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A New Typology for Mountains and Other Relief Classes

An Application to Global Continental Water Resources and Population Distribution

A new classification of 15 relief patterns at the global scale combines a relief roughness indicator and the maximum altitude at a resolution of 30′ × 30′. Classical geographic terms have been retained but assigned to fixed relief roughness (RR = maximum minus minimum elevation per cell divided by half the cell length in meters/kilometer, or ‰) and altitude boundaries. Plains (33.2 Mkm^2 of currently nonglaciated land surface) correspond to subhorizontal terrain (RR < 5‰). Lowlands (19.2 Mkm; 0–200 m) have a very low degree of roughness (5 <RR <20‰). Platforms and hills (30.5 Mkm^2) correspond to the 200–500-m mean elevation class and have a greater degree of roughness (RR > 20‰). Plateaus (16.8 Mkm^2), with mean elevations between 500 and 6000 m, have a medium degree of roughness (RR from 5 to 40‰). Mountains (33.3 Mkm^2) are differentiated from hills by their higher mean elevation (>500 m) and from plateaus by their greater roughness (>20‰ then >40‰) in each elevation class. Accordingly, Tibet and the Altiplano are very high plateaus, not mountains. These quantitative definitions of relief patterns were divided into 15 classes, then clustered into 9 main types and mapped at the global scale at a resolution for which water runoff depth and population were previously determined. We also differentiated between exorheic areas (115.6 Mkm^2 globally) and endorheic areas (17.36 Mkm^2 globally) of potential runoff. Mountains thus account for 25% of the Earth's total land area, 32% of surface runoff, and 26% of the global population. The presence or vicinity of a rough and elevated landscape is less limiting to human settlement than water runoff.

Keywords: *Mountain typology; relief roughness; relief classes; global water resources; global population.*

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Introduction

Mountains have a unique position in the Earth system. They are generally believed to be the world's water towers (Liniger 1995; Liniger et al 1998; Price et al 2000), to generate most of the particulate and dissolved material resulting from erosion (Milliman and Syvitski 1992; Meybeck 1979), and to be particularly sensitive to climate change due to marked altitudinal gradients. Geologists also regard mountains as specific areas of past and present tectonic activity. Yet mountains and other major relief types such as plains, hills, and plateaus are only loosely defined in geographic textbooks and encyclopedias (Fairbridge 1968 a, b, c; Goudie 1985), as pointed out by Gerrard (1990). The recent development of global data sets at very high resolutions now allows us to reconsider how mountains are defined and to articulate a more quantitative assignment of their key attributes.

Kapos et al (2000) published a global map of mountains based on a combination of elevation and slope at a very fine resolution. They gave an operational definition of 6 mountain categories ranging from 300 to 1000 m to more than 4500 m above mean sea level (MSL), with the aim of establishing a typology of mountain forests and their distribution. Our work is similar, although at a coarser resolution, from which we also derived distribution of water balance and population. We propose a working definition of 15 relief classes and subclasses, ranging from plains to mountains, based on a simple relief roughness indicator and on mean elevation in 30′ × 30′ cells. A first application of this typology is presented for water runoff and population distribution for both external and internal drainage areas of the nonglaciated landmass.

Global data bases

Geomorphology

The elevation data are derived from the GTOPO30 1-km digital elevation model (DEM) (Edwards 1989; US Geological Survey [USGS] 1996). The DEM was aggregated to a 0.5° resolution with an algorithm (ARC/INFO; ESRI) that determined a maximum topographic gradient as well as provisional direction of flow, with manual corrections when necessary, based on comparison with maps and atlases. The potentially discharging river network was already analyzed at the global scale (Vörösmarty et al 2000a,b). The currently glaciated areas of Greenland and Antarctica are not considered here, but local alpine-type glaciers are included. The Caspian and Aral Seas are considered here as "regional seas" and are not counted as parts of the continental landmass. All other lakes, including the largest, such as Lake Victoria and the North American Great Lakes, are considered as part of the landmass.

The distinction between endorheic (internal) and exorheic (external) drainage is based on the potential drainage; arheism (absence of drainage) is not taken into account. The Kerulen Basin (Mongolia), which is occasionally connected to the Amur Basin, has been considered here as part of the latter system, although classical Soviet literature defines it as a distinct endorheic basin (Korzoun et al 1978).

Contemporary runoff at 30′ grid resolution (latitude × longitude) was computed by a water balance model (WBM) constrained by monitoring data and converted to discharge by integrating along digitized rivers (Vörösmarty et al 1998; Fekete et al 1999). The data set was developed utilizing a gridded river network at 30-minute spatial resolution to represent the riverine flow pathways and to link the continental landmass to oceans through river channels. More than 630 selected

TABLE 1 Global distribution of relief roughness and examples (nonglaciated land).

Roughness class (‰)	Total area Mkm²	%	Typical examples (Europe; Asia; Africa; North America; South America; Australasia)
<5 (subhorizontal)	33.2	25.0	Western European plains; Caspian lowlands, West Siberian Plain, Great China Plain, Mandchu Plain, Kysil Kum, Karakorum, Takla Makan, Junggar Pendi, Indo-Gangetic Plain, Mesopotamia, Rhub al Kali; Senegal Plain, Tindouf Basin, Chad Basin, Sudd, Congo Basin, Kalahari; Gulf of Mexico coastal plain, North American plains; Llanos, Central Amazon Basin, Gran Chaco, Pampa; Gibson Desert, Nullarbor Plain, Simpson Desert, Murray Basin
5–10 (very flat) 10–20 (flat)	25.9 23.7	19.5 17.8	Brittany, south Sweden; Deccan, Gobi Desert, Nedj Plateau, Zereh Depression, Thar desert; Fezzan, Great Erg, Katanga, East African Lakes Plateau, South African Veld; Labrador, Great Plains; Mato Grosso, Tumuc Humac; MacDonnell Ranges, Barkly Tableland, Kimberley Plateau
20–40 (poorly dissected) 40–80 (moderately dissected)	22.4 19.5	16.8 14.7	Iceland, Massif Central, Spain, central Sweden, Carpathian Mts, Ural; Central Siberian Plateau, Iablonov Mts, Anadyr Plateau, Aldan Plateau, Sikhote Mts, Great Khingan, Outer Mongolia, Tibet, Tsaidam, Yunnan, Wuyi Shan, Burma, W and E Ghats, Borneo, Iran Plateau, Armenian Plateau, Anatolian Plateau, Hadramaut; Tellian Atlas, Hoggar, Tibesti, Adamawa, Namib Desert, Drakensberg, Zimbabwe, Ethiopian Plateau; Interior Plateau, Stikine Plateau, Appalachian Mts, Great Basin, Columbia Plateau, Colorado Plateau, Mexican Plateau, Sierra Madre Orientale; Pacarima Mts, Sierra de Espinhaço, eastern Patagonia, Altiplano (Bolivia); Australian Alps, Australian Cordillera, New Zealand Alps
80–160 (highly dissected)	7.7	5.8	Pyrénées, European Alps, Dinarides, coastal Norway; Pontorana Mts, Verkhoiansk Range, Tcherski Range, Kamchatka, Stanovoi Plateau, Stanovoi Range, western Saian Range, Tien Shan, Pamir, Hindu Kush, Kuen Luen, Altyn Tagh, Qilian Shan, Sulaiman Range, Kashmer, Zagros Mts, Elbruz, Great Caucasus, Little Caucasus, Taurus, Asir; Ethiopian Highlands, High Atlas; Brooks Range, Alaskan Range, Mackenzie Mts, Coastal Range (British Columbia to Oregon), northern, middle, and southern Rockies, Sierra Nevada (CA), Sierra Madre Occidentale, Sierra Madre del Sur; Coastal Cordillera of the Andes, Eastern Cordillera of the Andes; Maoke Mts (PNG)
>160 (extremely dissected)	0.6	0.4	Parts of the European Alps; most of the Himalayas, parts of Pamir and Karakorum; parts of the Alaskan Range; parts of the Andes
All classes	133	100	

