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A proposed limnological classification of small water bodies based on the climate, in a tropical region: Mexico

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Abstract. Small aquatic systems (<100 ha) in Mexico are commonly regulated by the climate. The climate generates a temporal unit of variation throughout the year along a latitudinal gradient, that is strongly modified by the altitude. The proposed grouping of small water bodies into limnological regions in Mexico is associated with six ecological areas that are defined by the climate: *a)* a humid tropical area that covers 4.7% of the country's surface, *b)* a sub-humid tropical area with 23%, *c)* a humid temperate area with 2.7%, *d)* a sub-humid temperate area with 20.5%, *e)* an arid and semi-arid area with 49% and *f)* an alpine area with 0.1%. The limnological characteristic that was used to group the small water bodies was the change in water volume. With respect to this, three regions can be defined: *a)* warm and temperate humid regions where the volume of water varies but does not dry up (perennial astatic systems), *b)* warm sub-humid, arid and semi-arid regions that dry up annually (seasonal astatic systems), and *c)* sub-humid temperate regions, as a transition group (semi-perennial astatic systems). Variations in the water level affect the dynamics of dissolved materials.

Key words: Mexico, small water bodies, climate, regionalization.

Propuesta de clasificación limnológica de pequeños cuerpos de agua basada en el clima, en la región tropical: México

Resumen. Los sistemas acuáticos de México (<100 ha) son comúnmente regulados por el clima, éste genera unidades temporales de variación a través del año, a lo largo de un gradiente latitudinal que es fuertemente modificado por la altitud. El propósito de agrupar pequeños cuerpos de agua dentro de regiones limnológicas en México, es asociarlas con

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seis áreas ecológicas que son definidas por el clima: *a)* área trópico-húmeda que cubre 4.7% de la superficie del país, *b)* tropical + subhúmeda con 23%, *c)* templada húmeda con 2.7%, *d)* templada subhúmeda con 20.5%, *e)* árida y semiárida con 49% y *f)* la alpina con 0.1%. La característica limnológica para agrupar los pequeños cuerpos de agua fue el cambio de volumen. Con respecto a esto último se definen tres regiones: *a)* calientes y templado húmedos donde el volumen de agua varía pero no llegan a secarse (sistemas astáticos perennes), *b)* calientes subhúmedos, áridos y semiáridos que se secan anualmente (sistemas astáticos estacionales) y *c)* templados subhúmedos como un grupo de transición (sistema astático semiperenne). Las variaciones en el nivel del agua afectan la dinámica de los materiales disueltos.

Palabras clave: Pequeños cuerpos de agua, México, clima, regionalización.

INTRODUCTION

Classifications of water bodies in Mexico have followed a technique established by the Comisión Nacional del Agua (SRH, 1976) and have been based on the grouping of hydrological basins into physiographic provinces, considering climate as a secondary factor. This has been done since 1970 with few modifications (Bassols, 1986; Arredondo-Figueroa and Aguilar, 1987; Alcocer and Escobar, 1996). We propose grouping small water bodies into limnological regions in Mexico according to the climate.

A general pattern of variation exists between the rainy and the dry seasons in the tropical and sub-tropical regions, so the dry season becoming more prolonged at higher tropical latitudes, notwithstanding altitude-dependent variations (Talling and Lemoalle, 1998). So, when water is scarce, the importance of small water bodies increases in agreement with their multiple uses. Small water bodies constitute the basis of several economic and social activities for 20 million people. Among the uses small water bodies provide are: agricultural irrigation, and water supply for domestic use, cattle, fishing and aquaculture activities, which are found together but are not integrated in most cases. Thus, it is important to define the regional patterns of the small water bodies in order to optimize their management.

