COMPARATIVE STUDY OF THREE METHODS FOR THE CALCULATION OF ENVIRONMENTAL FLOWS IN THE SANTIAGO RIVER, NAYARIT, MEXICO.

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Abstract

A comparative analysis of three methods for the calculation of water flows in the Santiago river was carried out: 1) Tennant method, modified for tropical areas, 2) Habitat Simulation method (software Physical HABitat SIMulation system), and 3) Multivariate Analyses considering hydraulic, physico-chemical and biological (fish community) characteristics of the river. The Tennant method provided water flows based on the seasonal climatic variations and on the annual and monthly averages of the ten years previous to the construction of the dam. The Habitat Simulation method (PHABSIM) indicated the available habitat when the river flow changed in response to the operation of the Aguamilpa dam. The multivariate analyses, including Principal Components and Clusters, described the river habitat and determined the scenarios of optimal flow for species in the Santiago river. Canonic Correlations Analysis (CCA) showed that 62.48% of the variation was explained by the conductivity, dissolved solids, oxygen, current velocity and depth, in contrast with the substrate, submerged vegetation and plant cover. Results pointed to current velocity, depth and substrate as the variables that explained the greatest percentage of the variation using the three methods.

Keywords: Environmental flows, preferential habitat, river management.

Introduction

Environments are generally treated marginally, notwithstanding that they are the key to a sustainable use of the water. The environment represents a special type of water user, and in many aspects it constitutes the main issue in the management of aquatic resources. This is critical for the development, reduction of poverty, population health, agricultural, industrial and energy productivity, and the sustainable development of communities established along rivers. Environmental strategies must consider and maintain a balance among the interests pertaining to a sustainable management of the water, an environmental sustainability and poverty (Davis and Hirji, 2003; Tharme, 2003; King and Brown, 2006).

Hydroelectric plants have affected the regimes of natural water flows, longitudinally fragmented rivers through construction and diversification, and modified sediment, organic matter and nutrient transportation, resulting in physico-chemical and biological changes in rivers and flood plains (Fischer and Kummer, 2000; Arthington et al, 2006; Rithcer et al, 2006).

Rivers below dams may be partly restored through controlled operation and management. The operation of dams should be based on a detailed analysis of the variables that control the system, in order to reduce the impacts caused down-river and in flood plains (Galat and Lipkin, 2000). However, the complex physico-chemical and biological processes in rivers do not make it easy to apply methods to calculate the flow that may be provided for use in urban areas, irrigation and electric energy generation without damaging the ecosystem (Gustard, 1992). Likewise, water management plans has been problematic due to the difficulty, cost and time required to determine the frequency and flow that is necessary to maintain the species, function and resilience of aquatic ecosystems, as well as the well being of the inhabitants that depend on rivers. A wide range of methods in which the concept of the habitat is essential has been developed for the conservation of river ecosystems (Bunn and Davies, 2000; Schiemer, 2000).

The advantage of measuring water flows lies in enabling decision makers to determine how much of the water may be destined for use by populations and how much of the alteration in the patterns of natural river flows has been induced by human consumption. Thus, measurement of water flows is indispensable in the planning of a sustainable water use (Dyson et al. 2003).

Study Area

The Santiago river is located on the Pacific watershed of Mexico. It starts in Chapala lake (Jalisco), passes through the state of Nayarit, and arrives at the Pacific Ocean at Boca de Asadero. The annual average flow of the river for 1982-1992 (CNA, 1994) was 199.5 $m^3 s^{-1}$. The maximum flow recorded during these years was 4,604 $m^3 s^{-1}$ in 1988, and the minimum was 6.9 $m^3 s^{-1}$ in 1984. The stretch of 1,524m of the river under study is located at 21^{o} 45' N and 104^{o} 55' W. It is characterized by riparian vegetation in a good to regular state of conservation, and areas of rapids, pools and uniform slopes, with a diversity of habitats and hydraulic characteristics corresponding to fast, slow and transition waters, as well as deep and shallow areas representative of most habitats (Figure 1; García et al, 1999). The width of the river varies from 100m in high areas to 280m in low-lying areas. The longitudinal profile in this stretch varies 6.2m. The greatest depth recorded at each section varied from 0.15 to 4m, and the current velocity varied from 0 to 0.57 m s^{-1}. The annual climatic variations responded to the pattern of summer rains. This river generates fishery resources at subsistence level for the rural population, for local commerce and for sports fishing. The construction and operation of the Aguamilpa dam, agricultural activities, the introduction of exotic species, and the construction of roads contribute to sedimentation, changes in water flow and a decrease in water quality that affect the habitat of native fish species in the Santiago river.

