Chapter 15

Hemiarid Lake Basins: Hydrographic Patterns

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'The Great Basin [of western North America]: . . . contents almost unknown, but believed to be filled with rivers and lakes which have no communication with the sea . . .'
Brevet Capt. J.C. Frémont, Corps of Topographical Engineers (1845).

Introduction

Lakes and other mappable bodies of standing water exist at the atmosphere-lithosphere interface. Over shorter time intervals, water body configurations (hydrography) respond directly to atmospheric (hydroclimatic) forcing. Over longer intervals, hydrography also reflects tectonic and volcanic forcing from the lithosphere. Hydrographic patterns in lake basins, in turn, strongly influence and even control many geomorphic and stratigraphic patterns (e.g. Mabbutt 1977). These linked patterns (hydroclimatic + tectonic → hydrographic → geomorphic + stratigraphic) make lakes and kindred water bodies superb instruments for gauging environmental change and recording palaeoenvironmental history.

Large quantities of lacustrine hydrographic and geomorphic information occur in spatial and temporal patterns, several of which are summarized in this and the following chapter. Although it is often convenient to view water bodies and associated features two-dimensionally (e.g. in plan or cross section), lacustrine spatial patterns are inherently three-dimensional (Fig. 15.1). Similarly, lacustrine temporal patterns that derive from changing spatial patterns are inherently four-dimensional. Therefore, X (easting), Y (northing), and Z (elevation) coordinates obtained by georeferencing technologies, such as a global positioning system (GPS), together with ages measured by chronoreferencing technologies, such as accelerator mass spectrometer (AMS) analysis of cosmogenic isotopes and optically stimulated luminescence (OSL) analysis of clastic sediments, are essential elements of hydrographic and geomorphic patterns.

Hemiarid Lake Basins

Hydrographic and topographic closure are fundamental, and quite distinct, aspects of surface water distribution in all drainage basins. By definition, every lake basin has topographic closure, or containment, but only those that have 'no communication with the sea' (Frémont 1845) also possess hydrographic closure. Most humid areas have hydrographically open drainage basins. Humid areas without topographic closure typically convey surface water in stream networks, while those with topographic closure contain externally drained lakes as part of the stream system (Sack 2001). Basins with hydrographic closure are described as internally drained, or basins of interior drainage. Areas that are hydrographically closed yet topographically open have little surface water and exist, for example, in hyperarid coastal deserts. Drainage basins that are closed both topographically and hydrographically and also contain or have contained bodies of standing water are hemiarid lake basins (Fig. 15.2), the subject of this and the following chapter.

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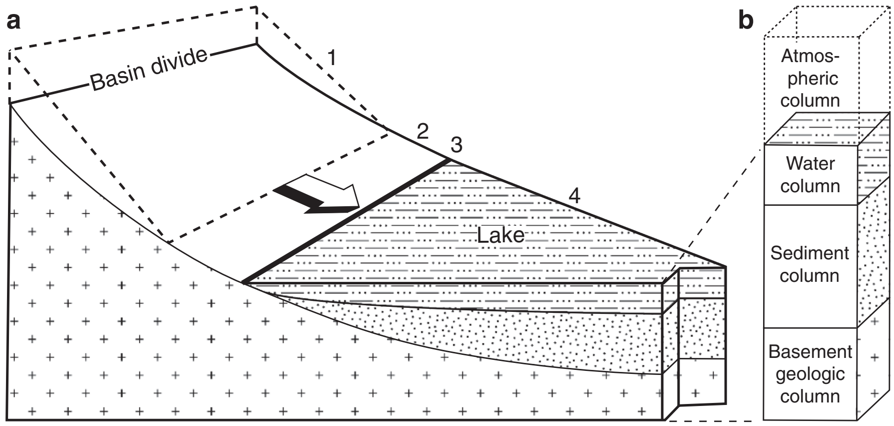

Fig. 15.1 Block diagram of a narrow sector in a hypothetical lake basin showing (**a**) water and sediment transfer from (1) the zone of net runoff and net denudation, through (2) the zone of maximum water and sediment transfer, to (3) the shoreline, and into (4) the zone of water body equilibration and net sedimentation; and (**b**) four-tiered environmental/palaeoenvironmental column in the basin

Hemiarid lake basins have dual hydroclimates. Highlands are nonarid with cumulative water balance surpluses, that is, annual precipitation is greater than annual evapotranspiration. Lowlands are arid, semiarid, or hyperarid with cumulative water balance deficits because annual precipitation is less than annual potential evapotranspiration. Highlands in hemiarid basins, therefore, are runoff producers; they provide water for stream flow and recharge the groundwater, both of which are conducted toward the lowlands. The lowlands mainly collect and evaporate (consume) surface and subsurface water, most of which is directed to them from the highlands. Water bodies in hemiarid lake basins tend to be classic examples of self-regulating, climate-driven systems (Thorn 1988). By undergoing sometimes dramatic size fluctuations in response to climate changes, water losses and gains maintain dynamic equilibrium (e.g. Mifflin and Wheat 1979, Street-Perrott and Harrison 1985). Gains, mainly from highland runoff and direct precipitation onto the lowland water body, increase lake surface area which promotes greater water loss by surface evaporation. The negative feedback role of surface area in water-body self-regulation is illustrated in Fig. 15.3.

	Hydrographically open basin	Hydrographically closed basin
Topographically open basin	Uncontained and externally drained (river system)	Uncontained and internally drained (influent system)
Topographically closed basin	Contained and externally drained (lake)	Contained and internally drained (hemiarid)

Fig. 15.2 Hemiarid lake basins (*lower right*) are closed both topographically and hydrographically, that is, they have both containment and internal drainage

Hydroclimatic zonation within hemiarid lake basins is mainly a function of elevation and slope aspect, but the areal extent of each zone is a planimetric variable (Fig. 15.4). The water-surplus higher part of a hemiarid lake basin has an area that can be expressed dimensionlessly by the surplus area ratio (SAR), where SAR is water-surplus area as a fraction of total basin area. The lower limit of the water-surplus zone, and upper limit of the water-deficit zone, is the hydroclimate equilibrium line altitude (HELA), which is the average elevation above sea level at which annual precipitation and evapotranspiration are equal. The water-deficit lower part of a hemiarid lake basin has an area that can be expressed by the deficit area ratio (DAR), where DAR + SAR = 1. Water-deficit subzones (Fig. 15.4) include dry lowlands, wet lowlands (except lakes and ponds), and open water (lakes and ponds). The area of open water can be expressed dimensionlessly by the water area ratio (WAR), where WAR is the area of open water as a fraction of total basin area. Completely nonarid basins (SAR = 1.0) with topographic closure invariably lack hydrographic closure, that is, they contain externally drained bodies of fresh water. Completely arid basins (DAR = 1.0) seldom contain water bodies larger than groundwater-fed brine pools.