Natural ecological terrestrial regions or phytogeographic units have been associated with temperature and humidity gradients (Rzedowski, 1978). One of the most recent and simplified divisions establishes six ecological areas based on climatic characteristics that correspond to predominant types of vegetation: *a)* a warm tropical humid area, *b)* a sub-humid tropical area, *c)* a temperate humid area, *d)* a temperate sub-humid area, *e)* an arid and semi-arid area, and *f)* an alpine area (Toledo *et al.*, 1989; Toledo, 1997). The establishment of the above-mentioned abiotic components as factors regulating productivity allows us to propose the temperature and humidity gradients as factors that regulate the physical, chemical and biological dynamics of the water column along an altitudinal gradient.

Although, there are another important factors related with the primary productivity such as morphometric and edaphic.

Because small water bodies play such an important role in the lives of many people in Mexico, the behavior of the water column in aquatic systems smaller than 100 ha in these six ecological areas is analyzed here using our own information and that available in the literature (Löffler, 1972; Rosas, 1976; Cortés, 1976; Arredondo-Figueroa and García-Calderón, 1982; Sánchez, 1984; Sánchez and Navarrete, 1987; Jaramillo and Sánchez, 1991; Hernández-Avilés and Peña-Mendoza, 1992; Ceja and Gazano, 1994; Elías, 1994; Hernández-Avilés, *et al.*, 2002). Some data on productivity are taken from other non-Mexican tropical regions.

GEOGRAPHICAL AND CLIMATIC BACKGROUND

Mexico is located between 14°32’ and 32°43’ N, in the tropics and sub-tropics, and between the Pacific and Atlantic oceans. It boasts a topographical heterogeneity that includes a high plateau surrounded by mountain chains that opens northwards to the North American plains, and a coastal plain, no more than a few hundred kilometers wide, that disappears where the mountains come in contact with the sea. The rest of the country alternates between mountains and valleys with the exception of the Yucatán peninsula which is a calcareous plain and the Baja California peninsula that includes a chain of mountains west of the Gulf of California. Within this contrasting territory there are 320 hydrographical basins (SEDESOL, 1993) and more than 14 000 water bodies most of which are small basins that flood more than one million and a half hectares (Athié, 1987).

The latitudinal range within which the country is located provides more than one thermal regime. This results in environmental variations, as in temperate latitudes where the four seasons of the year are clearly different, while in subtropical and tropical latitudes the humid-dry regime strongly affects the dynamics of aquatic systems.

The topographical heterogeneity and the distribution pattern of land and sea, with a Gulf to the east limited by the Yucatán channel, produces a circulation pattern that provides the Atlantic watershed with a greater humidity than the Pacific watershed, and establishes important variations in the humid-dry regime (Rzedowski, 1978).

To these climatic conditions (climatic component) one can add the other two abiotic factors determining water productivity: the size of the lake basin (morphometric component) and the dissolved materials (edaphic component) (Rawson, 1939; Cole, 1988). However, each of these components does not occur with the same intensity at all times. Instead, an asymmetry is often the case (Ryder, 1982), as happens with the climate that determines changes in the lake basins through rainfall and evaporation. These are two of the most important elements of climate that determine the temporality of water bodies. Thus, in addition to the morphometric and edaphic components, each type of climate generates a temporal unit of variation along a latitudinal range that is strongly modified by the altitude.

REGIONAL CLASSIFICATION

The six ecological areas for small water bodies in Mexico have been defined with respect to their main characteristics.

1. The warm tropical humid region (4.7% of the surface of the country) is characterized by high temperatures throughout the year with slight decreases during the winter months, high summer rainfall and a short dry season with occasional rainfall. The northers, winds that travel over the Gulf of Mexico and hit the southeastern part of the country, favor rainfall between October and March. This region has three climatic seasons: two are humid, one between October and February defined as the northers season and a rainy season between June and September, and one dry season between March and May. Water bodies in this region are permanent, with changes in depth less than 20% of maximum depth as a result of the accelerated rate of water renewal (Figure 1). These changes are not always harmonic as the northers cause important variations from one year to another. This pattern differs from that in water bodies located in basins that receive water through fractures.