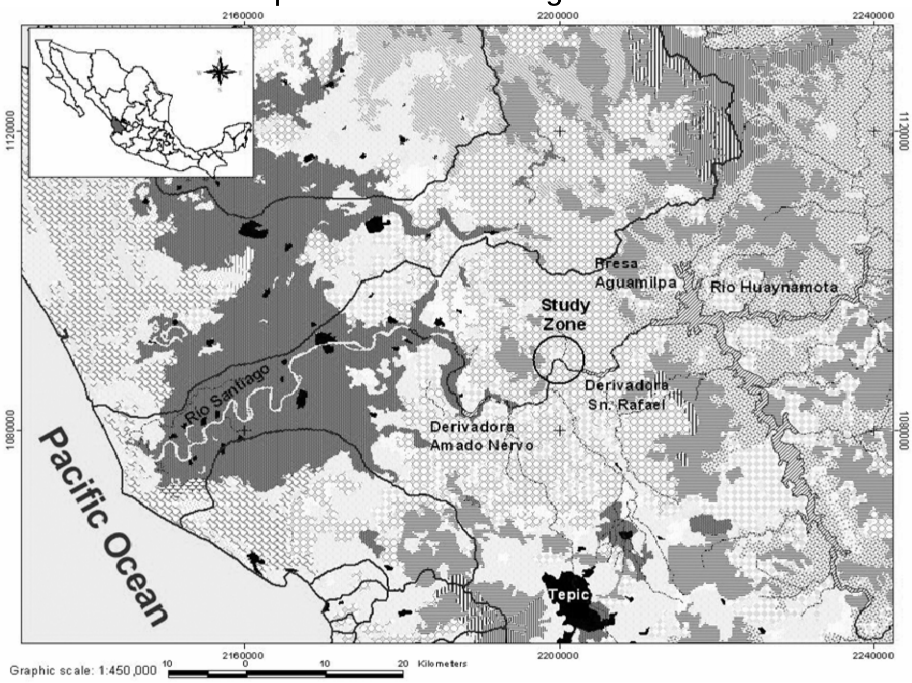


Figure 1. The Santiago river and study area.

Methods

Tennant or Montana method. This method was developed by the US Fish and Wild Life Service. Flows are calculated based on the annual averages of hydrometric records of at least ten years previous to the construction of the dam. It establishes the depth, current velocity and width at the surface of the river as the variables that determine the development of aquatic organisms and the good state of their habitat. It indicates that these three physical parameters increase when flow increases, and they vary markedly at lower flows. The width, depth and current velocity change markedly throughout the range from 0 to 10% of the annual average flow. Tennant (1976) concluded that 10% is the minimum flow necessary to guarantee the survival of most species in the river. He considered flows between 30 and 100% of the annual average flow as good and optimum for the development of aquatic organisms, and an increase in the flow by 100 to 200% of the annual average flow as very adequate for the development of most aquatic organisms.

Tennant method modified for tropical areas in Mexico (García et al, 1999). A few changes are introduced in this method:

- Calculations are based on the monthly average flows instead of on the annual averages to allow coincidence with the distribution of the natural monthly flows during the year.
- Flows are calculated for the climatic seasons characteristic of tropical areas in Mexico: November-May (dry season) and June-October (rainy season). These periods generally present slight variations depending on the region under study.
- The dry season includes the months with flow values below the annual average, and the rainy season includes the months with a monthly flow average greater than the annual average (annual seasonal climatic variation).
- A value of 20% is suggested for the recommended minimum flows instead of 10%.
- Additional analyses must be carried out to calculate the flows that maintain or repair the canal and/or change the quality and temperature of the water (hidroperid).
- Social, political and environmental problems must be adequately managed in order to avoid conflict among users.

Habitat Simulation method. This method includes a series of conceptual, empiric and mathematical models that are used to calculate the availability of habitats, and the possibility of using a variety of management alternatives. The models work with the biological information (population models), water quality data and hydraulic characteristics of the river that are provided to the Physical Habitat Simulation System (PHABSIM) programme (Bovee, 1986). The river is divided into a great number of rectangular or trapezoidal cells. The stretch of the river studied here was divided into eight transversal sections that included different types of habitats: Sections S-1, S-2 and S-3 were characterized by a moderate slope, sections S-4, S-5 and S-6 presented rapids (stones and rocks visible above the level of the water), and sections S-7 and S-8 were located in deep areas. Each cell had a unique combination of depth, current velocity, substrate type and plant cover values. A topographical analysis was also carried out along this stretch. The bathymetry was recorded with a precision of ±1cm at every 50m along the eight transversal sections. The depth and current velocity were recorded in each cell with a Rosbach-Price mill-cups. Substrate data was obtained from an area of 50cm^2 on the river bed. The riparian vegetation was classified for each section as: a) totally exposed to the Sun´s rays and above the surface of the water, b) water surface under vegetation shadow, and c) submerged vegetation (leaves, stems, trunks and/or roots). Dissolved oxygen (YSI Oxymeter), conductivity and total dissolved solids (TDS, with a Hach DRL-2000 conductimeter; García et al, 1999) were recorded in each cell.