Hydrographic features of several types, and represented by numerous names, generally connote hemiarid lake basins. These include alkali lakes, badwaters, bitter lakes, bolson lakes, brackish lakes, brine lakes, closed-basin lakes, dead seas, desert lakes, dry lakes, endoreic lakes, ephemeral lakes, hypersaline lakes, impermanent lakes, inland salt lakes, inland seas, intermittent lakes, landlocked

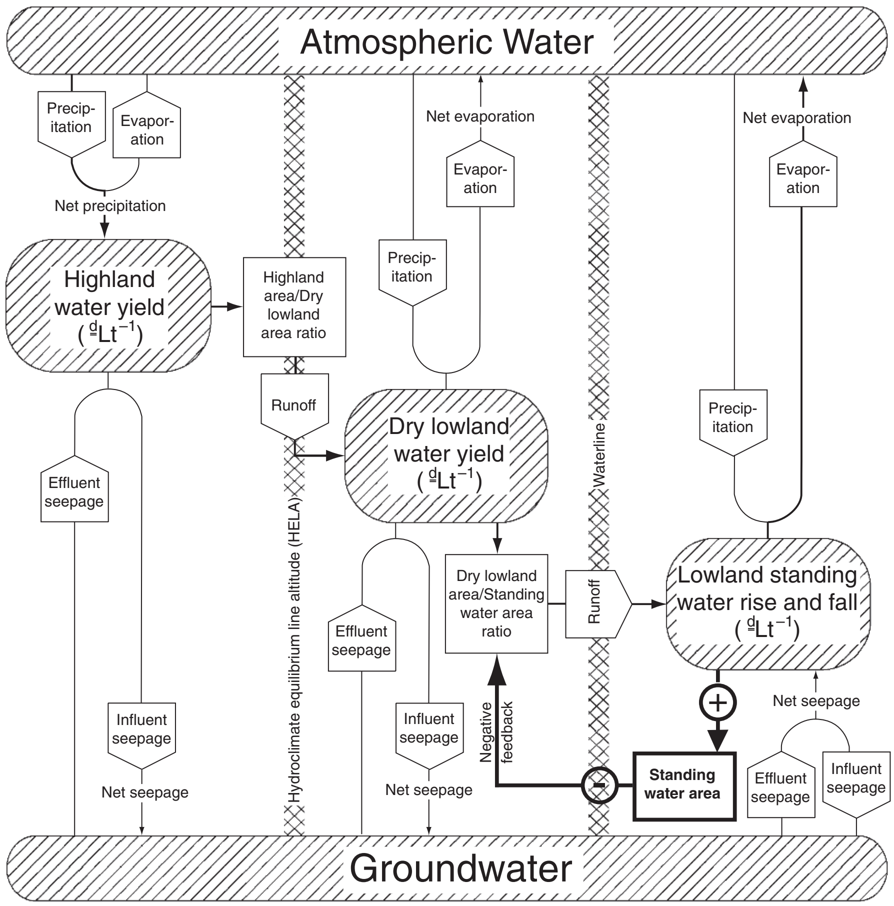

Fig. 15.3 Water balance transfers in hemiarid lake basins, where runoff originates in nonarid highlands (*upper left*), passes through water-deficit dry uplands and lowlands (*middle*), and terminates in hydroclimatically arid lowlands with standing water (*lower right*). Transfers are dimensionally equal to length (depth of water) per unit time. Negative feedback regulates runoff per unit area of lowland standing water, keeping inputs (mainly runoff) to the standing water and outputs (evaporation) from the standing water in dynamic equilibrium

lakes, lost lakes, mud lakes, oasis lakes, pan lakes, playa lakes, saline lakes, salt marsh lakes, salton seas, sink lakes, soda lakes, temporary lakes, terminal lakes, undrained lakes, and many others. Terrestrial water bodies below sea level indicate hemiarid lake basins unless the water derives mainly from seawater or groundwater. In addition, many so-called pluvial lakes of Pleistocene and Holocene age (e.g. Morrison 1968, Reeves 1968, Smith and Street-Perrott 1983) occurred in what were and still are hemiarid lake basins, although the sites of some of these palaeolakes have been breached and dissected by through-flowing drainage (e.g. Meek 1989).

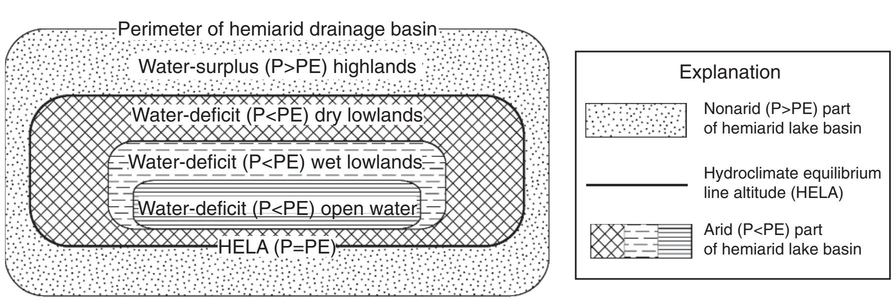

Fig. 15.4 Schematic plan view of a hypothetical hemiarid lake basin showing water-surplus (nonarid) and water-deficit (arid) hydroclimatic zones; P = annual precipitation and PE = annual potential evapotranspiration (Mather 1978). This basin has a surplus area ratio (SAR) of 0.5 and a water area ratio (WAR) of 0.1

Table 15.1 Structural (tectonic and volcanic) origins of lake containment basins,* where underlying causes of topographic closure are structural blockage (B) of basin outlets and structural lowering (L) of basin floors. Very shallow (1), shallow (2), moderately deep (3), and deep (4) topographic closure depths are typical of occurrences in North American deserts and semideserts

	Typical closure depths			
Structural causes of topographic closure	(1)	(2)	(3)	(4)
Tectonic lake containment basins:				
major half-grabens (L)			•	•
major grabens (L)			•	•
transcurrent faulting sag ponds (B)	•	•		
transcurrent-faulting-blocked valleys (B)	•	•		
horst-dammed valleys (B)			•	
anticline-dammed valleys (B)			•	
diapir-dammed valleys (B)		•	•	
doubly plunging syncline basins (L)			•	
ring-fracture-bounded basins (L)		•	•	
volcano-tectonic collapse basins (L)			•	•
Volcanic lake containment basins:				
calderas (L)			•	•
craters (L)		•	•	
maars (L)		•	•	
volcano-dammed valleys (B)			•	
lahar-dammed valleys (B)		•	•	
ash-flow-dammed valleys (B)			•	
lava-flow-dammed valleys (B)		•	•	
collapsed lava tubes (L)	•	•		

* Compiled from Hutchinson (1957, p. 156–163).

Hydroclimatic zones and hydrographic features in hemiarid lake basins are always subject to change. Figure 15.5 shows five annual hydroclimatic outcomes – much drier, drier, little net change, wetter, much wetter – that can result from nine possible combinations of deviation in annual precipitation, annual evaporation, or both. Annual precipitation and evaporation values, in turn, derive from 81 possible combinations of seasonal changes in those variables, which are represented in the figure by the outer tier of nine lettered cells (seasonal precipitation) and nine numbered cells (seasonal evaporation). A G3 seasonal scenario, for example, would be expected to produce a much wetter annual outcome, as would any combination of a G, H, or I seasonal precipitation trend with a 1, 2, or 3 seasonal evaporation trend. If the location is a subtropical desert, a G3 scenario would probably involve significant intensification of monsoonal circulation (Magee et al. 1995, Schuster et al. 2003, DeVogel et al. 2004).

Basin Origins

Hemiarid lake basins exist in regions where aridity and tectonic activity coincide (Fig. 15.6). Tectonic activity, with or without syntectonic volcanism, is generally the underlying cause of topographic closure (e.g. Thornbury 1965, Eaton 1982, May et al. 1999). Exogenic geomorphic processes, which can enhance or degrade topographic closure, are commonly important secondary causes.

Tectonism and volcanism cause topographic closure in two ways: (a) by blocking basin outlets, and (b) by lowering basin floors (Table 15.1). The greatest depths of topographic closure typically result from block faulting in regions of extensional tectonics and from subsidence due to partial emptying of magma chambers beneath volcanic terranes (e.g. Le Turdu et al. 1999).