gauging stations from the Global Runoff Data Center data archive in Koblenz were coregistered to a simulated topological network (STN-30p) developed at the University of New Hampshire. Interstation regions between gauging stations along the STN-30p network were identified. Interstation discharge and runoff were calculated from the WBM and compared with observed runoff. Correction coefficients based on the ratio of observed and simulated runoff for interstation areas were calculated and applied against simulated runoff to create best estimates of composite runoff fields.

Population density

The population data base at 0.5° resolution was derived from a 1-km gridded polygon file (ESRI 1995) that defined the spatial extent of 242 countries for which 1995 country-level population statistics were available (World Resources Institute [WRI] 1996). Country-level urban population was spatially distributed among a set of geolocated city polygons with demographic data ($n = 1858$) (Tobler et al 1995) and across 1-km pixels classified as city lights from remote sensing (Elvidge et al 1997a,b). Rural population was distributed uniformly among digitized points in populated places (Environmental Research Systems Institute [ESRI] 1993) outside urban spatial extents. A total of 5.7 billion people are represented on the 0.5° digitized global landmass, accounting for 99.7% of the total global population reported (WRI 1996).

Discussion: geomorphology and hydrology

Analysis of relief roughness at the global scale

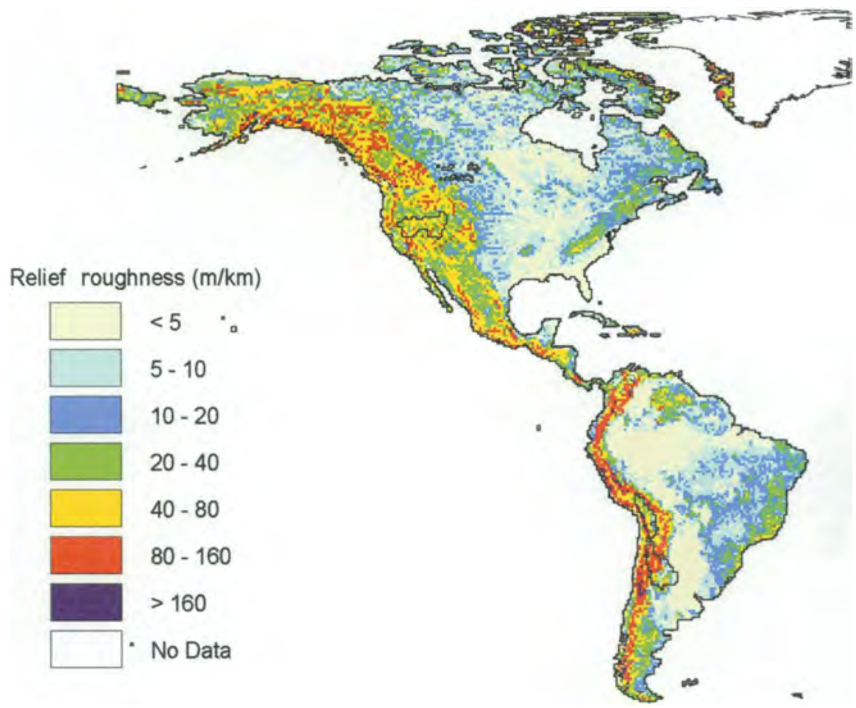
We focus here on the description of relief roughness at the global scale, ie, on how to characterize mountain ranges rather than individual mountains or hills. Relief roughness (RR) is defined here in operational terms as the difference between maximum and minimum elevation, at a 1-km resolution from the GTOPO30, in a $30' \times 30'$ cell of land, divided by half the cell length connecting the center of each grid cell, depending on latitude and direction of flow (Vörösmarty et al 2000a,b). The roughness has a slope dimension in meters/kilometer, or ‰, and varies from less than 1‰ to 399‰. As roughness distribution is heavily skewed toward the lower classes, we adapted a geometric progression in 7 classes, from subhorizontal to extremely dissected terrains (Table 1). Their geographic distribution is presented in Figure 1.

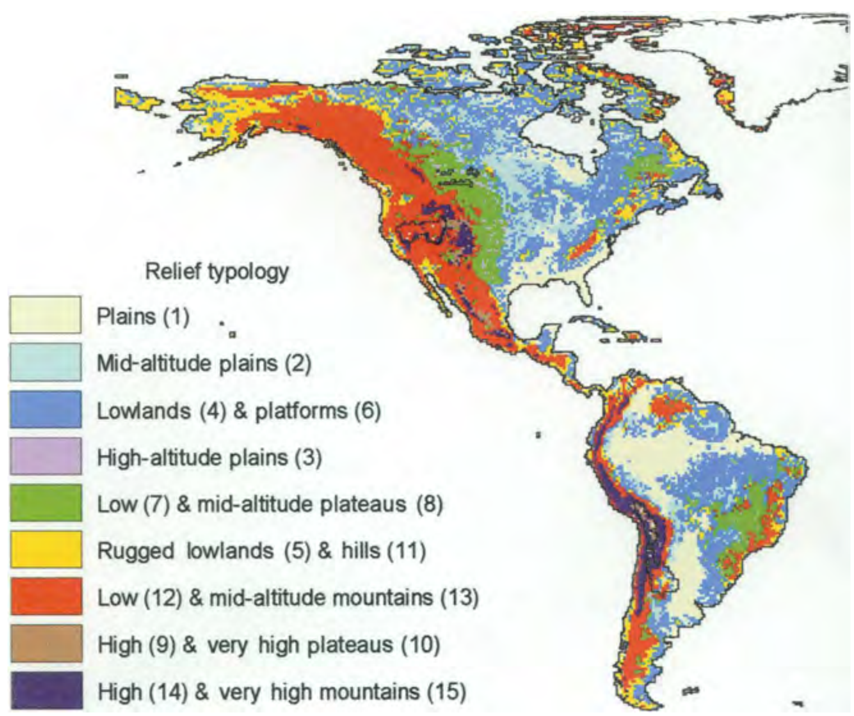
The subhorizontal terrains (RR < 5‰) represent 33.2 Mkm^2 of a total of 133 Mkm^2 of nonglaciated land, ie, 25% of the landmass. They are found on all continents, generally at very low elevations, but also at higher elevations in Central Asia (Takla Makan, Junggar Pendi Depression) and Africa (Kalahari).