The fishing technique was chosen considering that fish could not be located in the water column due to the high turbidity and current velocity during the rainy season, the great depth, the drastic changes in the water flow caused by the management of the dam, the width of the river, and the presence of crocodiles. Fish were collected with a 30m long, 2m wide and 1cm^2 mesh size net that was throw three times per site. Species were identified following the criteria of Álvarez (1970) and Castro-Aguirre (1978). Each specimen was measured, weighed and classified according to its calculated age. Data were gathered for 287 individuals. The size at reproductive recruitment was determined using the Nikolski scale (Schreck and Moyle, 1990; Rodríguez, 1992). The available microhabitat area was calculated for each species at different water flows using the PHABSIM programme (García et al, 1999). *Dorosoma smithii* was selected as it is a facultative river species, it is sensitive to changes in currents, it demands particular environmental conditions of oxygen concentration and food and water flows, it reflects changes in patterns of habitat use, and it makes it possible to generate a maximum of information based on its adaptation to environmental conditions. It is supposed that the needs of this species are representative of those of the other species it coexists with in the river.

Multivariate methods. A data matrix was generated with data on locality, sampling hour, current velocity, depth, substrate, dissolved oxygen, conductivity, dissolved solids, vegetation, fish species, developmental stage, weight, length, abundance, species richness and diversity (Shannon-Weiner Index) for four transversal sections of the river. Analyses included: 1) Principal Components (PC) to identify environmental gradients, 2) Cluster Analysis (Euclidian Distances and Non Ponderated Averages, CA) to define environmental groups in the river, and 3) Canonic Correlations to determine the habitats preferred by the fish (CCA; García et al, 1999). Statsoft Statistica Software (1995) was used in all cases.

Results

Modified Tennant method for tropical areas in Mexico. Table 1 and Figure 2, show the natural and minimum flows recommended for the Santiago river considering a value of 20% as minimum during dry season and 30% for the rain season of the yearly flow averages of 10 years of hydrological records. Other flows can be implemented in deferent periods of de year depending of the conditions of the fluvial system.

Table 1. Flows calculated for the Santiago river with the Modified Tennant Method (Garcia et al, 1999).

Month	Natural flow (m^3/s)	Minimum flow recommended 20 – 30% (m^3/s)	Good flow recommended 30 – 50%	Excelent flow recommended 40 – 60%	Exceptional flows 60 -100%
January	52.95	37.11	55.67	74.23	111.35
February	41.02	37.11	55.67	74.23	111.35
March	35.62	37.11	55.67	74.23	111.35
April	48.96	37.11	55.67	74.23	111.35
May	36.62	37.11	55.67	74.23	111.35
June	117.42	37.11	55.67	74.23	111.35
July	465.80	55.67	92.79	111.35	185.58
Augusta	508.33	55.67	92.79	111.35	185.58
September	478.99	55.67	92.79	111.35	185.58
October	238.36	55.67	92.79	111.35	185.58
November	118.44	37.11	55.67	74.23	111.35
December	72.62	37.11	55.67	74.23	111.35
Average	185.58				