Exogenic geomorphic processes also cause topographic closure by blocking basin outlets and lowering basin floors (e.g. Trauth and Strecker 1999) (Table 15.2). These geomorphic contributions to topographic closure are usually limited to low-relief embellishments of pre-existing structural basins. Some geomorphic processes cause structural basins and systems of interconnecting structural basins to become segmented into shallow, topographically closed subbasins (e.g. Hunt et al. 1966, Peterson 1981). Large alluvial fans and compound barrier beaches are particularly important as sills between subbasins (e.g. Russell 1885, Benson and Thompson 1987, Sack 2002).

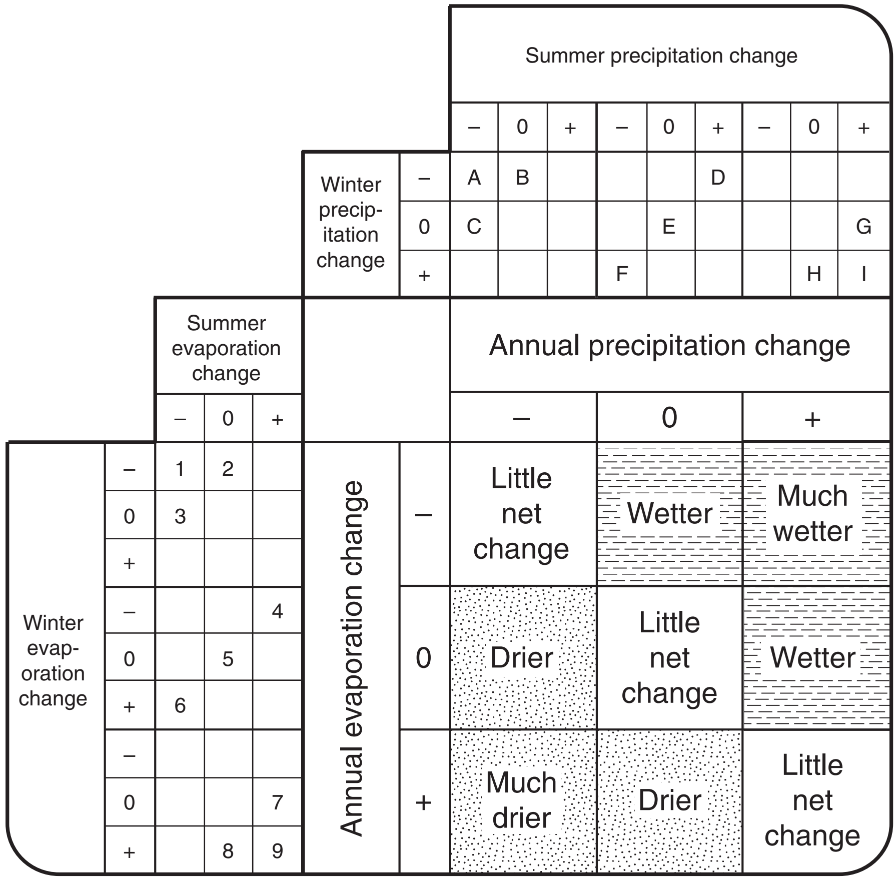

Fig. 15.5 Hydroclimatic change in hemiarid lake basins, with five annual outcomes appearing in nine large cells at *lower right*. These are produced by 81 seasonal scenarios portrayed by groups of smaller cells at *upper right* and *lower left*. Symbols: − = decrease, 0 = no change, and + = increase annually or seasonally; see text for further explanation

Basin Changes

A hemiarid lake basin can contain lakes up to a maximum size (basin capacity) that is controlled by the height of the basin threshold, and it can contain shallow water bodies that are identifiable as lakes down to a minimum size (basin capability) that is controlled by the shape of the basin floor. Many geomorphic and structural factors affect basin capacity and basin capability. Geomorphic processes may degrade or aggrade basin thresholds and basin floors, but threshold degradation and aggradational widening and flattening of basin floors predominate (Fig. 15.7). As a result,

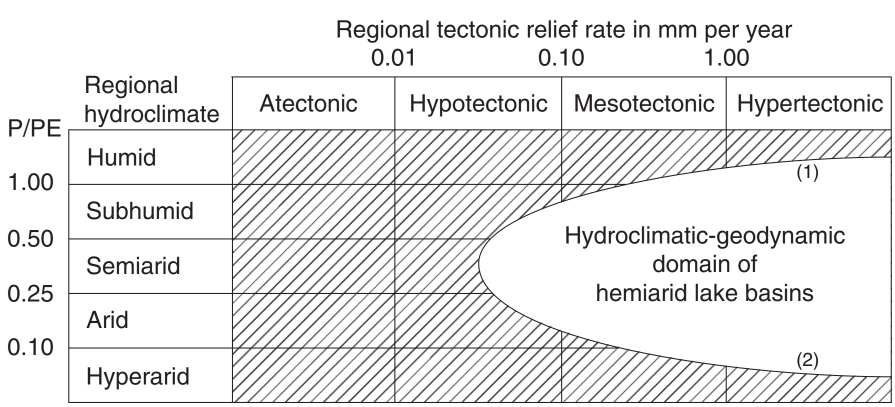

Fig. 15.6 Hemiarid lake basins occur in regions where aridity and tectonic activity coincide; P and PE as in Fig. 15.4. Hypertectonism extends the domain of hemiarid lake basins by causing (1) intrazonal rainshadows in humid zones, and (2) intrazonal orographic precipitation in hyperarid zones

Table 15.2 Geomorphic origins of lake containment basins,* where immediate causes of topographic closure are geomorphic blockage (B) of basin outlets or geomorphic lowering (L) of basin floors. Very shallow (1), shallow (2), moderately deep (3), and deep (4) topographic closure depths are typical of occurrences in North American deserts and semideserts

	Typical closure depths			
Geomorphic causes of topographic closure†	(1)	(2)	(3)	(4)
Mass wasting lake containment basins:				
landslide-dammed basins (B)	•	•	•	
slump rotation basins (L)	•	•		
Glacial lake containment basins:				
ice-dammed basins (B)				
moraine-dammed basins (B)	•	•	•	
glacially scoured basins (L)				
kettles (L)	•	•		
Periglacial lake containment basins:				
cryofluction-dammed basins (B)				
thermokarst basins (L)				
nivation hollows (L)	•			
Solution lake containment basins:				
travertine- and sinter-rimmed pools (B)	•	•		
sinkholes (L)	•	•		
cavern pools (L)	•	•		
Fluvial lake containment basins:				
natural-levee-dammed basins (B)	•	•		
alluvial-fan-dammed basins (B)	•	•	•	•
delta-dammed basins (B)	•	•	•	
abandoned waterfall plunge pools (L)	•	•		
abandoned channels (L)	•	•		
flood-scoured pools (L)	•	•		
Aeolian lake containment basins:				
interdune swales (B)	•	•		
dune-dammed basins (B)	•	•		
blowouts (L)	•	•		
deflation basins (L)	•	•	•	
Seashore lake containment basins:				
barrier-beach-enclosed lagoons (B)				
barrier-reef-enclosed lagoons (B)				
shore platform tide pools (L)				
Lakeshore lake containment basins:				
barrier-beach-enclosed lagoons (B)	•	•		
barrier-complex-dammed subbasins (B)	•	•	•	•
Phytogenic lake containment basins:				
bog-rimmed pools (B)	•			
Zoogenic lake containment basins:				
beaver ponds (B)	•	•		
animal wallows (L)	•			
Cosmogenic lake containment basins:				
meteorite impact craters (L)	•	•	•	

* Compiled from Hutchinson (1957, p. 156–163).
† The absence of any indication of closure depth adjacent to a particular lake type signifies that lake type is not found in deserts.

some basins lose part or all of their capacity to contain large lakes and become incapable of containing small lakes. As basin capacity and capability diminish with time, the range of lake sizes that a basin can accommodate becomes narrower and there is a decrease in the range of hydroclimatic variation that the lake basin can document in its geomorphic and stratigraphic record.