Very flat (5 < RR < 10‰; 19.5% of the landmass) and flat (10 < RR < 20‰; 17.8% of the landmass) terrains are difficult to differentiate from one another (Figure 1) but are clearly distinct from subhorizontal terrains, as in eastern Canada, the Mato Grosso, Central Siberia, and Central Australia. In the geographic literature, they are variously referred to as plains, basins, velds, plateaus, and deserts.

Poorly dissected (20 < RR < 40‰; 16.8% of the landmass) and moderately dissected (40 < RR < 80‰; 14.7% of the landmass) terrains are generally found in clustered cells and are termed hills, mountains, plateaus, ghats, and cordilleras.

Highly dissected terrains (80 < RR < 160‰; 5.8% of the landmass) are not found on all continents. They are closely associated with the most recent alpine orogenesis in Europe, Asia, Australasia, and the Americas or with mountains rejuvenated during this period, such as the Rocky Mountains and the Eastern Cordillera of the Andes (Fairbridge 1968b). They are found in New Guinea but not in Australia; in Africa, they are only present in the High Atlas, which also corresponds to the alpine orogenesis, and in the Rift Valley. Rifting and active volcanism are the second origin of this class of relief roughness, as is the case in the Asir Range in Yemen and major volcanoes in the circum-Pacific belt (in Japan, Mexico, the Andes), in Java and Sumatra, Cameroon,





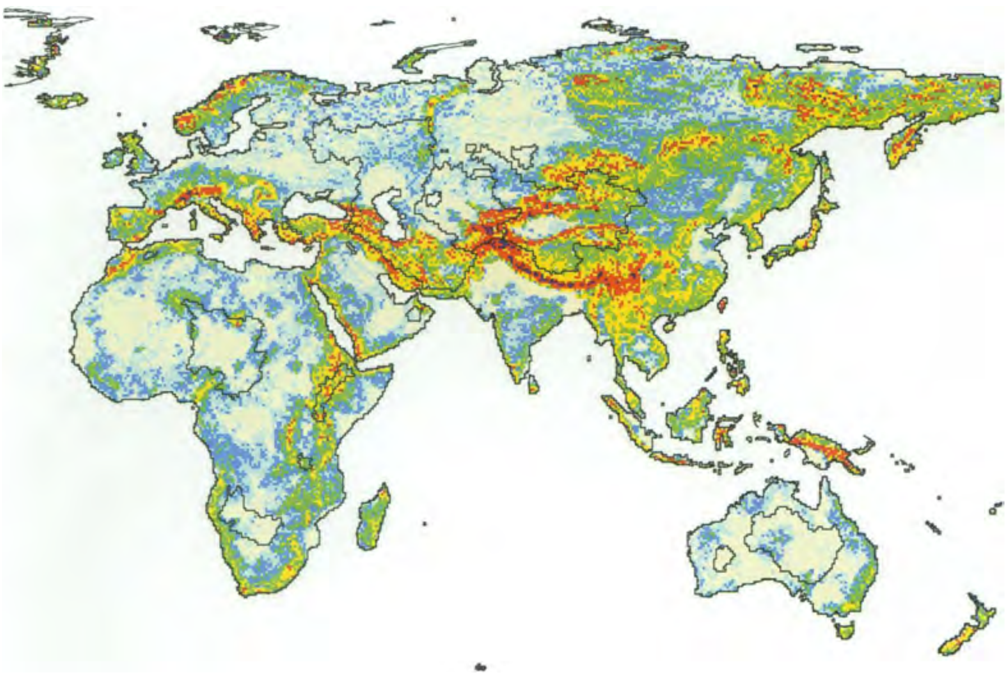


FIGURE 1 Global distribution of relief roughness (RR in ‰) at a resolution of 30′ × 30′. Endorheic regions are delineated for each continent.

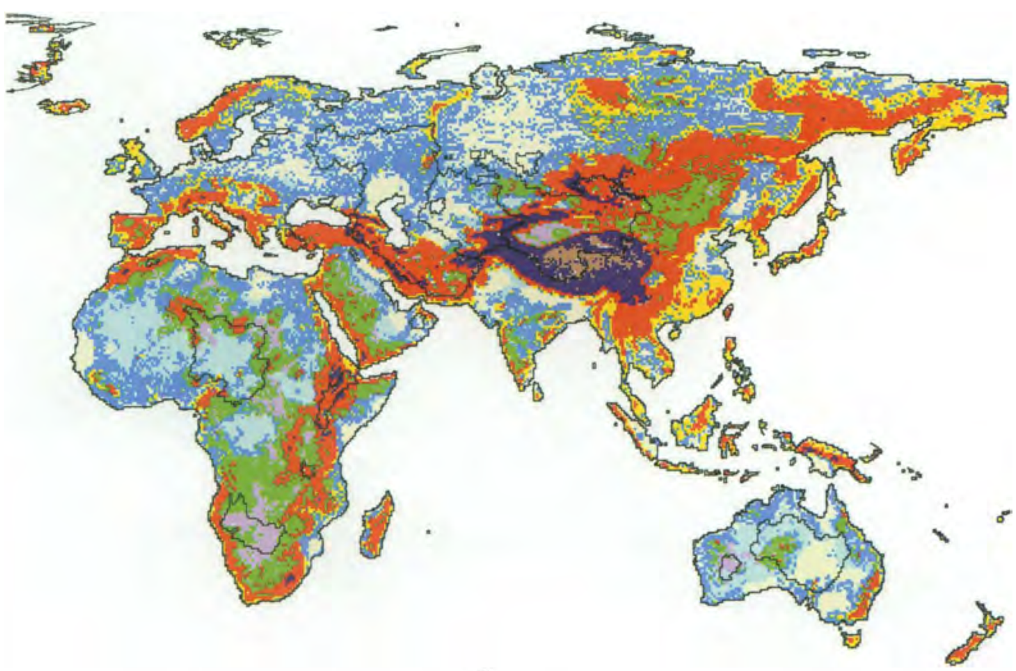


FIGURE 2 Global distribution of 9 aggregated relief types from the 15 classes defined in Table 2, at a resolution of 30′ × 30′. Limits of endorheic basins are also indicated. Numbers refer to the relief classes presented in Tables 2 and 3.