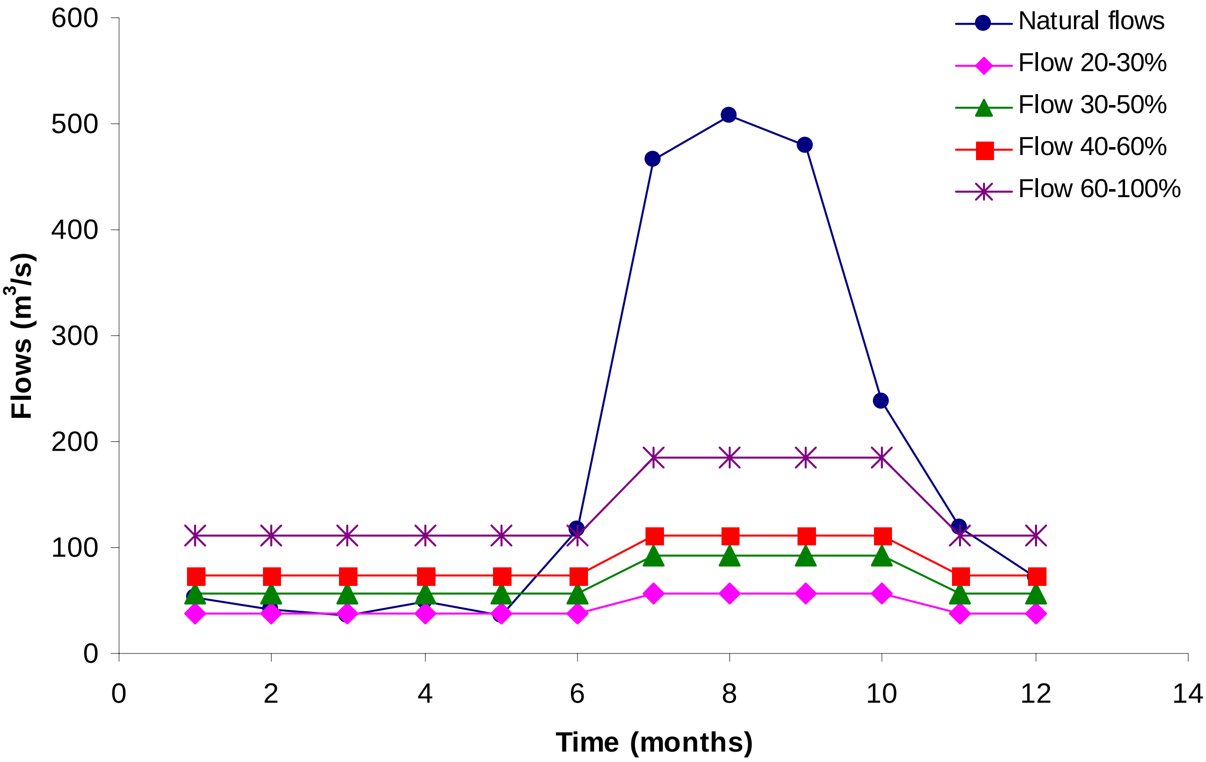


Figure 2. Natural and recommended flows for the Santiago river, calculated by the Modified Tennant Method for tropical areas in Mexico (modified from García et al. 1999).

Habitat Simulation method.

A total of 287 specimens of the species *D. smithii* with an average size of 7.1cm were collected, mostly in currents of 15 to 26.5 cm s^{-1}, at depths of 1.35 to 2.6m, on gravelly substrates and sunny areas with no or little submerged vegetation. It is a detritivorous species that is associated with medium deep waters, sandy and gravelly substrates and fast currents, as its feeding habits make it prefer oxygenated waters with suspended organic matter. It is a secondary amphidromous species common in this part of the river, which indicates that its biological cycle is adapted to changing currents (Lowe-MacConnell, 1975).

The river habitat suitability estimated by the preference curves for depth and current velocity for this species indicates that the water surface level of the river increases with an increase in flow, with a maximum level at 350 m^3 s^{-1}, as is shown in the figure for Potential Usable Total Surface Area *vs* Flow (Fig. 3).

The figure for Habitat *vs* Flow represents the total sum of potentially usable areas of the river for flows from 0 to 300 m^3 s^{-1} and establishes the relationship between the flow and the habitat availability in that stretch of the river (Fig. 4). The figure shows that there is a continuous increase in the availability of habitat, with a first optimum maximum of 5800 m^2 per 1000m of the river under study or of the area adequate for the development of species, with a flow of 64 m^3 s^{-1} which is associated with the filling of the main channel of the river. Flow catalogued as optimum minimum in order to maintain the river habitat (Table 2). A second smaller peak of 4500 m^2 per 1000m of river indicates the creation of an ideal habitat for *D. smithii* with a flow of 185 m^3 s^{-1} that may be associated with the flooding of the secondary channel or the flood plain and defines the maximum flow to preserve the margins and flood plain during the rains.

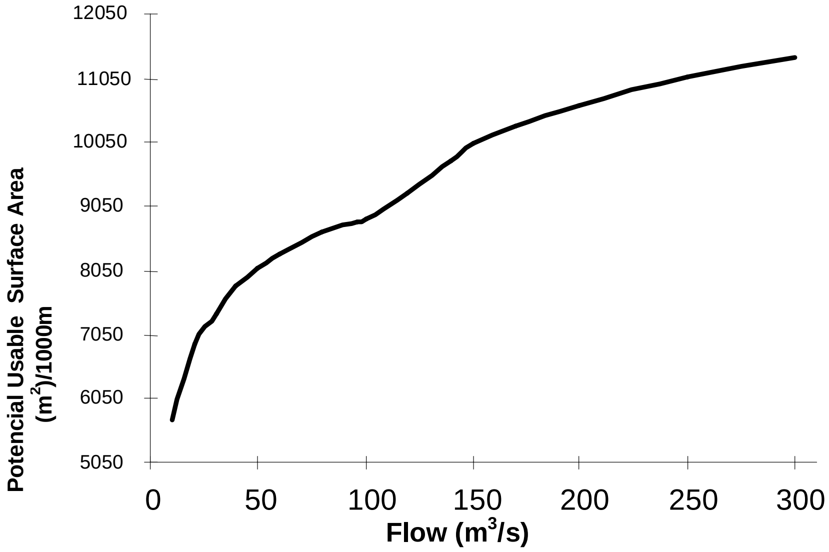


Figure 3. Potentially Usable Total Surface area *vs* Flow in the Santiago river (modified from García et al, 1999).