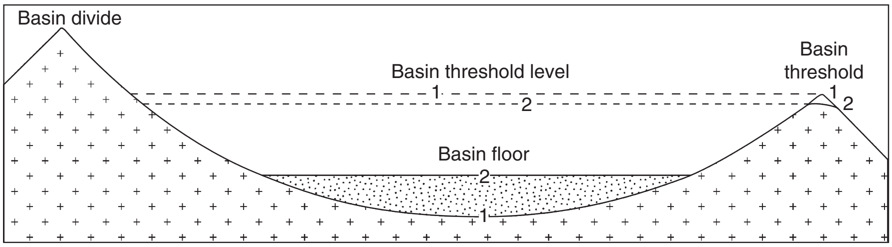

Fig. 15.7 Schematic cross section of a hypothetical lake basin showing basin threshold (bt) and basin floor (bf) changes produced by geomorphic and structural activity (Tables 15.3 and 15.4) through time (1 = earlier; 2 = later). Basin fill sediments overlie bf_1 and underlie bf_2. Topographic closure decreased due to both the threshold lowering from bt_1 to bt_2 and the basin floor aggrading from bf_1 to bf_2

Basin threshold height, which ultimately controls basin capacity, is subject to change from a variety of geomorphic and structural causes (Table 15.3). The greatest change in threshold height is likely to occur the first time a lake transgresses to its basin threshold. In that situation, observations from several hemiarid lake basins in western North America suggest the following sequence of geomorphic events, listed in order of occurrence: (1) piping and sapping by pre-flood subsurface overflow beneath and downstream from the threshold, (2) channel incision by pre-flood surface overflow downstream from the threshold, (3) headward erosion of the pre-flood overflow channel, (4) hydraulic failure when headward erosion reaches the threshold, (5) scouring of the flood path into a deep flood channel upstream and downstream from the threshold, (6) scouring an overdeepened kolk in the flood channel floor near the site of the former threshold, (7) landsliding along the flanks of the flood channel, (8) alluviation of the flood channel by waning-flood and postflood overflow, (9) segmentation of the flood palaeochannel by small alluvial fans that build from either side, and (10) colluviation of the flood palaeochannel by slopewash that includes reworked loess.

Table 15.3 Basin threshold morphodynamics*

Causes of basin threshold change	Threshold height change†
Geomorphic causes:	
fan toe accretion	+
loess accretion	+
aeolian sand accretion	+
aeolian deflation and abrasion	−
cryptoluvial piping and sapping	−
surface overflow incision	−
surface overflow headward erosion	−
hydraulic failure of threshold	−
flood channel scouring	−
flood channel kolk overdeepening	−
flood-triggered landsliding	+
palaeochannel alluviation	+
palaeochannel colluviation	+
Structural (tectonic and volcanic) causes:	
far-field isostatic deflection	+ or −
near-field hydroisostatic deflection	+ or −
near-field lithoisostatic deflection	−
near-field glacioisostatic deflection	0
extensional seismotectonic displacement	+ or −
transcurrent seismotectonic displacement	+ or −
compressional seismotectonic displacement	+ or −
volcanic flow emplacement	+ or −
cinder cone construction	+
tephra deposition	+

* Adapted from Currey (1990).
† Symbols: + = threshold raised; 0 = insignificant in most hemiarid lake basins; and − = threshold lowered.

Basin floor elevation and breadth, which are also subject to change from a variety of geomorphic and structural causes (Table 15.4), tend to increase as basin fill sediments aggrade through time. As a result, the capability of many hemiarid lake basins to accommodate small lakes gradually decreases. In theory, decreasing basin capability should be offset by processes, such as faulting, volcanism, and to a lesser extent aeolian deflation and abrasion (Magee et al. 1995, Hoelzmann et al. 2001), that create new basin floor relief. In practice, however, aggrading sediments are readily distributed over very low gradients on basin floors that alternate between subaqueous and subaerial conditions and that are subject to recurring hydroaeolian planation. This repeatedly restores and enlarges basin floor horizontality in many hemiarid lake basins, and repeatedly flattens many sites that might otherwise contain small lakes.

Table 15.4 Basin floor morphodynamics*

Causes of basin floor change	Height change†	Breadth change‡
Geomorphic causes:		
proluvial (fan toe sandflat) deposition	+	−
deltoid (Mabbutt 1977) deposition	+	0 or −
deltaic deposition	+	0 or −
offshore deposition	+	0
lakeshore erosion	+	0 or +
lakeshore deposition	+	0 or −
evaporite deposition	+	0 or +
evaporite dissolution	−	0 or −
spring bog deposition	+	0
spring mound deposition	+	0
hydroaeolian planation	+	+
aeolian erosion	−	0 or +
aeolian deposition	+	0 or −
Structural (tectonic and volcanic) causes:		
far-field isostatic deflection	+ or −	−
near-field isostatic deflection	+ or −	−
seismotectonic displacement	+ or −	−
salt diapir doming	+	−
magma chamber inflation or deflation	+ or −	−
volcanic flow emplacement	+	−
volcano accretion	+	−
volcano tectonic subsidence	−	−
tephra deposition	+	0

* Adapted from Currey (1990).
† Symbols: + = basin floor raised; 0 = level of basin floor unchanged; and − = basin floor lowered.
‡ Symbols: + = basin floor enlarged; 0 = area of basin floor unchanged; and − = basin floor reduced in size.

Basin Hydrographic Connections

Intrabasin hydrographic connections consist of waterways that move water, solutes, and sediments from one area to another within a hemiarid lake basin. Interbasin hydrographic connections are cascades that transport water, solutes, and sediments from one hemiarid lake basin to another. It is common for two or more basins to be connected by subsurface cascades (e.g. Harrill et al. 1988); it is less common for two or more hemiarid lake basins to be connected by surface cascades (e.g. Hubbs et al. 1974, Mifflin and Wheat 1979, Williams and Bedinger 1984). Indeed, surface cascades occur only (a) infrequently, when threshold-controlled 'minipluvial' highstands happen in basins with shallow topographic closure, (b) rarely, when threshold-controlled 'plenipluvial' highstands occur in basins with deep topographic closure, or (c) extrinsically, when runoff acquired through drainage diversion or stream capture leads to threshold control (e.g. Bouchard et al. 1998).

There are two kinds of intrabasin waterways: (a) input waterways act as conduits directing runoff into lakes from the surrounding drainage basin, and (b) throughput waterways form links between distinct morphological subdivisions within lakes. Lakes that lack major perennial or intermittent input waterways are simple lakes, whereas complex lakes receive inflow from one or more major input waterway (Fig. 15.8).