TABLE 2 Global occurrence (M km^2) of relief roughness (RR in ‰) with mean elevation (in meters) in cells at a resolution of 30', and the 15 principal clusters defining relief classes of nonglaciated land (see also Table 3 and Figure 2)[a]

Relief roughness (‰)	Mean elevation (m) 0–200	200–500	500–1000	1000–2000	2000–3000	3000–4000	4000–5000	5000–6000	Total (Mkm^2)
> 160		0.04	0.05	0.15 (13)	0.11 (14)	0.13 (14)	0.08 (15)	0.01 (15)	0.57
80–160	0.04	0.45 (11)	1.57 (12)	2.95 (13)	1.35 (14)	0.68 (14)	0.53 (15)	0.08 (15)	7.65
40–80	0.70 (5)	3.92 (11)	5.90 (12)	6.13 (13)	1.28 (14)	0.42 (14)	0.81 (15)	0.30 (15)	19.46
20–40	3.43 (5)	7.11 (11)	6.47 (12)	4.30 (13)	0.43 (9)	0.09 (9)	0.41 (10)	0.19 (10)	22.43
10–20	5.66 (4)	8.76 (6)	6.31 (7)	2.87 (8)	0.08 (9)	0.02 (9)	0.05 (10)	0.03 (10)	23.78
5–10	9.34 (4)	10.21 (6)	4.71 (7)	1.57 (8)	0.01	0.01			25.85
< 5	18.74 (1)	11.12 (2)	2.26 (3)	1.11 (3)	0.01				33.24
Total (Mkm^2)	37.91	41.61	27.27	19.08	3.27	1.35	1.88	0.61	133.01

[a](1) Plains, (2) mid-altitude plains, (3) high-altitude plains, (4) lowlands, (5) rugged lowlands, (6) platforms, (7) low plateaus, (8) mid-altitude plateaus, (9) high plateaus, (10) very high plateaus, (11) hills, (12) low mountains, (13) midaltitude mountains, (14) high mountains, (15) very high mountains.

and Kenya. The third origin is linked to glacial scour and isostatic rebound on the borders of continents in northeastern Labrador, Greenland, Norway, the Taymir Peninsula (Byrranga Range), North Central Siberia (Putorana Range), and North and East Siberia (Verkhoyansk, Cherskogo, Kolyma, and Stanovoy ranges).

The most striking feature of highly dissected terrains is their lineation, which closely follows that of most alpine ranges (Figure 1). These include the Alaska Range and the Coast Ranges of North America, from South Alaska to Oregon, the Sierra Madre del Sur in Mexico, the Coastal Cordillera of the Andes, the Alps-Dinaric Alps-Taurus-Zagros, the Little Caucasus-Elbruz, the Pamir-Tien Shan, and the Karakorum-Himalaya.

The Colorado Canyon is one rare example of highly dissected relief linked to a negative volume, while other relief features are associated with positive volumes. This canyon is associated with several joined cells with 80 < RR < 160‰.

Extremely dissected terrains (RR > 160‰; 0.4% of the landmass) are only found in the highest parts of alpine ranges, particularly in the Pamir, Karakorum, Himalaya, Andes, and Alaska Range, and in a few isolated volcanoes.

Change of relief roughness with elevation

The 7 roughness classes were combined with 9 classes of mean elevation found in each 30′ × 30′ cell. Again we assumed a geometric increase in elevation, with classes from 0 to 200 m, 200 to 500 m, 500 to 1000 m, and then every 1000 m (Table 2). At this resolution, the mean elevation is preferable to the maximum elevation because it smoothes the relief variability, particularly when few local single mountains such as volcanoes are present in flat land, especially in endorheic regions. A previous attempt at classification using maximum elevation in cells showed less regionalization of the classes; 2 and even 3 classes were frequently merged in one in a given geographic entity.

The general pattern is an increase in roughness with elevation. Subhorizontal terrains (RR < 5‰) are rarely found (<0.03 Mkm^2) at mean altitudes above 2000 m. Conversely, the highly dissected terrains (RR > 160‰) are practically unknown below 1000 m (<0.13 Mkm^2). Subhorizontal terrains are largely located at low elevations (0–500 m), but there is still 3.41 Mkm^2 of subhorizontal land between 500 and 1000 m. In the lower elevation classes (200–1000 m), 6 classes of roughness have enough grid cells to be mapped. But above 2000 m, this is true for only 3–4 classes.

Proposed definitions of relief classes at the global scale

We defined and named 15 major relief classes according to various combinations of roughness and elevation. Out of 56 possible combinations, 30 combinations cover 99% of the currently nonglaciated land (Table 2). They can be clustered into 15 types or subtypes, using 6 classical geographic terms: plains, lowlands, platforms, hills, plateaus (or plateaux; Fairbridge 1968c) and mountains (Table 2). The remainder of the continents (<1% of the global area) was aggregated with these 15 types. For example, the few cells (0.04 Mkm^2) of flat area (5 < RR < 10‰) that exceed 2000 m were aggregated with very high plateaus in our global statistics, yet the typical roughness of very high plateaus is between 10 and 40‰. Aggregation of the 15 main classes that resulted from the 30 potential classes was effected after several mapping tests and consideration of the classical geographic literature, particularly atlases.

- Plains are defined here primarily by their subhorizontal relief. They have been subdivided into 3 categories (low, midaltitude, and high plains) according to their average elevation.

- Lowlands are restricted here to the lowest area of the continents (200 m maximum mean elevation). Lowlands and rugged lowlands are still very close to plains, and their relatively greater roughness can be due to minor or moderate valley incisions.
- Platforms are defined here by their intermediate altitude (200–500 m) and roughness (5–20‰). They can be considered as very low altitude plateaus.
- Plateaus correspond with low or medium roughness in each of the maximum elevation categories. At 500–1000 m, the low plateau corresponds to very flat terrain. Roughness gradually increases to the poorly dissected level for high plateaus above 2000 m.
- Hills correspond to all rough terrains ($20 < RR < 160$‰) at low altitude (200–500 m mean elevation).
- Mountains are defined by their mean elevation, which should exceed 500 m in any cell, and by their roughness. Roughness exceeds 20‰ at low and medium altitudes (500–2000 m) and 40‰ at high and very high altitudes (2000–4000 m and 4000–6000 m).

Due to major differences in definitions of mountains, the aims and approach of Kapos et al (2000) are somewhat difficult to compare with those of our study with regard to both mountain distribution and statistics. Kapos and her colleagues defined 6 mountain types, according to altitudinal range: (1) 300–1000 m, with local elevation range >300 m; (2) 1000–1500 m, with slope ≥5° or local elevation range >300 m; (3) 1500–2500 m, with slope ≥2°; (4) 2500–3500 m; (5) 3500–4500 m; and (6) ≥4500 m. They used the GTOPO30 digital elevation model to generate slope and local elevation range (5-km radius) on a 30 arc-second grid. Their resolution is therefore much finer than ours. Their category for lower mountains is very similar to our hills and low mountains. The major basic discrepancy between our work and theirs is our differentiation between high and very high plateaus and mountains. As slope is no longer a determining factor above 2500 m in their classification, the Altiplano (Peru/Bolivia) is considered a mountain. The same is true for many regions of Central Asia classically termed plateaus, such as Tibet. By our definition, mountains represent 33.3 Mkm^2, as against a total of 35.8 Mkm^2 for Kapos et al. If high and very high plateaus as we define them are added to our total, our figure rises to 34.7 Mkm^2.

Previous definitions of mountains

Both the definitions suggested by Kapos et al (2000) and ourselves differ greatly from the largely qualitative classical definitions of mountains, plains, hills, and plateaus, which are quite imprecise and relative. Gerrard (1990) undertook an excellent and very detailed review of existing definitions of mountains, originally based on altitude and morphology, then on generic factors (similar to the mountain systems used in the geological community), and more recently on climatic factors using criteria such as snow line, cryonival processes, and treeline. As he rightly pointed out, "The altitude alone is not sufficient to define mountains. The high plateaux of Bolivia and Peru and the high interior of the Tibetan Plateau are not mountains or mountainous area." Following some of his predecessors such as Price (1981, quoted by Gerrard), he insists that dissection is as much a major criterion of mountain definition as altitude.