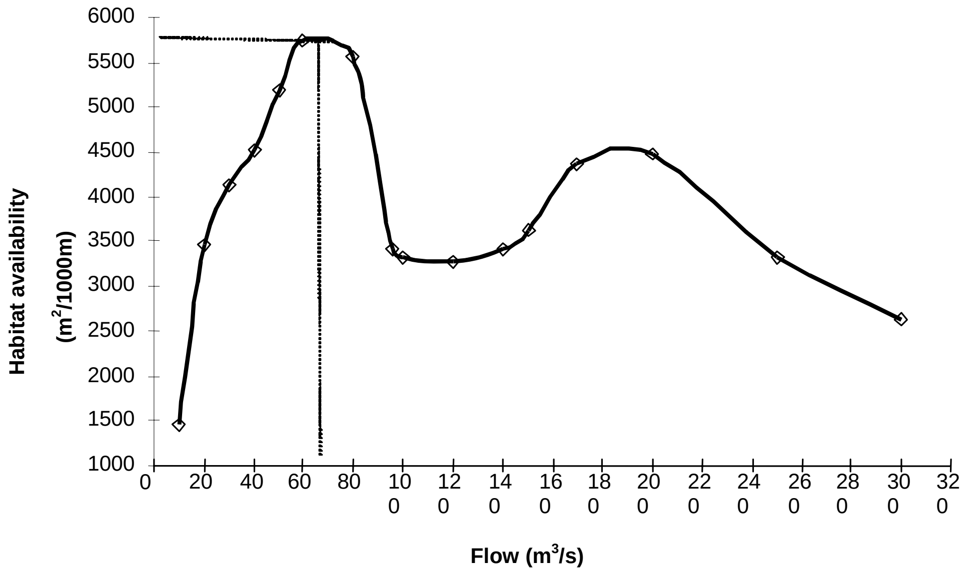


Figure 4. Habitat Suitability *vs* Flow in the Santiago river (modified from García et al, 1999).

After this second peak, the curve continues to descend indicating that the areas with habitat adequate for the development of fish decrease with an increase in flow (350 to 500 m^3 s^{-1}), as a result of strong currents that re-suspend sediment and organic matter. Flow defined for times when it is necessary to drain a dam quickly during the rainy season in order to protect the morphology of the channel. A flow of 40 m^3 s^{-1} is recommended for short periods of time as an indispensable minimum during the dry season in order to conserve the habitat.

Table 2. Flow management in the Aguamilpa dam.

Season	Flow (m^3/s)	Pattern	Importance
Dry season (March-April)	40	Indispensable minimum	Scarce resource
Post-regulation	64	Optimum minimum	To maintain the habitat
Rainy season (June – August)	200	Maximum flow	To preserve the margins and flood plain
Rainy peak season (September)	350 - 500	Fast drainage	Morphological conservation

Multivariate methods. A total of 6,911 fish of 12 species were collected: six secondary species (s) tolerant of changes in salinity, and six strictly freshwater primary species (p). Of these last six species, three were native (n) and three introduced (i). The most abundant species were *Lepomis macrochirus* and *Poeciliopsis latidens*. The fish community changed from 1992 to 1997 as a result of changes in the conditions of the ecosystem. A substitution of species was observed (only 33% of the original species remained) and 20% decreased in number (Table 3 and Table 4). The ratio of native species/introduced species was 1. The construction of roads, seasonal agriculture, the presence of two dams, the introduction of exotic species and changes in the fish community structure characterize the Santiago river as a significantly altered ecosystem with marked changes in the fish community, according to Moog and Chovanec´s (2000) criteria. The physico-chemical characteristics of the river guarantee the suitability of the habitat for fish.

Table 3. Fish and number of individuals collected in 1992 in the Santiago river (IBUNAM).

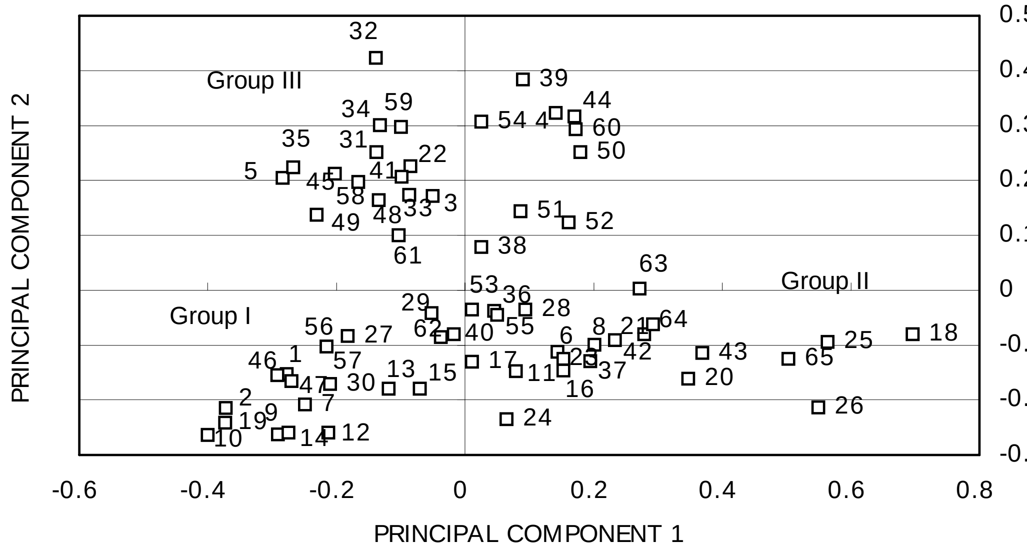
No.	**species**
1	*Cyprinus carpio*
2	*Notropis* sp
3	*Yuriria alta*
4	*Moxoxtoma austrinum*
5	*Ictalurus dugesi*
6	*Arius liropus*
7	*Gobiesox fluviatilis*
8	*Poecilia reticulata*
9	*Poeciliopsis latidens*
10	*Atherinella c. Crystallina*
11	*Cichlasoma beani*
12	*Oreochromis mossambicus*
13	*Agonostomus monticola*
14	*Awaous trasandeanus*
15	*Poecilia blutleri*