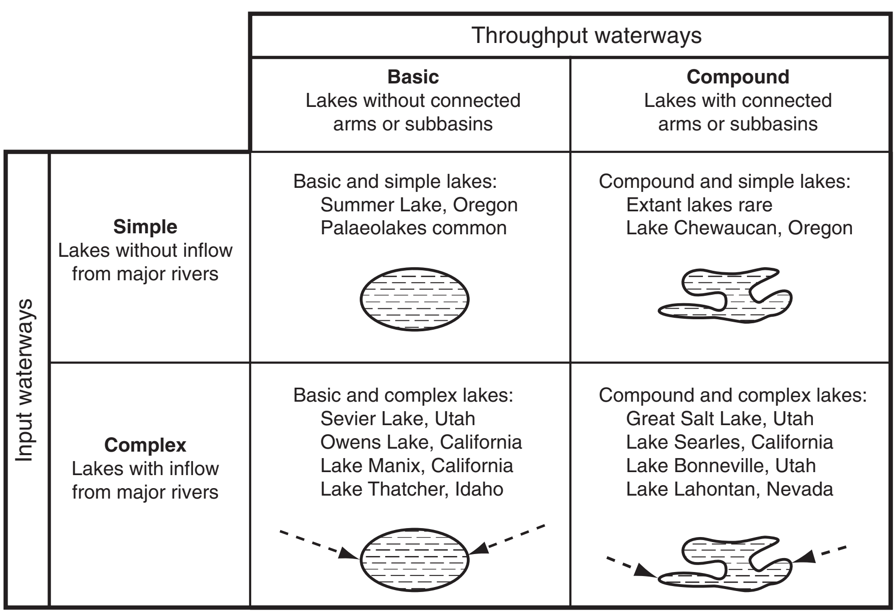

Fig. 15.8 Hemiarid lakes are described as complex or simple according to the presence or absence of input waterways, and as compound or basic depending on the presence or absence of strait-connected arms and/or sill-connected subbasins (modified from Currey 1990). These concepts are illustrated with plan-view sketches of primary attributes. Listed example lakes include extant lakes and palaeolakes

The presence or absence of throughput waterways distinguishes compound from basic lakes. Compound lakes consist of strait-connected arms or sill-connected subbasins, and tend to be large lakes. Intrabasin waterways strongly influence lacustrine geomorphic patterns in lakes that are compound and complex, like former Lake Lahontan (Benson and Thompson 1987, Benson and Paillet 1989).

At a very general level, all hemiarid lake basins occupy one of four possible positions in subsurface and surface cascades (Fig. 15.9) and many basins have attributes that reflect their cascade position. For example, cascade-head basins are typically low-salinity environments, whereas cascade-terminus basins often contain brines and saline sediments. In surface cascades, water, solutes, and usually sediments move from one basin to another at comparatively high, even torrential, rates for relatively brief periods. In subsurface cascades, water and solutes, but not sediments, move from basin to basin at low rates, sometimes moistening and salinizing basin floors from beneath, for extended periods. As they enter, cross, and leave hemiarid lake basins, surface and subsurface cascades interact with basin morphology in distinctive patterns.

Certain cascade patterns are repeated spatially and temporally in many hemiarid lake basins. Spatially, five patterns prevail in hydrologically and topographically closed terminal and near-terminal basins (Fig. 15.10, right-hand column). Such basins seldom have completely dry surfaces and commonly store solute and sediment yields from large upstream regions. Temporally, five stages of cascade evolution are common in upstream basins (Fig. 15.10, middle column): (1) tectonically young basins commonly store sediments and spill mainly water and solutes; (2) with geomorphically reduced topographic closure, basins increasingly pass sediments downstream as well; (3) with deepening threshold incision, stored materials are released at rates that range from gradual to catastrophic; (4) some basins are eventually opened completely by through-flowing surface drainage; and (5) when stream discharge wanes, through-flowing drainage can be limited to groundwater and solutes in the subsurface. Regional cascades of water, solutes, and sediments that are typical of hemiarid lake basins are illustrated in Fig. 15.11.

	Relative to cascade head	
Relative to cascade terminus	Most headward basin H	Basin downstream from head h
Basin upstream from terminus t	Cascade-head basin Ht	Mid-cascade basin ht
Terminal basin T	Cascade with one basin HT	Cascade-terminus basin hT

Fig. 15.9 Basin positions in regional cascades of water, solutes, and sediments

Hydrographic Continuum

Despite water's long term regional scarcity, it exists in a remarkable variety of forms on the floors of hemiarid lake basins (e.g. Langbein 1961, Houghton 1986). These forms belong to a hydrographic continuum that can be subdivided into several definable, but intergradational, hydrographic realms and subrealms (Table 15.5). In essence megalakes, lakes, and ponds are runoff-collecting and runoff-evaporating water bodies. Aquatic wetlands, saturated wetlands, and unsaturated wetlands are groundwater-discharging and groundwater-evaporating basin floors. Playas and microplayas are stormwater-wetted, stormwater-infiltrating, and stormwater-evaporating basin floors.

Ecologically, lacustrine habitats are limited mainly to water bodies with depths greater than 2 m; shallower water bodies are the realm of palustrine habitats (Cowardin et al. 1979). Geomorphically, well developed evidence of lacustrine processes is limited mainly to water bodies with depths greater than 4 m. In shallower water bodies (a) aerodynamic turbulence causes frequent mixing of the water column and vigorous hydrodynamic stirring of the offshore sediment record, and (b) gently shelving topography suppresses onshore propagation of waves in other than low energy bands of the wave spectrum, which effectively limits onshore and longshore transport of beach-forming sediments.

In low-lying areas that contain little or no standing water much of the time, as well as in low-lying areas that are adjacent to lakes, mixed wetlands form complex mosaics on the floors of many hemiarid lake basins. In order of increasing salinity, mixed wetlands commonly range from spring-fed aquatic marshes, to seep-fed muddy marshes, to alkali meadows, to saline mudflats, and ultimately to phreatic saltflats (Table 15.5).