In Goudie's (1985) *Encyclopaedic Dictionary of Physical Geography*, mountains are defined as "substantial elevations of the earth's crust above sea level which result in localized disruptions to climate, drainage, soils, plants and animals." There is no semantic distinction made between old eroded mountain ranges, which sometimes do not exceed 1000 m, and the world's highest mountains.

A plateau is either defined as an "elevation with a flat top" (Derruau 1968) or as an extensive area of relatively flat land in an area of high relief (Goudie 1985). Fairbridge (1968c) defines plateaus (or plateaux) as "table-lands or high level regions" and makes a distinction between intermontane plateaus, such as Colorado, Tibet, and Pamir, and the marginal plateaus of the Appalachian Plateau. Another category consists of the lava plateaus (Columbia Plateau, Deccan Plateau, Ethiopian Plateau). Fairbridge also considers steep margins of high plateaus, such as the Western Ghats of the Deccan, to be mountains.

According to the *Oxford English Dictionary* as quoted by Derruau (1968), hills have an elevation under 2000 feet (600 m) and "mountains are a natural elevation ... rising more or less abruptly from the surrounding level and attaining an altitude which is impressive or notable." Yet "mountains have height superior to that of a hill" (*Encyclopaedia Britannica*, quoted by Derruau). For some authors, the maximum hill altitude is 700 m (Temple 1972; Brunoden and Allison 1986, both quoted by Gerrard 1990).

According to Mescherikov (1968), a plain is "an area of land surface featuring small difference in topographic elevation" or a "flatland." Among the examples of "plains" given by this author are the East Siberian Plateau, the Caspian Lowlands, the South African Veld, and the North American Plains. He makes no marked distinction between plains, plateaus, and upland platforms.

For Fairbridge (1968b), a mountain also has a geological connotation related to its tectogenesis: it is a geological structure that has been disturbed through folding, uplift, or volcanism. In his article on mountain systems, Fairbridge also divides the world's mountains into 5 main orogeneses: Caledonian, Hercynian, Mesozoic, Caenozoic, and Alpine.

Our approach does not contradict these various definitions, particularly the definition of a plateau, which we believe should relate to the surrounding mountain range, as in the case of Tibet. We have not considered definitions strictly according to climatic criteria, such as the Pleistocene snow line or the tree line (Hollerman 1973, quoted by Gerrard 1990) since some tropical high mountains (eg, most of the Andes or New Guinea) do not have this mountain landscape (Gerrard 1990). As suggested by Gerrard, we have combined relief roughness, a major cause of most river fluxes of dissolved and particulate material, and elevation.

Relief typology

From the 15 main classes defined in Table 1, we further aggregated some very similar classes that were sometimes embedded on maps without any marked geographic entity, such as lowlands and platforms or high and very high plateaus, constituting 9 supertypes that were subsequently mapped (Figure 2).

Although we applied a purely quantitative approach, many of our relief classes also have a generic connotation and are highly aggregated in the global distribution map, corresponding to many landscape entities as they are generally defined today. As determined by their subhorizontal surface, plains include alluvial plains or basins (the Amazon, Mississippi, Volga, Chang Jiang or Yangtze, Indo-Gangetic, and Tarim Basins), dry lake basins (Chad, Eyre), and coastal plains (Florida). Lowlands have very similar origins, although they are not absolutely flat due to river valley incision or sand dune accumulation. Hills and low mountains have multiple origins and are found in formerly glaciated areas (East Labrador, Scandinavia, Scotland, Byrranga Range). They also result from erosion of the oldest mountain ranges, as in central and eastern Siberia, the Appalachians, southeastern China, and many parts of Africa. High and very high mountains are essentially linked to alpine orogenesis or to the rejuvenation of mountains during this period. Our definition of plateaus largely follows the Fairbridge (1968c) classification of marginal plateaus in China and North America, intermontane plateaus (the Colorado, Altiplano, East African lakes, Iran, Gobi, Tibet, Anatolia), and lava plateaus (the Columbia River, Deccan, Ethiopia). Relief roughness (Figure 1) is indeed a good indicator, resulting from a combination of the balance between surface erosion, sediment transfer, sediment deposition, tectonic uplift, and previous glacial erosion.

TABLE 3 Global distribution of relief classes in endorheic and exorheic regions, with corresponding surface runoff, population, and population density (mean elevation in cell).

Relief classes[a]	Total area[b,c] (Mkm²)	Exorheic areas[c] (Mkm²)	Endorheic areas[c] (Mkm²)	
1 Plains	18.74	16.33	2.41	
2 Mid-altitude plains	11.12	8.81	2.31	
3 High-altitude plains	3.37	2.57	0.8	
4 Lowlands	15.01	13.56	1.44	
5 Rugged lowlands	4.18	4.08	0.1	
6 Platforms	18.97	17.31	1.67	
7 Low plateaus	11.01	9.58	1.43	
8 Mid-altitude plateaus	4.44	4	0.44	
9 High plateaus	0.64	0.42	0.22	
10 Very high plateaus	0.68	0.29	0.39	
11 Hills	11.52	11.12	0.4	
12 Low mountains	13.99	12.85	1.14	
13 Mid-altitude mountains	13.53	11.02	2.51	
14 High mountains	3.98	2.53	1.45	
15 Very high mountains	1.82	1.17	0.65	

[a]See definitions in Table 2.
[b]With minor adjacent areas (see text).
[c]Vörösmarty et al (2000a,b).
[d]Vörösmarty et al (2000c).

Exorheism, endorheism, and global relief distribution

Mountains are generally regarded as the major providers of river-borne material to the oceans (Meybeck 1979; Milliman and Syvitsky 1992; Ludwig et al 1996). Any computation of river inputs to oceans needs to take account of where mountains are located with regard to the connection between land and ocean. They may be facing oceans (external drainage or exorheism) or facing internal drainage basins (endorheism), as in the case of the Caspian Basin, Central Asia, the Chad Basin, the Bolivian Altiplano, the Great Basin, and the Lake Eyre Basin.

We combined the boundaries of exorheic runoff, as defined by the potential runoff of world rivers at a resolution of 30′ (Vörösmarty et al 2000a,b), and the distribution of relief types (Table 2). These boundaries are indicated in black in Figures 1 and 2. The nonflowing or arheic regions, defined here in terms of an annual runoff of less than 3 mm/y, are distributed between exorheic and endorheic areas but are not specifically identified here. In existing global hydrology publications, the arheic regions are generally mapped separately or aggregated with endorheic regions (Korzoun et al 1978). The Kerulen River in Mongolia was considered

	Exorheic runoff[c] (km^3/y)	Endorheic runoff[c] (km^3/y)	Exorheic runoff depth[c] (mm/y)	Endorheic runoff depth[c] (mm/y)	Population in exorheic areas[d] (millions)	Population in endorheic areas[d] (millions)	Population density in exorheic areas[d] (p/km^2)	Population density in endorheic areas[d] (p/km^2)
	6724	80	412	33	911	34.4	55.8	14.3
	1077	0	122	0	167	22.5	19.0	9.7
	211	0	82	0	22	8.0	8.4	9.9
	4558	137	336	95	827	41	60.9	28.4
	2089	19	512	202	489	5.6	119.9	58.9
	3723	73	215	44	500	27.6	28.9	16.6
	1592	37	166	26	235	11.7	24.5	8.2
	513	6	128	14	115	8.3	28.9	18.8
	34	12	81	53	21	5.4	50.1	24.2
	42	38	147	97	7	2.3	25.8	5.9
	4946	41	445	103	743	14.5	66.8	36.2
	5567	72	433	64	576	34.6	44.8	30.3
	4585	163	416	65	443	107	40.2	42.7
	1116	182	442	125	163	52.6	64.4	36.3
	421	78	358	120	97	8.1	83.0	12.5

here as part of the Amur Basin, but the Okawango Basin was separated from the Zambezi River. These basins alternate between endorheism and exorheism, depending on climatic conditions. Exorheic regions currently represent 115.6 Mkm^2, or 87% of the nonglaciated landmass.