Considering that the climate regulates changes in the dissolved materials of the water column, increased rainfall, a constant flushing of the soil and an increase in the rate of renewal of the water column, favor constant low concentrations of total dissolved solids that result in the ionic composition of reservoir and lake water to become similar to that of rain water (Gibbs, 1970). Although these low concentrations should cause low productivities (<500 $gCm^{-2}year^{-1}$; Erikson *et al.*, 1998), there is a compensating effect from the organic matter

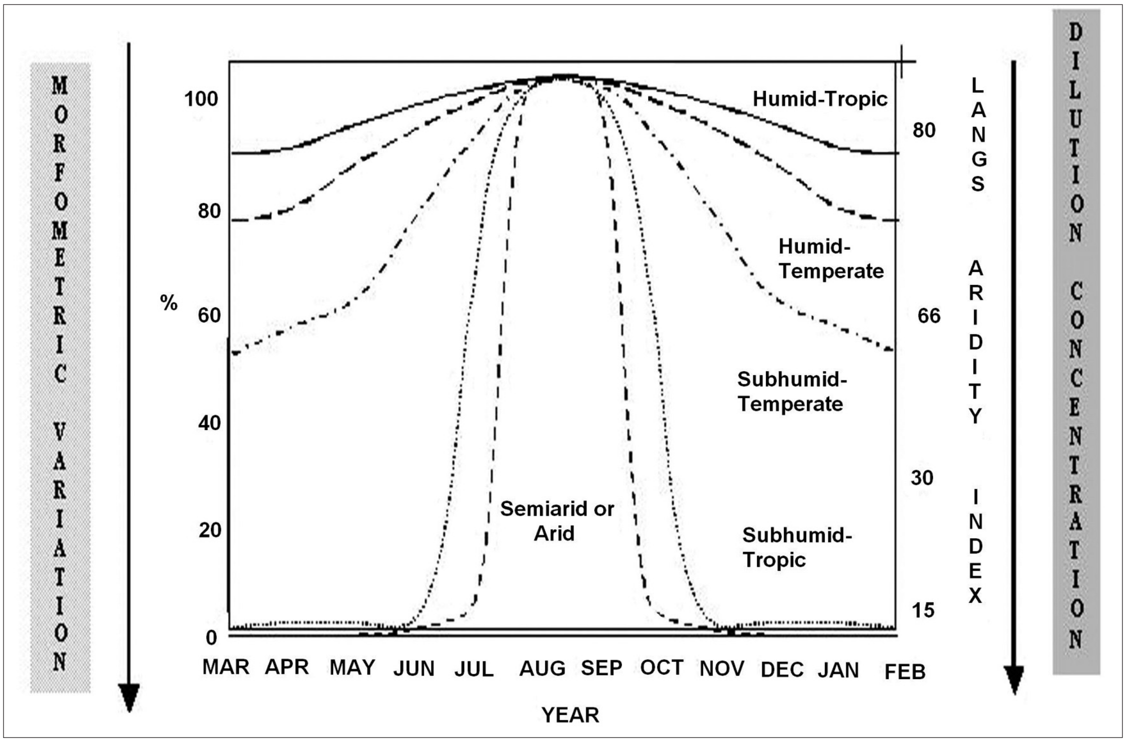

Figure 1. Model of the perceptual volumetric variation for different climatic conditions in fluctuating or astatic systems.

contributed by the basin. Water bodies in the Sierra Madre Oriental in the Gulf of Mexico watershed maintain high ionic concentrations as a result of the calcareous geomorphologic characteristics present in that area.

The Yucatán peninsula is a calcareous plain formed by ancient reefs. Its karstic water bodies have no runoff, but seepage and solution result in high ionic concentrations that are not affected by the rate of renewal through the water table. These characteristics make the Yucatán peninsula a region where the effects of temperature and rainfall are less strong than those of the geomorphic features. For this reason the Yucatán peninsula is not included in the proposed regionalization.