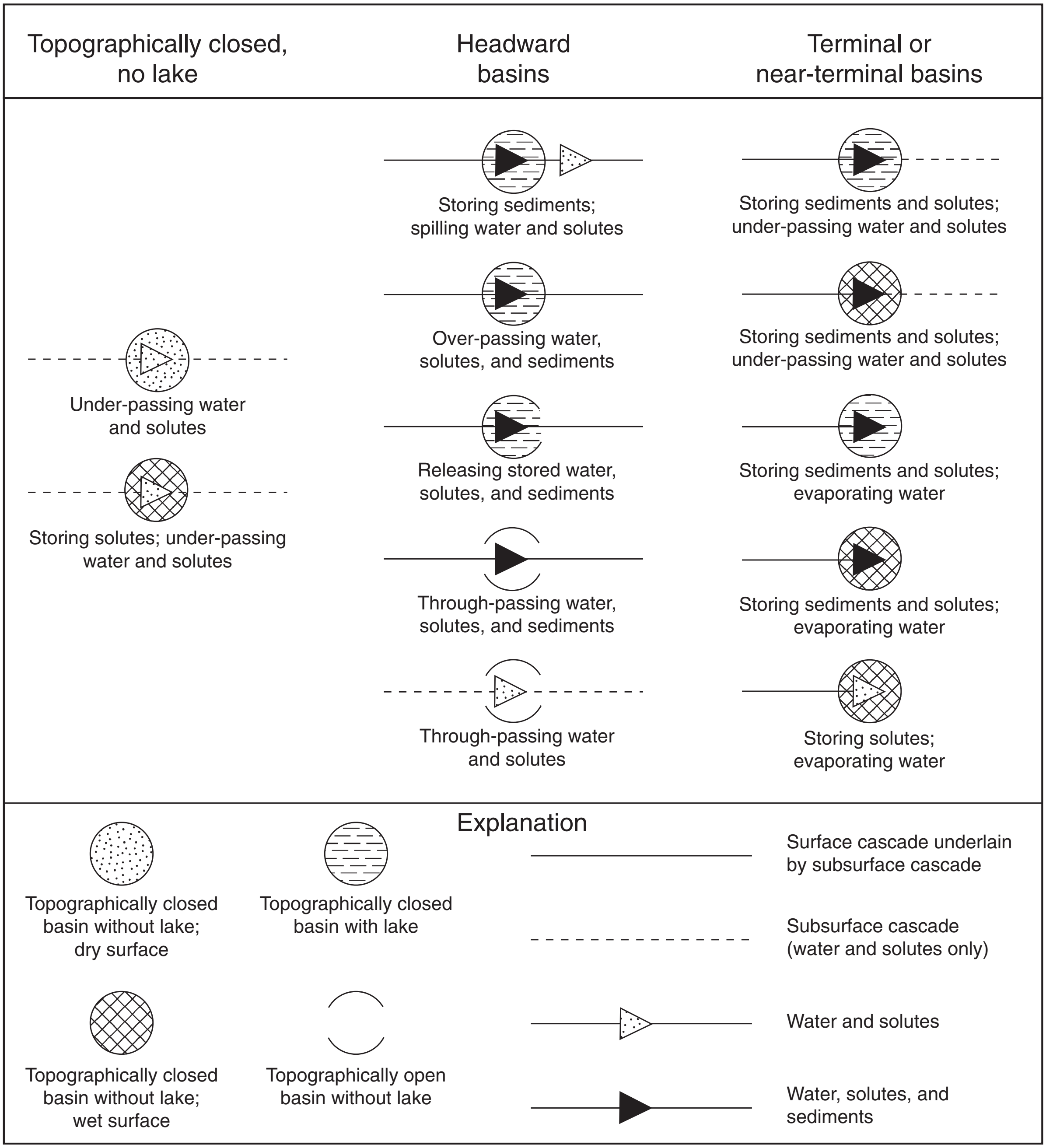

Fig. 15.10 Plan view symbols depicting cascades of water, solutes, and sediments in hemiarid lake basins. Direction of flow in each case (indicated by triangles) is *left to right*

Hydrographic Change

Hydrographic change is a hallmark of hemiarid lake basins (e.g. Street and Grove 1979). It takes many forms and has many causes. Transgression, stillstand, or regression each can result from several causes (Fig. 15.12). Spatial, temporal, and kinematic analysis of net hydrographic change and its components is fundamental to lacustrine geomorphology, thus hydrographic change is viewed here from basinwide spatial, temporal, and spatiotemporal perspectives.

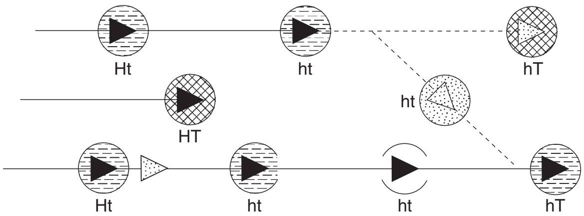

Fig. 15.11 Schematic plan of two hypothetical regional cascades, a one-basin cascade (HT) and an eight-basin cascade that has two terminal basins (hT). For explanation of symbols see Figs. 15.9 and 15.10

Hydrographic change occurs within spatial limits that are set by basin morphometry. As described above in the section on basin changes, the upper limit of potential hydrographic change, that is, basin capacity, is threshold controlled and the lower limit, basin capability, is controlled by the basin floor. A large range of uninterrupted hydrographic change is possible only in hemiarid lake basins with deep topographic closure and small basin floors (Fig. 15.13).

Hydrographic responsiveness expresses the vertical (surface elevation) change that a water body undergoes in response to a given hydrologic (surface area) change. Steep-sided basins (e.g. Fig. 15.13) are responsive to hydroclimatic change, while basins with very low sloping sides are relatively unresponsive – that is, hydrographic responsiveness is a direct function of basin slope (Street-Perrott and Harrison 1985, Bartov et al. 2002).

Hydrographic fitness expresses how well late Pleistocene and Holocene highstands and lowstands in hemiarid lake basins fit their containment basins (Fig. 15.14). Full geomorphic and stratigraphic records of hydrographic change are found in continuously fit basins, such as the Lake Lahontan basin in Nevada and California, in which the water body is contained below the threshold at highstands and above the minimum level for lacustrine processes at lowstands. Less than complete records of hydrographic change are found in overfit basins, including the Lake

Table 15.5 Hydrographic realms and subrealms on the floors of hemiarid lake basins have characteristic surface water and groundwater hydrology, and characteristic geomorphic and geodynamic features

Hydrographic realms and subrealms	Surface water and groundwater hydrology	Geomorphic and geodynamic features
Lakes: megalakes	Permanent* bodies of open standing water; static water surfaces >100 m above basin floors over large areas (>1000 km^2); total areas >10 000 km^2; far-field tributary networks, usually with surface runoff from more than one climatic region and several highland life zones	Well developed evidence of shore (backshore, foreshore, nearshore) and offshore sedimentation; tributary networks usually derive terrigenous sediments from several geologic terranes; measurable evidence of near-field hydroisostatic deflection; possible evidence of lithoisostatic deflection near depocentres
lakes	Persistent* or permanent bodies of open standing water; static water surfaces >4 m above basin floors; usually with surface runoff from more than one life zone	Well developed evidence of shore sedimentation; commonly evidence of offshore sedimentation; terrigenous sediments commonly from more than one geologic terrane; little evidence of near-field isostatic deflection, but possible evidence of far-field deflection
Quasi-lakes: ponds	Transient* or persistent bodies of open standing water; static water surfaces 1 to 4 m above basin floors; standing water mostly from surface runoff	Too shallow for well developed evidence of shore sedimentation; too shallow for unreworked evidence of offshore sedimentation; hydroaeolian planation and, in shallow basins, brim-full sedimentation tend to transform ponds into wetlands and playas; evaporite ponds floored with soluble salts occur in subbasins where evaporating brines are replaced by saline surface waters, sometimes from adjacent water bodies by restricted inflow across low barriers
Wetlands: aquatic	Ground surfaces covered by transient layers of local standing water <1 m deep; standing water mostly from groundwater discharge	Range from biotically productive aquatic marshes dominated by emergent hydrophytes to clear evaporite pools floored with soluble salts and saline pools floored with saline muds

Table 15.5 (continued)

Hydrographic realms and subrealms	Surface water and groundwater hydrology	Geomorphic and geodynamic features
saturated	Surficial materials water saturated; groundwater tables that coincide with basin floors discharge water and solutes	Range from muddy marshes and spring bogs dominated by hydrophytes to nonvegetated phreatic saltflats (= saltpans, etc.) where perennial evaporite pavements are renewed or enlarged by recurring precipitation of soluble salts from saline groundwaters that saturate basin floors; unless renewed as phreatic saltflats, limnogenous saltflats (evaporite pavements formed by desiccation of antecedent lakes) undergo dissolution into saline mudflats or playas, or burial by younger muds
unsaturated	Surficial materials damp, but usually drier than field capacity; groundwater tables that underlie basin floors discharge capillary water and solutes through evaporative pumping, also termed the wick effect	Range from alkali meadows dominated by salt-tolerant grasses and shrubs to sparsely vegetated saline mudflats; undergo precipitation of efflorescent salts during seasons of strong evaporative pumping, followed by dissolution of efflorescent salts during seasons of surface wetting
Drylands: playas	Surficial materials usually drier than wilting point; water tables much below basin floors; capillary fringes do not intercept basin floors; wetted briefly by rain or snowmelt, and flooded occasionally by stormwater runoff from surrounding piedmont and upland source areas	Relatively salt-free, fine-grained surfaces (= nonsaline mudflats, claypans, etc.) where stormwater runoff events spread suspended sediments widely and dump coarser sediments locally; in absence of effective effluent seepage or evaporative pumping, occasional influent seepage effectively leaches soluble salts from playa surfaces
microplayas	Very small playas, usually with areas $<1\,km^2$	Playas that develop in local depressions such as blowouts and former lagoons, rather than on basin floors of more general extent

* See Fig. 15.15.