When all relief classes are taken together, the global proportion of endorheic regions is 13% of the total surface of the Earth. The distribution of exorheic and endorheic regions in some relief classes varies a great deal with respect to this global proportion (Table 3):

- Lowlands, rugged lowlands, platforms, and hills are somewhat more abundant in exorheic regions (93% exorheic versus 7% endorheic, compared with the average of 87% versus 13%). This discrepancy could be attributed to the more organized surface water network that carries away erosion products in exorheic regions, while in the drier endorheic regions, erosion and weathering products may remain on site or be accumulated by aeolian transport. Another possible explanation is that these classes could be linked to old eroded mountain ranges, possibly more abundant in exorheic drainage regions. Both these hypotheses need to be verified.
- High and very high plateaus are greatly overrepresented in endorheic drainage regions (46% endorheic as opposed to the global average of 13%). This overrepresentation is due to the many high plateaus in Central Asia and the Bolivian Altiplano.
- High and very high mountains are also overrepresented in endorheic regions (36% endorheic versus 13%) for the same reason: most of the Tien Shan and the Altai, all of the Pamir, and parts of the Karakorum and the Andes drain toward internal regions. The Himalaya basically drains to the oceans, thanks to the Indus and Brahmaputra rivers, both of which penetrate very deeply into this mountain range.

Relief types and surface runoff

The sum of surface runoff in each 30′ cell was computed for each relief type and was divided by its total corresponding area to give an average of runoff depths, in millimeters/year, for each relief area. Water runoff in exorheic regions around the world was differentiated from runoff in endorheic regions, excluding glaciated areas in Greenland and Antarctica (Table 3).

Globally, endorheic regions are much drier, with an average runoff of 54.1 mm/y, compared with 321.5 mm/y for exorheic regions. The difference between endorheic and exorheic areas is noted for every type of relief. For instance, plains in endorheic regions are extremely arid, with precipitation between 0 and 33.8 mm/y, compared with 82–412 mm/y for exorheic plains. When both endorheic and exorheic runoff are plotted against each other for all relief class-

TABLE 4 Global overview of major relief types with corresponding runoff amount and depth, population, and population density at a relief roughness resolution of 0.5° (mean elevation in cell).

	Area (km²)	Runoff (km³/y)	Runoff depth (mm/y)	Population (millions)	Population density (p/km²)
Exorheic regions					
Total/average	115.64	37,198	322	5315	46
Low + flat[a]	62.67	18,382	293	2915	46.5
Plateaus[b]	14.29	2182	153	379	26.5
Hills[c]	11.12	4946	445	743	67
Mountains[d]	27.57	11,689	424	1279	46
Endorheic regions					
Total/average	17.36	939	54	383	22
Low + flat	8.73	309	35	139	16
Plateaus	2.49	93	37.5	27.6	11
Hills	0.40	41	102	14.5	36
Mountains	5.75	495	86	202	35
Whole globe					
Total/average	133.00	38,136	287	5699	43
Low + flat	71.40	18,690	262	3054	43
Plateaus	16.77	2275	136	406	24
Hills	11.52	4987	433	757	66
Mountains	33.31	12,184	366	1481	44

[a]Classes 1–6 in Tables 2 and 3.
[b]Classes 7–10.
[c]Class 11.
[d]Classes 12–15.

es, the dryness of endorheic regions becomes very apparent. Endorheic flatlands have only 12% of the runoff depth of exorheic flatlands (plains + lowlands + platforms, Table 4). Endorheic mountain runoff depth is about 20% of exorheic mountain runoff depth, and endorheic plateaus and hills account for 25% of the runoff depth of exorheic plateaus, respectively, 23% of runoff depth of hills.

This well-known relative dryness of endorheic areas has multiple causes. For example, these areas are generally located in the middle of continents, far away from oceanic sources of moisture and/or beyond mountain ranges that block atmospheric precipitation on their external side. From hills (200–500 m) to high mountains (2000–4000 m), mean elevation is not a major cause of runoff depth at the global scale. Water runoff depth does not vary much in these categories in either exorheic (400 ± 40 mm/y) or endorheic regions (95 ± 30 mm/y). But relief roughness could be one major cause of water runoff in the exorheic regions.

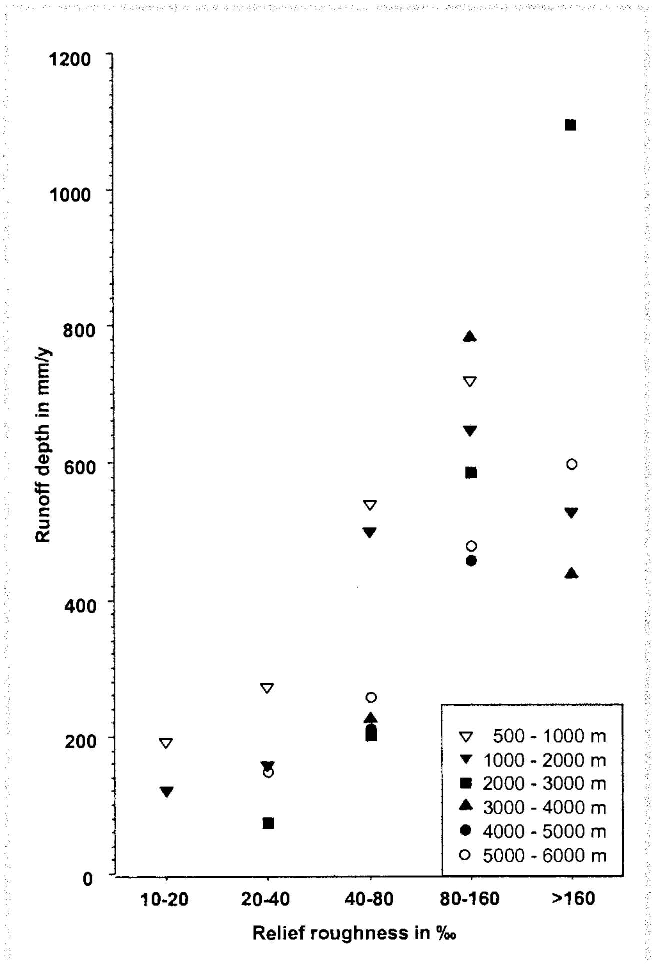
When average global runoff depth is considered in a given maximum elevation class above 500 m in the exorheic regions, there is a general increase in runoff depth with relief roughness in any elevation class (Figure 3) except for RR > 160‰. The well-known orographic gradient with increasing elevation between 5 and 750 mm/100 m (Liniger et al 1998) could be related more closely to relief roughness than to altitude. This hypothesis should be carefully tested for individual mountain ranges since the great heterogeneity of mountain climates at the global scale, ranging from subarctic to equatorial, probably masks relief–runoff relationships at the local scale. Endorheic regions do not present this general relationship.