In other regions, such as the Sierra Madre Oriental watershed, the runoff promotes flushing and the solution of calcareous rock, characteristic of this mountain range, that result in much higher concentrations, as occurs in similar regions of Africa (Kilham, 1990). The coastal plain has many water bodies that are associated with the rivers, that form after floods and vary constantly, with Gleyson soils, redox processes and sodium accumulation, and a high turnover rate that prevents an increase in dissolved materials in the water column, as occurs in the Papaloapan and Grijalva-Usumacinta basins, and others throughout the damp tropics (Tamayo, 1962). Also found in these low lying lands are Fluvisols and Planosols on alluvial deposits, often associated with fluctuations in the water level, as happens in Tabasco (Rodríguez, 2002) where there are floodplains with iron oxides (hermatin) covered by alluvial deposits. Other natural water bodies are associated with volcanoes (Vázquez *et al*., 2004) or with small depressions in volcanic areas that flood temporarily and dry up more by loss of water through fractures than by evaporation, or that remain flooded in spite of filtration as occurs in Los Tuxtlas, Veracruz (Torres-Orozco *et al*., 1996). This area has few artificial water bodies as water is always available. The areas near the mountains are characterized by Feozem, Cambisol, Castanozem and Luvisol soils with calcareous structures (Oaxaca) and with calcareous and volcanic soils (Chiapas). Along the Pacific can be found Gleysol, Regosol and Fluvisol soils and metamorphic and sedimentary rocks below the mountains.

2. The tropical sub-humid region (23% of the surface of the country) has high temperatures throughout most of the year, but in contrast with the previous region it has a well-defined dry season. Two seasons can be distinguished in this region: a warm-dry season between October and May and a warm-humid season between June and September. This contrast in humidity causes the volume in small water bodies to vary by 40% (Figure 1). However, this effect is masked in the water bodies throughout the Gulf of Mexico watershed by the effect of the northers. Since the contrast between the dry and the humid seasons is bigger here than in water bodies in humid tropical regions, there is a stronger relationship between the periods of concentration and solution and the seasons, and this becomes more marked with increases in the water deficit. One could say that these environments are productive (500-1 000 $gCm^{-2}year^{-1}$) during the diluted phase and very productive (>1 000 $gCm^{-2}year^{-1}$) in the concentration phase (Quiroz, 1996). The temperature may also collaborate since it favors mineralization processes, and the productivity increases with higher concentrations of dissolved materials in the water column up to the point when an excess results in loss of nutrients through sedimentation.

The water bodies in the tropical sub-humid region of the central plateau are very turbid as a result of changes in the use of the land and a pronounced topography with marked slopes, and also have a very limited primary productivity (80-100 $gCm^{-2}year^{-1}$; Lind *et al*., 1994). However, there is evidence that suspended solids trap organic matter that constitutes conglomerates of bacterial communities that serve as food for fish. This has been recorded for these water bodies and confirms that the heterotrophic chain is more important than had been thought (Lind and Dávalos-Lind, 1991; Lind *et al*., 1994). The soils types are very diverse and derive from sedimentary, volcanic and metamorphic geological structures. This area has the most productive water bodies as both the edaphic and climatic characteristics favour productivity. The basins of these water bodies present ocric and calcic Cambisols, Litosols, luvic Castanozem and haplic Acrisol, in a topographic where low lying hills and mountains with sharp slopes alternate. The construction of a great number of water bodies indicates the importance of storing water for productive activities. The water bodies that are constructed in the fields among the pasture grounds in lying hills of the coastal plain of the Gulf of Mexico are used as water holes. Initial evaluations of yields is small water bodies have been carried out in this area (Arredondo-Figueroa and García-Calderón, 1982), with later evaluations including management concepts (Porrás *et al*., 1981; Blanquel, 1999).