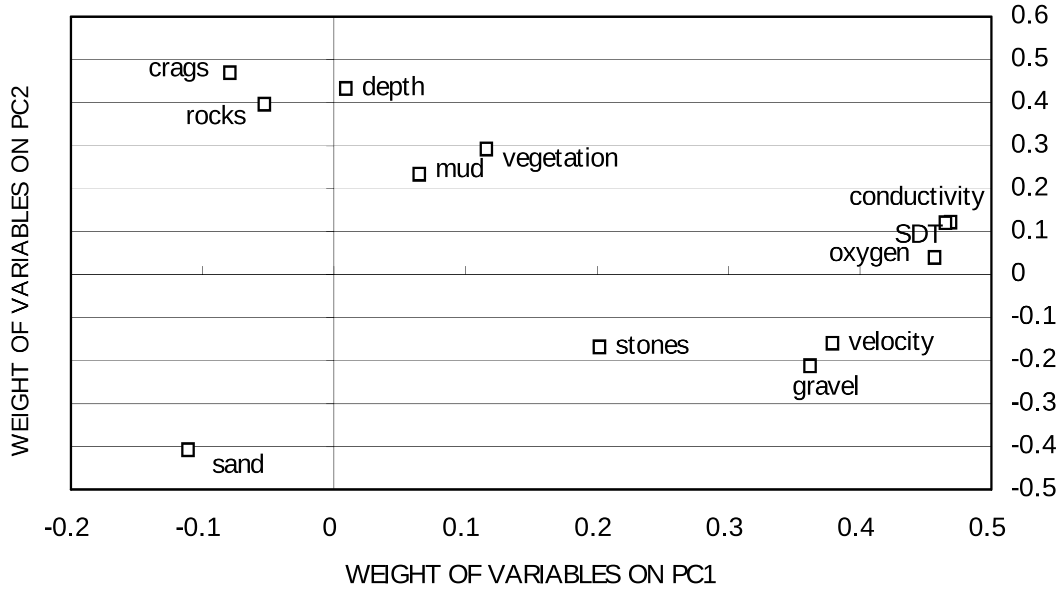
Table 4. Number of fish collected in the Santiago river in 1997 (García et al, 1999).

No.	**species**	**Individulas (number)**	**Total (%)**
1	*Lepomis macrochirus* (p)(i)	3596	52.03
2	*Poeciliopsislatidens* (p)(n)	1329	19.23
3	*Poecilia sphenops* (p)(n)	573	8.29
4	*Micropterussalmoides* (p)(i)	349	5.05
5	*Cichlasoma beani* (p)(n)	324	4.69
6	*Dorosoma smithii* (s)	287	4.15
7	*Lile stolifera* (s)	250	3.62
8	*Atherinella crystallina* (s)	177	*2.56*
9	*Agonostomusmonticola* (s)	15	0.22
10	*Awaous tajasica* (s)	*5*	0.07
11	*Oreochromis mossambicus*	4	0.06
12	Gobiidae (s)	2	0.03
	TOTAL	6911	100

(p)=primary; (i)=introduced; (n)=native; (s)=tolerant

Figures 5a and 5b show the weight of the environmental factors and the grouping of sites on the graphic space of the Principal Components (PC). The first component (PC1) captured 31.29% of the variation and included conductivity (0.47), total dissolved solids (0.47), oxygen (0.46) and current velocity (0.38), and contrasted slightly with sand (-0.11). PC2 explained 19.89% of the variation and contrasted with the big rocks (0.47), the depth (0.43) and the rocks (0.4) *versus* the sand (-0.41), the gravel (-0.21) and the stones (-0.71). PC3 explained 11.3% of the variation and was also a contrast among the sand (0.52), the vegetation (0.41) and the mud (0.29) *versus* the big rocks (-0.33) and the current velocity (-0.28).





Figures 5a and 5b. Diagram of the weights of the environmental variables in PC1, 2 and 3 (modified from García et al 1999).

These results reveal three main environments: 1) sandy areas with little vegetation, a moderate slope and shallow to medium depths (Group I), 2) medium deep areas with rapids and high current velocities, a high content of oxygen and dissolved solids, and a gravelly and rocky substrate (Group II), and 3) deep areas with plant cover, slow currents, big rocks and interstitial mud (Group III).