Discussion: Population density

Distribution of global population according to relief classes

Population distribution at a resolution of 30′ was recently established on the basis of national census and nocturnal light emission (Vörösmarty et al 2000c). The total population for each relief class was computed from this data base for both endorheic and exorheic

FIGURE 3 Global water runoff depth versus relief roughness in the exorheic regions for 6 classes of mean elevation (30′ resolution).



runoff (Table 3); also calculated was the average population density at the global scale for each relief type (total population divided by total area).

Again there is a difference between endorheic and exorheic areas, although it is less important than one might expected. The overall exorheic density is only twice the overall endorheic density, 45.9 versus 22.1 people/km^2 (p/km^2).

When considering population distribution in detail, it is obvious that density at the global scale is not primarily linked to relief types. Plains and lowlands can either be extremely populated, as is the case in India and East China, or have very low population densities, as in the Central Congo Basin, Amazon Basin, Northern Siberia, and North Central Canada. Actually, at the global scale, plains, hills, lowlands, low, high, and very high mountains are associated with population densities exceeding the world's average—from 56 to 120 p/km^2 for exorheic regions. In endorheic regions, the population density in lowlands, hills and low to high mountains is higher (28 to 59 p/km^2) than the global average and much lower (<15 p/km^2) in plains. According to our data, there are 115.2 million people living in cells with mean altitudes exceeding 4000 m (30′ resolution), ie, they may live in deep valleys between 3000 and 4000 m with summits exceeding 5000 or 6000 m or on very high plateaus such as the Altiplano and Tibet.

At the global scale, population density seems to be closely linked or proportional to water runoff when the continents are partitioned and reaggregated into the 15 basic relief classes (Figure 4). There is a marked increase in population density with increasing runoff in both endorheic and exorheic regions.

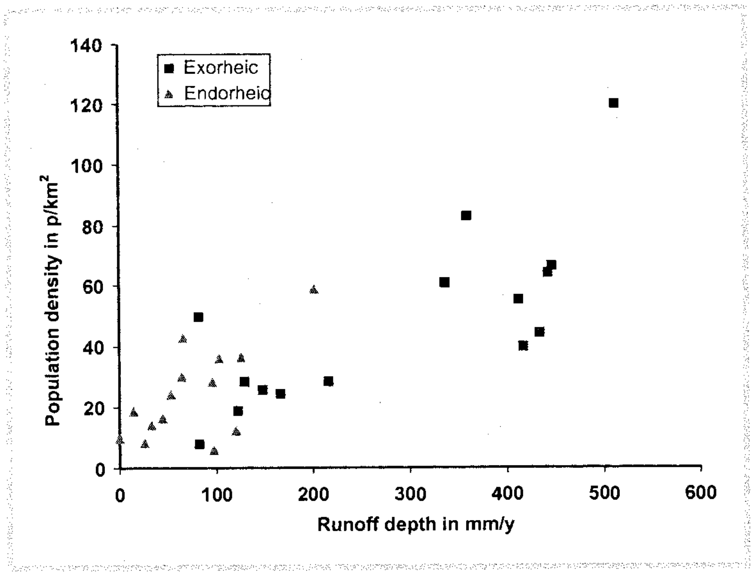
Conclusions and perspectives

Global databases and GIS tools allowed us to propose a classification of gross relief types at a resolution of 30′ × 30′. Our original target was to establish an operational definition of mountains that would allow global mapping of water resources in mountains, as described in earlier works. We found that it was possible to differentiate between hills, low, midaltitude, high, and very high mountains, as well as between other relief types such as plains, platforms, and plateaus. The latter had been only loosely or diversely defined in the classical geographical literature, with the exception of the recent work by Kapos and her colleagues (2000). Our combination of both elevation and relief roughness is only a first step in analyzing relief types acceptable at the global scale. At the regional to local scale, the 30′ × 30′ resolution is probably too coarse to properly describe landforms and their relation to surface runoff distribution and population density. These relationships should now be examined for each mountain range within the context of the local climate. The following general conclusions can be drawn at the global scale.

As defined here, mountain regions of the world account for 23.8% of currently nonglaciated exorheic land surface, 31.5% of the water runoff—generated on 30′ × 30′ cells—and 24% of the global population. For endorheic regions, these figures are 33.2, 52.8, and 52.8%, respectively. In exorheic regions, mountains are relatively more humid than the global average (424 mm/y versus 322 mm/y). Plains and lowlands (293 mm/y) and plateaus (153 mm/y) are much drier, but hills are also humid (445 mm/y). In endorheic regions, where water runoff depth is 2–10 times lower than in similar relief classes, the following contrast is also found: hills (102 mm/y) and mountainous regions (86 mm/y) are more humid than plains and lowlands (35 mm/y) and plateaus (37.5 mm/y).

The global population, which has been distributed at the same 30′ × 30′ resolution in a companion paper (Vörösmarty et al 2000c), is allocated in this article to

FIGURE 4 Population density (p/km^2) versus runoff depth in exorheic (■) and endorheic (▲) regions for 15 relief classes (30′ resolution).



the 15 major relief classes in both endorheic and exorheic regions. Again, a major contrast was observed between endorheic (22.1 p/km^2 on average) and exorheic regions (45.9 p/km^2). Population density appears to be linked with runoff for the 15 relief classes in both regions, but this relationship may not hold at finer regional and local scales where other determining factors such as temperature, vegetation, health, population dynamics, and socioeconomic development play a major role. For instance, as pointed out by Vörösmarty et al (2000c), high population densities and/or megacities can also be observed in arid and semiarid regions either along the course of allochtonous rivers or where water resources are controlled or where both are the case, as in Egypt, the southwestern United States, Pakistan, and Central Asia.

At the coarser scale used here, relief roughness does not seem to be a primary limiting factor with respect to population density. However, one must not forget that, according to our definition, high mountain grid cells are characterized by an average altitude of 2000–4000 m. This corresponds to valley floors with altitudes from 1000 to 3000 m over an area of 50 km × 50 km in the middle latitudes. For our low and midaltitude mountains, the valley floors are at even much lower elevation. Some hybrid cells may also combine plains or lowlands and elevated mountains, as in northern India. Given this resolution, it is probably more appropriate to refer here to mountainous regions rather than to mountains in the strict sense.

A closer look at the data set would suggest allocation of many megacities of the world, such as Jakarta, Mexico City, Tokyo, and many cities in China, northern India, and South East Asia to low, midaltitude, and even high-altitude mountains. This explains why our population distribution accounts for 1481 million people in low to very high mountains. Finally, it must be pointed out that 88% of the population is located in low and midaltitude mountains, ie, in grid cells where the maximum altitudes probably do not exceed 1000–3000 m. They are sometimes 20–30 km away from city centers, which can be located at much lower altitudes.