3. The temperate humid region is the second most restricted in the country (2.7% of the surface). It is often located near humid tropical regions at altitudes over 1 000 m. With respect to annual rainfall, it lies between the humid and the sub-humid tropics although the temperature is approximately ten degrees Celsius lower than in the tropics. It has three climatic periods: a temperate-humid between October and February, a warm-dry between March and May, and a warm-humid between June

and September. Variations in the level of the water are minimal and usually less than 10% since the temperature does not increase notably (Figure 1). The concentration of dissolved materials is practically constant throughout the year and productivity can be considered from moderate (500-1 000 $gCm^{-2}year^{-1}$) to low (<500 $gCm^{-2}year^{-1}$; Hernández-Avilés, unpublished), with little variation. Water bodies in this region are relatively few since the topography and geomorphology considerably limit the presence of lake basins. Soils formed from volcanic rocks are Andosols and Cambisols, with volcanic ash and pumice stones, whereas those formed from calcareous rocks are calcic Xerosols. These basins provide abundant dissolved materials, although the turnover rate of water decreases the productivity of these water bodies in comparison with that of subhumid temperate areas.

4. The temperate sub-humid region (20.5% of the surface) is characterized by low rainfall and moderate temperatures. It has two climatic periods: one is cold and dry between October and February and the other is humid and temperate between March and September. The region next to the Gulf of Mexico watershed, above 2 000 m and behind the mountain range of the Sierra Madre Oriental, has a particularly dry season although the northers (November to March) tend to ease it.

Notwithstanding that the northers are highly variable, they not only favor maintaining the volume of water in water bodies but they also increase it through the rains they bring. Decreases in the water level follow higher temperatures and the lack of rainfall just before the summer rainfalls. Regions without the effect of northers have more marked differences. Changes in the water level are around 50% with no clear difference between the solution and concentration phases (Figure 1). This results in a low primary productivity (<500 $gCm^{-2}year^{-1}$) that is favored by low temperatures and high abiogenic turbidity, that in turn are compensated by secondary productivity (Hernández-Avilés, 1999) as occurs in the sub-humid warm regions. The variety of soils includes Regosols, Rendzina, Cambisols, Feozem and Litosols associated with miscellaneous rocks (lavic flows), with Vertisols and Gleysols distributed throughout the plain.

This area of the central region of the country has among the greatest number of small water bodies, as well as the greatest information, particularly the state of Tlaxcala (Elías and Navarrete, 1998; Navarrete *et al*., 2000; Contreras *et al*., 1999; Hernández-Avilés, 1999; Oliva *et al*., 2005).

5. The arid and semi-arid regions (49.1% of the surface) present two climatic seasons: a dry one between October and May and a humid one between June and September. The temperature regime shows important variations, particularly in the arid areas of the center and south of the country where temperature values are higher. This can modify the pattern and produce a hot and dry phase in spring and a hot and humid phase in the summer. As an example, the rainy season in some areas in the center of the country lasts only four months, from June to September, with average monthly values around 100 mm, after which the dry season sets in with average monthly values lower than 25 mm.

The extreme conditions in these environments during the dry seasons favor the drying of the water bodies and a drastic reduction in the water volume (Figure 1), and also establish the concentration phase and an increased production (500-1 000 $gCm^{-2}year^{-1}$; Piet and Vijverberg, 1999; Badillo and Navarro, 2001). This is also favored by high temperatures common during the summer although the low permanence of the water column represents an important limiting factor. In the semiarid and arid areas of the central plateau it is common to find calcareous horizons (caliche or tepetate) characteristic of Feozem soils, together with Fluvisols and regosols formed by alluvial and coluvial processes respectively. The plains that area called bajíos are rich in humidity and alluvial deposits. Small water bodies are constructed here for multiple purposes and become the basis for subsistence and productive activities. Soils here include Xerosols, Castañozem and Solonchak. There are also small natural water bodies, lakes and relicts of ancient lacustrine systems.