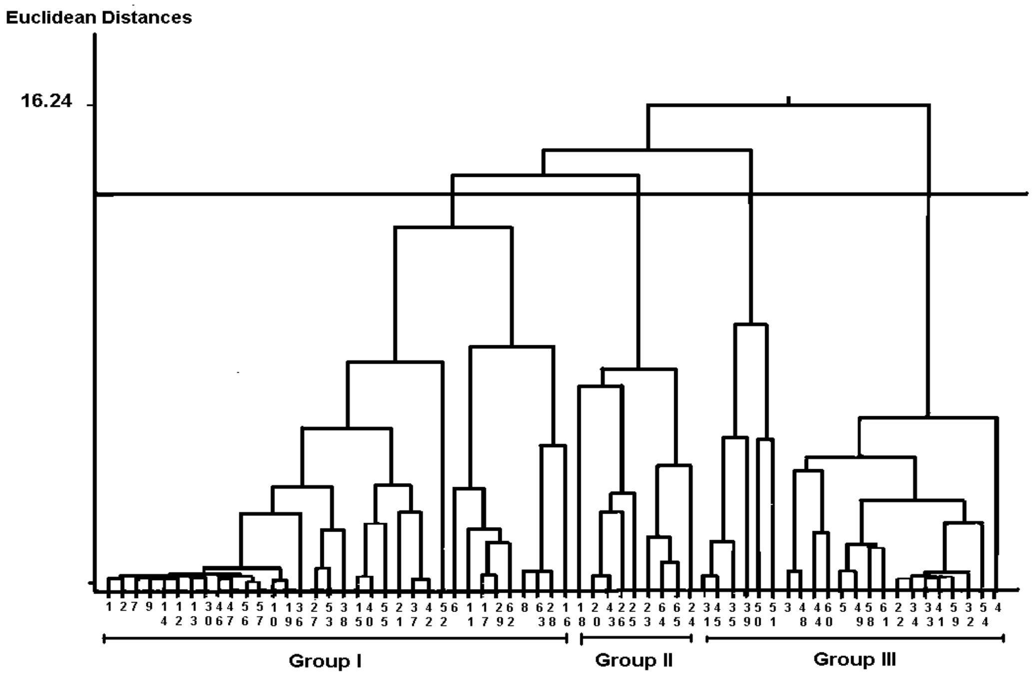
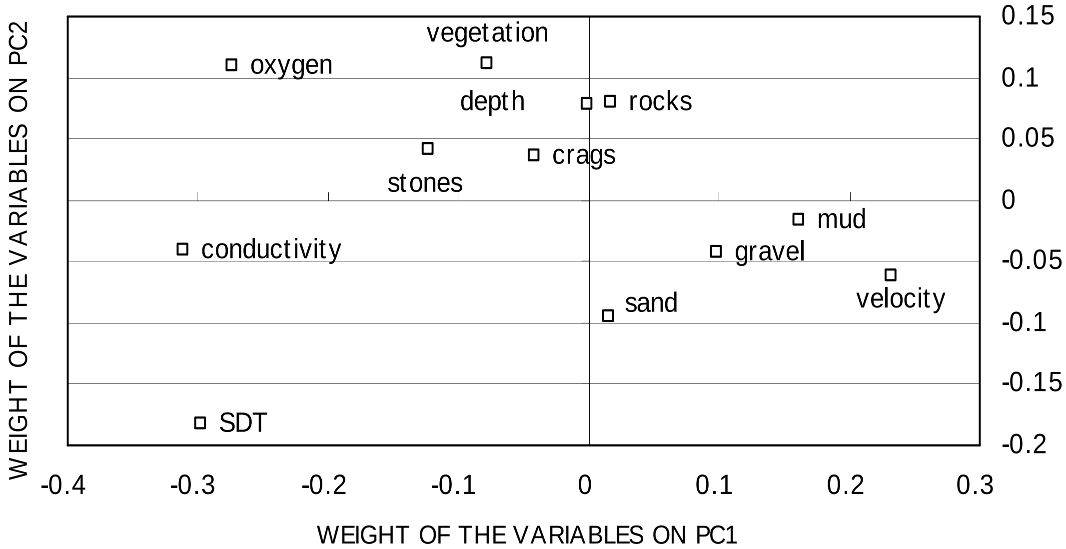


