages 51–58 *in* W. Back, J. S. Rosenshein, and P. R. Seaber, editors. Hydrogeology. DNAG O-2. Geological Society of America, Boulder, Colo.

Welsh, S. L. 1989. On the distribution of Utah's hanging gardens. Great Basin Naturalist 49:1–30.

Welsh, S. L., and C. A. Toft. 1972. Biotic communities of hanging gardens in southeastern Utah. National Geographic Society Research Reports 13:663–681.