6. The alpine region (<1% of the surface) is characterized by cold climate, high tundra and extreme changes of temperature, in spite of which the climate is considered isothermic. Rainfall occurs during summer, whereas snow creates a snow layer (1 meter or more) which prevails until spring during the humid and extremely cold winters. There are two high mountain water bodies in Mexico: "El Sol" and "La Luna" in the Nevado de Toluca volcano. Only a small variation in the water level has been recorded in these systems, although this can vary by seven meters over periods of decades. The concentration of dissolved salts in these environments can be similar to that of pure water with a low productivity (<500 $gCm^{-2}year^{-1}$; Vicent *et al*., 1986; Banderas *et al*., 1991).

DISCUSSION

The division between each climatic condition is variable, so much so that the transition phase may occur on a geographical or temporal scale. Some regions present an abrupt change between dry and humid conditions whereas in others there is a gradual change (García, 1996).

In spite of the differences recorded for small water bodies in accordance with the water deficit, one common characteristic is the annual change in water level (astatic systems; Hartland and Rowe, 1972). Although the water level in water bodies in both warm and temperate humid regions changes, these never dry up (perennial astatic systems), while those in warm sub-humid, semi-arid and arid regions may dry up (seasonal astatic systems). There are transition areas between these two types, such as the sub-humid temperate regions that constitute a unit with sub-perennial astatic systems (Figure 2).

The main consideration here is the rainfall-evaporation rate that is conditioned by the dry season, followed by temperature that is conditioned by the altitude (Moss, 1988). Thus, the temperature must be considered together with the rainfall in the central plateau and mountain regions of the country.

This classification schematically and regionally locates the three types of systems. The perennial astatics are located in humid warm and humid temperate regions, the sub-perennial astatics are in sub-humid temperate regions, and the seasonal astatics are in sub-humid warm, arid and semi-arid regions, with characteristic types of vegetation and climate for each type of system (Figure 2, Table 1), transition areas between each of these require field observations.

Within a regional context, the perennial astatic systems cover 10% of the country and are restricted to the region south of the Gulf of Mexico and a small area in the Soconusco. Although the coastal plains along both the south of the Gulf of Mexico and the Pacific coast have sub-humid warm climates, they represent transition areas towards the perennial astatics. The sub-perennial astatics can be found in 25% of the country and are associated with the mountain ranges and locations with a marked topography in sub-humid temperate climates. The seasonal astatics can be found in 65% of the country and correspond to the arid and semi-arid regions in the northern half of the territory, the río Balsas basin and the coastal plains in the north (Figure 3).

Variations in the annual change in the water volume are related to the dynamics of the materials as well as to the production, in such a way that in general an increase in the volume lowers the concentration of dissolved materials, even though for some ions in particular this does not happen, and this can be recorded through lower conductivities and