We believe that our approach, which combines relief types and water runoff, can provide major new insights into the global distribution of sediment sources, transfers, and sinks, provided that new global GIS layers are available at the same resolution as lithology, rainfall energy, soil type, and lake occurrence. Human activities have already considerably altered sediment transfer through river damming worldwide (Vörösmarty et al 1997), particularly in mountain regions where sediment production is at its highest. Combining relief classes with relief genesis can also be a step forward in global morphostructural analysis. For instance, initial attempts to combine mountain age with lithological composition and river water chemistry are very promising.

Further analysis of population distribution and runoff in combination with relief and of their modification due to climate change and direct human impacts at the regional scale (10^6–10^7 km^2) and local scale (10^4–10^6 km^2) should combine relief, water balance, human impacts, and needs. Such analysis should definitively be carried out at a much finer resolution (≤10′). Databases are already available for relief and land cover, and some water budget models exist for a few basins at such resolution. Extending them to the global scale may actually be limited by the difficulty of collecting relevant socioeconomic data sets at a 10′ scale. Indeed, data on population density, economic production, water use, irrigation, etc., still remain to be collected in many countries. This is a major challenge faced by the community concerned with global change, as represented by the International Geosphere Biosphere Program, the International Human Dimension Program, and the HELP program favored by UNESCO.

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REFERENCES

Derruau M. 1968. Mountains. *In:* Fairbridge RW, editor. *The Encyclopaedia of Geomorphology*. New York: Rheinhold, pp 737–739.
Edwards M. *1989.* Global Gridded Elevation and Bathymetric (ETOPO5), Digital Raster Data on a 5-Minute Geographic Grid. *Boulder CO: National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center.*
Elvidge C, Baugh KE, Kihn EA, Kroehl HW, Davis ER. 1997a. Mapping city lights with nighttime data from the DMSP operational linescan system. *Photogrammetric Engineering & Remote Sensing* 63:727.
Elvidge C, Baugh KE, Kihn EA, Kroehl HW, Davis ER, Davis CW. 1997b. Relationship between satellite observed visible-near infrared emissions, population, economic activity, and electric power consumption. *International Journal of Remote Sensing* 18:1373.
Environmental Research Systems Institute (ESRI). 1993. *The Digital Chart of the World. 1:1M Scale Digital Map*. Redlands, CA: ESRI.
Environmental Research Systems Institute (ESRI). 1995. *Arc World Supplement 1:3M Scale Digital Map*. Redlands, CA: ESRI.
Fairbridge RW, editor. 1968a. *The Encyclopaedia of Geomorphology*. New York: Rheinhold.
Fairbridge RW. 1968b. Mountain systems. *In*: Fairbridge RW, editor. *The Encyclopaedia of Geomorphology*. New York: Rheinhold, pp 747–757.
Fairbridge RW. 1968c. Plateau. *In*: Fairbridge RW, editor. *The Encyclopaedia of Geomorphology*. New York: Rheinhold, pp 856–859.
Fekete BM, Vörösmarty CJ, Grabs W. 1999. *Global, Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances.* World Meteorological Organization—Global Runoff Data Center (WMO-GDRC) Report 22. Koblenz, Germany: WMO-GRDC.
Gerrard AJ. 1990. *Mountain Environments: An Examination of the Physical Geography of Mountains*. London: Belhaven.
Goudie A, editor. 1985. *The Enclyclopaedic Dictionary of Physical Geography*. Oxford: Blackwell Reference.
Kapos V, Rhind J, Edwards M, Price MF. *2000. Developing a map of the world's mountain forest.* In: *Price MF and Butts N, editors.* Forest in Sustainable Mountain Development: A State of Knowledge Report for 2000. *Wallingford, UK: Commonwealth Agricultural Bureau (CAB) International.*
Korzoun VI, Sokolv AA, Budyko MI, Voskresensky KP, Kalinin GP, Konoplyantsev AA, Korotkevich ES, L'vovich MI, editors. *1978.* Atlas of World Water Balance and Water Resources of the Earth. *Leningrad: USSR Committee for the International Hydrological Decade. [English translation, Paris: UNESCO.]*
Liniger HP. *1995.* Endangered Water. A Global Overview of Degradation, Conflicts and Strategies for Improvement. *Development and Environment Report 12. Berne: Centre for Development and Environment (CDE), Institute of Geography, University of Berne.*
Liniger HP, Weingartner R, Grosjean M. *1998.* Mountains of the World: Water Towers for the 21st Century. *Berne: Centre for Development and Environment (CDE), Institute of Geography, University of Berne.*
Ludwig W, Probst J-L, Kempe S. 1996. Predicting the oceanic input of organic carbon in continental erosion. *Global Biogeochemical Cycles* 10:23–41.
Mescherikov YA. 1968. Plain. *In*: Fairbridge RW, editor. *The Encyclopaedia of Geomorphology*. New York: Rheinhold, pp 850–856.
Meybeck M. 1979. Concentration des eaux fluviales en éléments majeurs et apports en solution aux océans. *Revue de Géologie Dynamique et Géographie Physique* 21:215–246.
Milliman JD, Syvitski PM. 1992. Geomorphic/tectonic control of sediment discharges to the ocean: the importance of small mountainous rivers. *Journal of Geology* 100:525–544.
Price M, Kohler T, Wachs TR, editors. 2000. *Mountains of the World. Mountain Forests and Sustainable Development*. Berne: Centre for Development and Environment (CDE), Institute of Geography, University of Berne.
Tobler W, Deichmann U, Gottsegen J, Maloy K. 1995. *The Global Demography Project*. Technical Report TR-95-6. Santa Barbara, CA: National Center for Geographic Information and Analysis (NCGIA).
US Geological Survey (USGS), Eros Data Center. 1996. http://edcdaac.usgs.gov/gtopo30/gtopo30.html.
Vörösmarty CJ, Fekete BM, Meybeck M, Lammers RB. 2000a. The global system of rivers: Its role in organizing continental landmass and defining land-to-ocean linkages. *Global Biogeochemical Cycles* 14:599–622.
Vörösmarty CJ, Fekete BM, Meybeck M, Lammers RB. 2000b. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution. *Journal of Hydrology* 237:17–39.
Vörösmarty CJ, Green P, Salisbury J, Lammers RB. 2000c. Global water resources: Vulnerability from climate change and population growth. Science 289(5477):284–288.
Vörösmarty CJ, Federer CA, Schloss A. 1998. Potential evaporation functions compared on U.S. watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling. *Journal of Hydrology* 207:147–169.
Vörösmarty CJ, Fekete M, Meybeck M, Sharma K. 1997. The potential impact of neo-Castorization on sediment transport by the global network of rivers. *In*: Walling D, Probst J-L, editors. *Human Impact on Erosion and Sedimentation.* Wallingford, UK: International Association of Hydrological Sciences (IAHS), pp 261–272.
World Resources Institute (WRI). 1996. *World Resources: A Guide to the Global Environment 1996-97.* Washington, DC: WRI.