Bonneville-Great Salt Lake basin in Utah and the Lake Russell-Mono Lake basin in California. Water bodies in overfit basins lie above the minimum level for lacustrine processes at lowstands but become threshold-controlled at highstands. Far from complete records of hydrographic change are found in misfit basins, like Lake Searles, California, which display spilling lakes at highstands and also experience lowstand levels below the minimum for lacustrine processes. Underfit basins, such as Death Valley, California, likewise encode incomplete records. Although they are well contained at highstands, lowstands are too shallow to leave significant lacustrine evidence. In addition to hydrographic fitness, lakeshore configuration and sediment supply are important factors in the geomorphic recording of hydrographic change. These topics are reviewed fully in the next chapter.

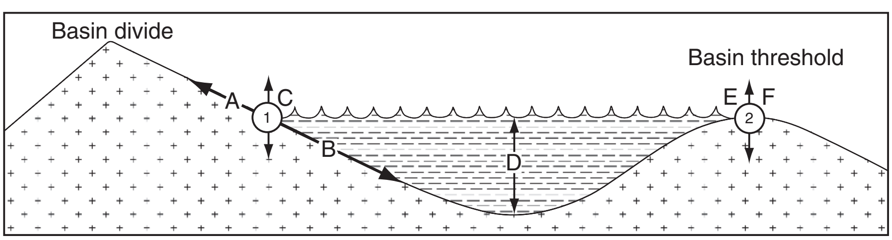

Fig. 15.12 Schematic profile through a lake basin, showing possible net hydrographic change (A = transgression and B = regression) at a shoreline locality (1) due to possible combinations of upward or downward neotectonic deformation (C), hydrologic change of the lake (D), and geomorphic change (E) or neotectonic deformation (F) of the lake threshold (2)

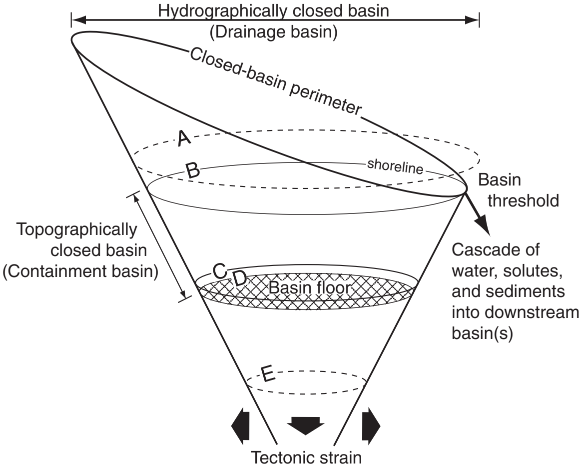

Fig. 15.13 'Dixie cup' (conical graben) model of a hypothetical hemiarid lake basin showing (A) off-scale highstand inferred by extrapolating from geomorphically recorded hydrographic history, (B) threshold-controlled shoreline, (B–C) hydrographically fit lake stages, (C) low-water limit of lacustrine processes, (C–D) ponds and aquatic wetlands, (D) saturated and unsaturated wetlands on basin floor, and (E) off-scale lowstand inferred by extrapolating from geomorphically recorded hydrographic history (after Currey 1990)

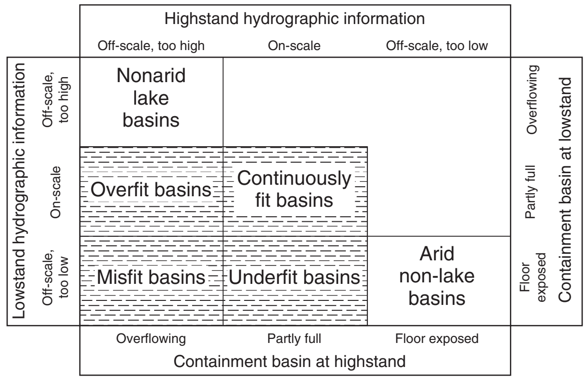

Fig. 15.14 Hydrographic fitness defined in terms of late Quaternary highstands and lowstands (after Currey 1990); hemiarid lake basin cells (shaded) may be continuously fit, overfit, misfit, or underfit

Temporal measures of hydrographic change in hemiarid lake basins include persistence and recurrence of open standing water (Fig. 15.15). Persistence is the average length in years of periods of continuous inundation expressed as a proportion of recurrence. Recurrence is the length of the average continuous inundation interval plus the average length in years of continuous subaerial periods. Water bodies vary greatly in their persistence and recurrence, which are particularly important as factors in the geomorphic development of basin floors. Transient lake-playa regimes with relatively short inundation and subaerial periods (high- to medium-frequency cycles of lake-playa alternation, Fig. 15.15) strongly favour geomorphic processes that tend to flatten and widen basin floors, and thus reduce the capability of such basins to contain small lakes.

Temporal domains of hydrographic change in hemiarid lake basins are historic, protohistoric, and prehistoric and consist of written records of change, archaeological evidence related to change, and change prior to human habitation, respectively. In all three temporal domains the basic tool for storing, correlating, and displaying basinwide spatiotemporal information about hydrographic change is the hydrograph (Fig. 15.16). Hydrographs have spatiotemporal coordinate systems, typically with y-axis water levels, areas, or volumes plotted as functions of x-axis time. Figure 15.16 spans historic, protohistoric, and latest prehistoric time. In accordance with graphical norms, time is plotted flowing from left to right.

Hypsographs have spatial coordinate systems but can also display selected spatiotemporal information (Fig. 15.17). Dimensionless spatial coordinates derived from indices of comparative water body morphometry facilitate direct size comparisons of present and past water bodies in one or more basins (Benson and Paillet 1989, Bengtsson and Malm 1997). Two such indices are the palaeolake height index (PHI), where ϕ is a water body's depth at a particular time as a fraction of its greatest late Quaternary depth, and the palaeolake surface index (PSI), where ψ is a water body's area at a particular time as a fraction of its greatest late Quaternary area (Currey 1988). Figure 15.17 spans a greater spatiotemporal range than, and provides a basinwide frame of reference for, Fig. 15.16.

Published graphical representations of hydrographic change in hemiarid lake basins are not documents of absolute certainty and authority. Clearly, the reliability of such representations can be no better than the quality of the geomorphic information (see following chapter) on which they are based. They are most appropriately viewed as thought-provoking working hypotheses of explanation that will continue to be refined as research proceeds.