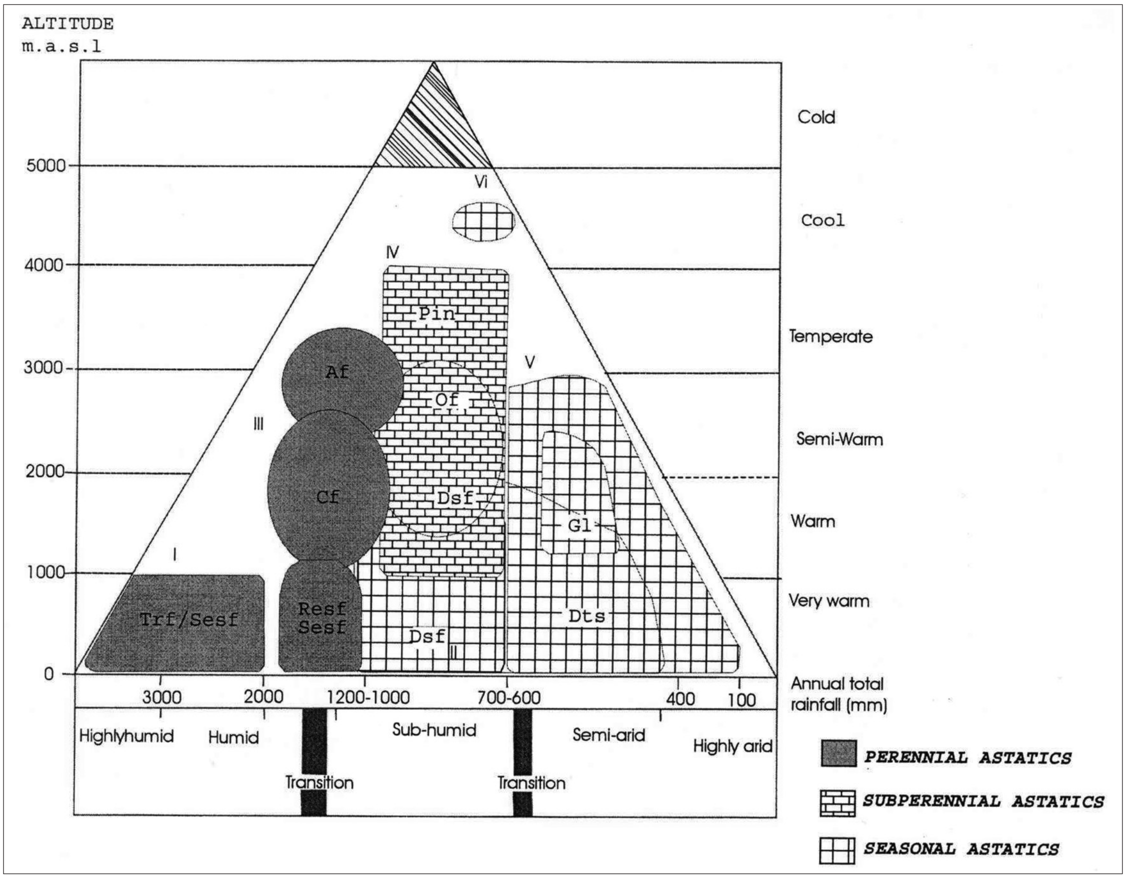

Figure 2. Mexican small reservoirs in Toledo's ecological zone classification. Ecological Zone: I Humid-tropic; II Sub-humid-tropic; III Humid-temperate; IV Sub-humid temperate; V Semi-arid and arid (Trf=Tropical rain forest, Sesf=Semi-evergreen seasonal forest, Resf=Rain evergreen seasonal forest, Cf=Cloud forest, Af=Abies forest, Pin=Pine forest, Of=Evergreen oak forest, Dsf=Deciduous seasonal forest, Gl=Grassland, Dts=Desert tropical scrub).

low to moderate productivities. In contrast, a reduction in volume, due primarily to evaporation, increases the concentration of materials as well as production (Arredondo-Figueroa and García-Calderón, 1982). This occurs in perennial systems. Small changes in the water level are defined less clearly in the case of the seasonal astatics. Thus, in the humid warm regions, high rainfall favors an accelerated rate of renewal in the water column and maintains a diluted environment, in contrast with the arid and semi-arid systems where each phase is clearly marked.

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Table 1. Classification of small water bodies and their environmental characteristics

Limnological region[a]	Ecological area[b]	Characteristic terrestrial vegetation[b]	Climate[c]	Soil[d]
Perennial Astatic	Humid-tropic	Tropical rain forest	Af	Luvisols
		Semi-evergreen seasonal forest	Am	Acrisols
		Rain evergreen seasonal forest	Aw	Cambisols
				Verstisols
	Humid-Temperate	Cloud forest	Cf	Regosols
Subperennial astatic	Subhumid-temperate	Abies forest	Cm	Andosols
		Pine forest	Cw	Cambisols
		Ever-green oak forest		Regosols
Seasonal astatic	Subhumid-tropic	Deciduous seasonal forest	Aw	Xerosols
	Semiarid	Grassland	BS, BW	Vertisols
		Desert tropical scrub		Regosols

[a] Hartland-Rowe, 1972; [b] Toledo, 1997; [c] García, 1996; López-García *et al.*, 1991.
Am=Humid-warm with summer rains, Af=Warm-wet with rains all year, Aw=Tropical wet-dry, Cf=Humid-temperate with rains all years, Cm=Humid-temperate with summer rains, Cw=Subhumid-temperate with summer rains, BS=Dry or steppe, BW=Desert or very dry.