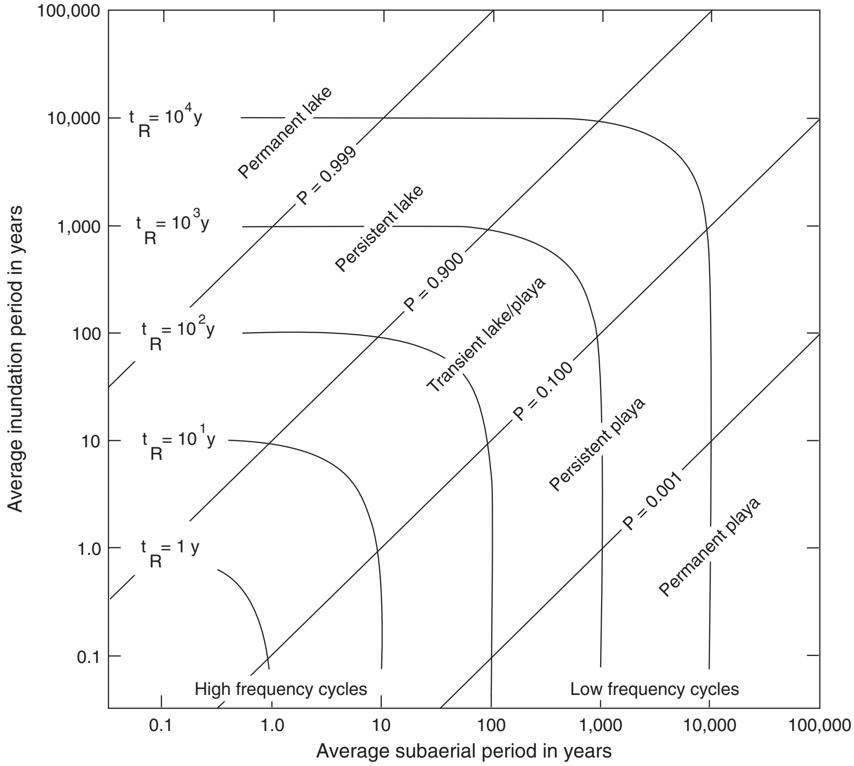

Fig. 15.15 Persistence (P) of standing water on floors of lake basins is a dimensionless number from 0.0 to 1.0 that expresses average continuous inundation period in years as a fraction of recurrence. Recurrence (t_R) is time in years of average continuous inundation period plus average continuous subaerial period (after Currey 1990). Frequencies of episodic inundation range from ultra-high to ultra-low

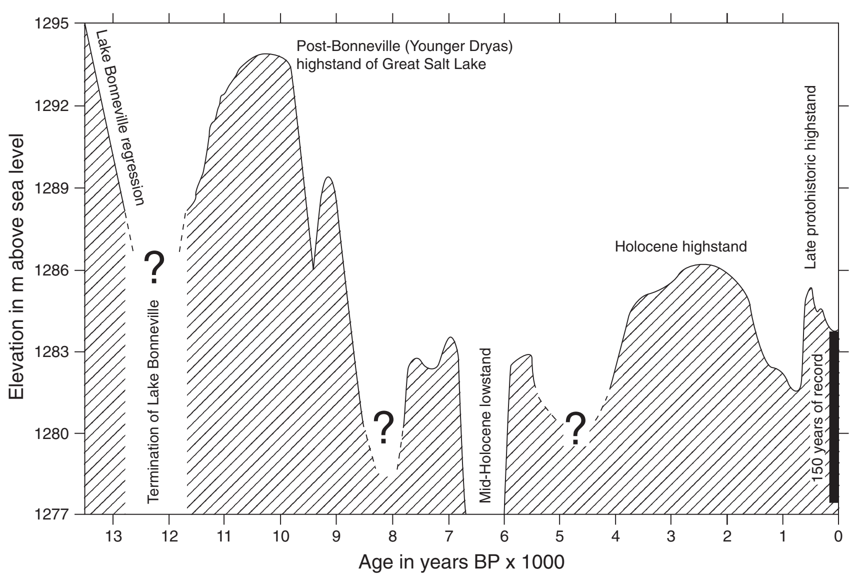

Fig. 15.16 Example hydrograph showing upper envelope of lake levels (upper limit of static water at high stages) in the basin of Great Salt Lake, Utah, during the last 13,000 years (after Murchison 1989). Lower envelope, delimiting low stages during that time, is poorly known. Earliest known human habitation in the basin occurred between 11 and 10 ka at Danger Cave (1314 m; Jennings 1957). Historic hydrologic record has been summarized by Arnow and Stephens (1990)

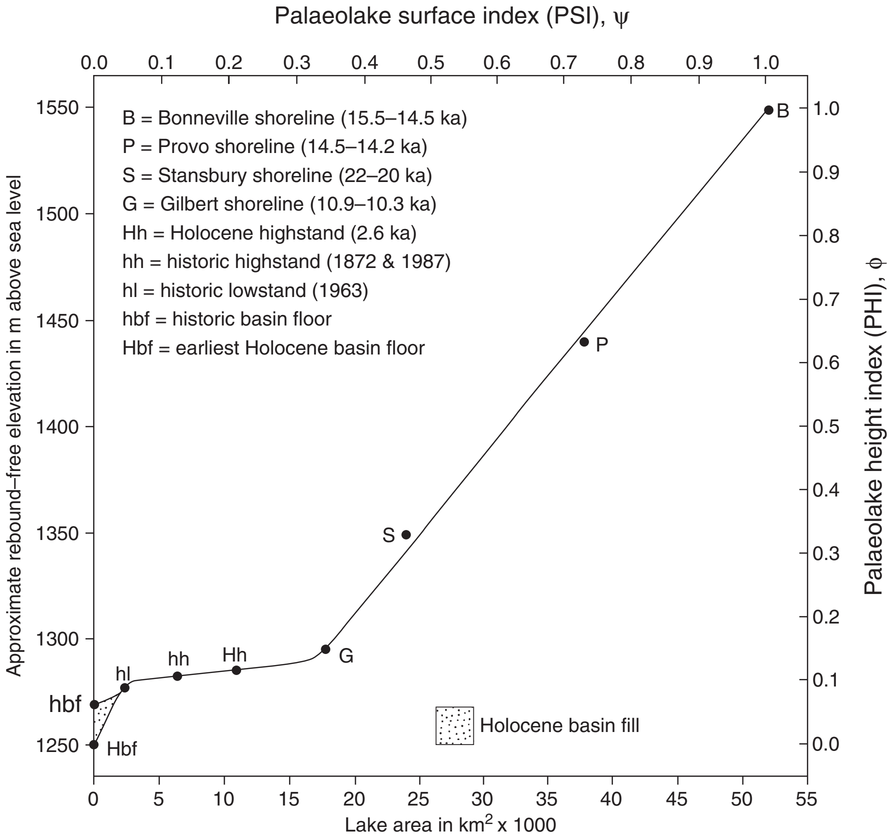

Fig. 15.17 Example hypsograph showing containment basin topography (*sloping line*) and selected late Pleistocene and Holocene lake levels (*plotted points) in the Lake Bonneville basin, western USA (after Currey 1990); chronology from Currey and Burr (1988), Oviatt (1988), Oviatt et al. (1990), and Benson et al. (1992). Estimated rebound-free elevations (Currey and Oviatt 1985) simplify basinwide studies. In this example, PHI is scaled from 0.0 on the terminal Pleistocene basin floor to 1.0 at the highest late Quaternary (threshold-controlled Bonneville) shoreline; PSI is scaled from 0.0 at no standing water, which is unlikely in this basin, to 1.0 at the Bonneville shoreline*

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