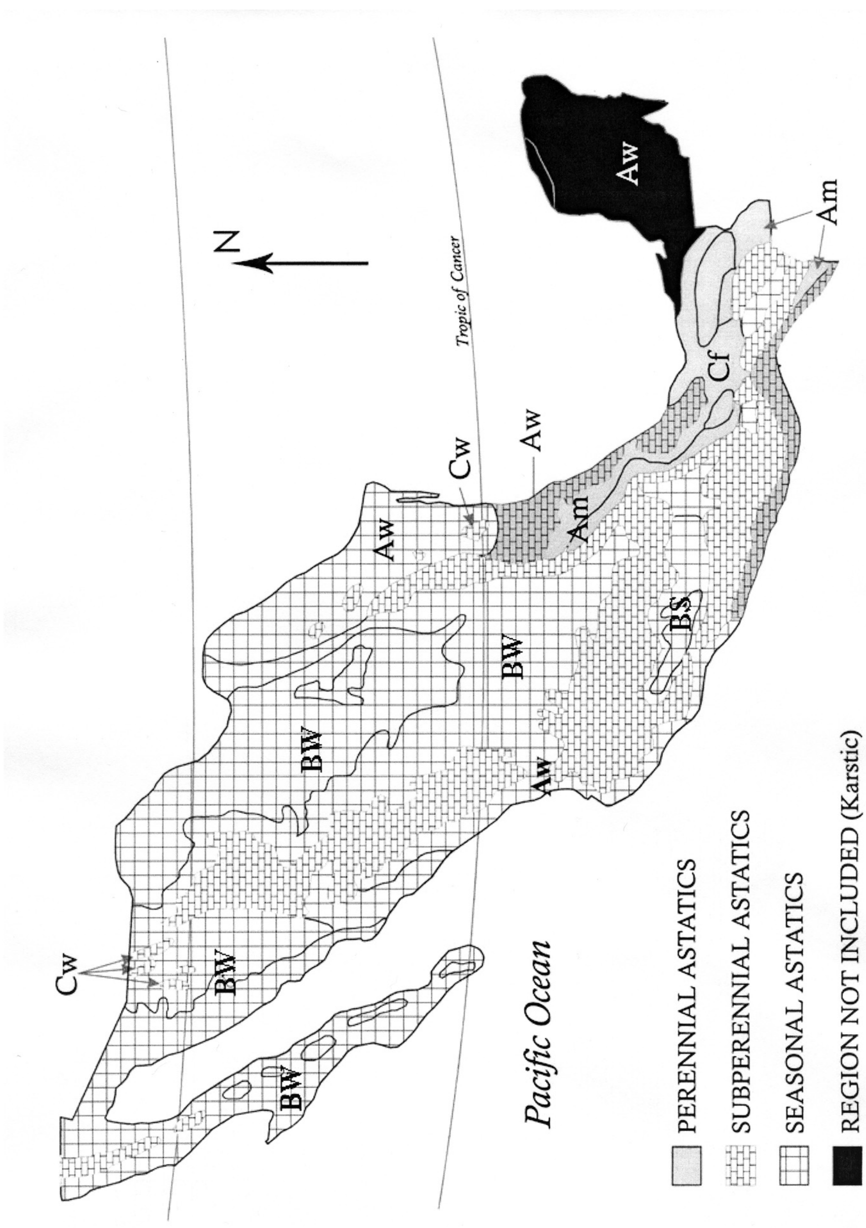

Figure 3. Regionalization of small astatic water bodies in relation with the climate (Am=Humid-warm with summer rains, Af=Warm-wet with rains all year, Aw=Tropical wet-dry, Cf=Humid-temperate with rains all years, Cm=Humid-temperate with summer rains, Cw=Subhumid-temperate with summer rains, BS=Dry or steppe, BW=Desert or very dry).

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