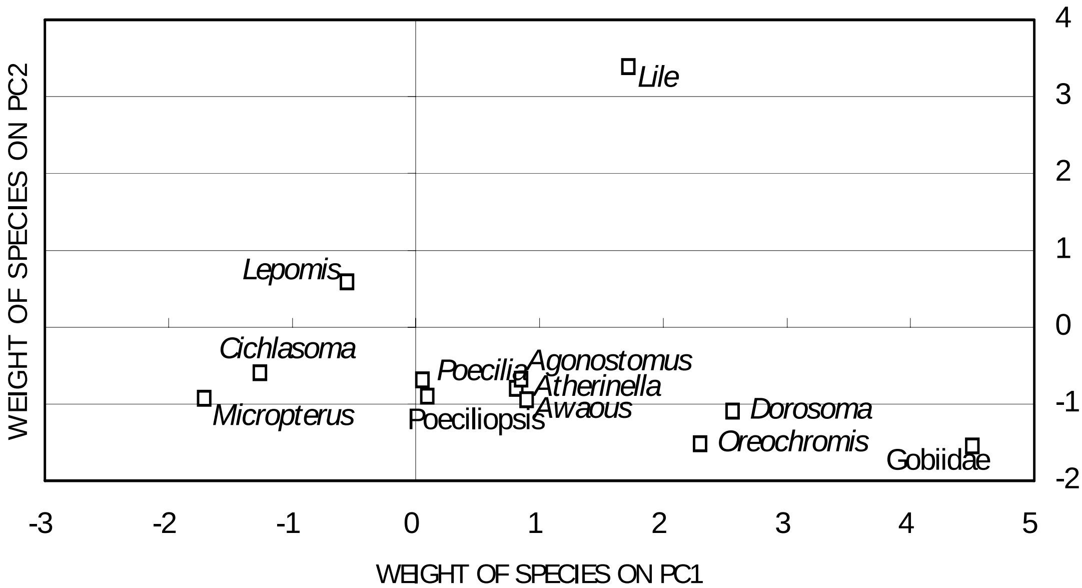
Figure 6. Classification of sampling sites through Cluster Analysis.

The Cluster Analysis classified sites into three environmental groups (Fig. 6). Group I included 34 subsamples (or sites) with moderate current velocity (0 - 0.29 m s^{-1}, with an average of 0.13 m s^{-1}), depths of 0.53 to 1.67m, a sandy substrate (60 - 100%) and scarce vegetation. These sites presented a great number of small fish species (7 - 10), for which reason they were considered nursing, feeding and refuge areas. Group II with 9 subsamples was characterized by high current velocities (0.24 - 0.57 m s^{-1}), depths of 0.38 to 1.70m, sandy and gravelly substrates (60 - 100% and occasional rocks), and areas completely exposed to the Sun´s rays with low diversity plant cover. Group III included 22 subsamples, also with a moderate current velocity (0 - 0.29 m s^{-1}), with greater depths (0.47 - 4 m), small and large rocks (70 - 80%), with and without plant cover, and a low species richness. The low species diversity responded to the spatial segregation of *Dorosoma smithii* in the areas of rapids (Group II) and of *Lepomis macrochirus* in the deep areas (Group III).

The first three factors of the Canonic Correlations Analysis (CCA) explained 79% of the variation in the abundance of the species. The species *Atherinella crystallina*, *Agonostomos monticola*, *Awaous tajasica*, *Poecilia sphenops* and *Poeciliopsis latidens* preferred habitats with a moderate current velocity and shallow waters, with sand and scarce gravel (as the sites defined for Group I), considering the distribution of the weights assigned to the abiotic variables and the species (Figs 7a and 7b; Table 5).

Dorosoma smithii, *Oreochromis mossambicus* and the Gobiidae were found in waters with a high current velocity, gravelly substrates, scarce plant cover and submerged roots (similar to Group II). *Lepomis macrochirus*, *Cichlasoma beani* and *Micropterus salmoides* were associated with high levels of dissolved solids and conductivity, an average oxygen concentration, a low current velocity, deep areas, rocky substrates and no plant cover (similar to Group III). *Lile stolifera* was found associated with deep areas, rocky substrates with mud, a moderate current velocity and plant cover.





Figures 7a and 7b. Diagram of the weights of the fish species and abiotic variables in the CCA (modified from García et al, 1999).

Table 5. Grouping of fish per sites (habitats) in the Santiago river.

Group	Sites (No)	Type	Species
1	34	Sandy and muddy, with vegetation, moderate slope, medium depth and velocity, high diversity.	*Atherinella crystalina* *Agonostomus monticola* *Awaous tajasica* *Poecilia sphenops* *Poeciliopsis latidens*
2	9	Rapids, medium depth, high oxygen and dissolved solids content, increased flow, gravel and rocks, exposed areas, low diversity.	*Dorosoma smithii* *Oreochromis mossambicus* *Gobiidae* sp
3	22	Deep areas, no plant cover, slow-current pools, muddy areas with big rocks, low diversity.	*Lepomis macrochirus* *Cichlasoma beani* *Micropterus salmoides*
	1	Terrestrial plant cover, low currents, deep areas, big rocks and interstitial muds.	*Lile stolifera*

Table 6, shows the ranges for the current velocity, depth and flows recommended by the three methods for the Santiago river. Noteworthy is the high similarity in the ranges considered optimum for the development of species, of the current velocities obtained by the modified Tennant method and by the multivariate analyses. The range that Phabsim considered ideal lies within the margin indicated by the other two methods. In the case of the depth, the multivariate analyses show values that include those obtained by the modified Tennant method and Phabsim. Another noteworthy case is that of the indispensable minimum flow (dry season) and the optimum minimum flow (rainy season) recommended both by Tennant and Phabsim, with a similarity in results and a variation error of 8.5%.

Table 6. Comparative table of the preferred ranges for habitat, and results obtained by applying the flow values to the Santiago river.

	Tennant adapted to Mexico	Phabsim	Multivariate
Current velocity ($m\ s^{-1}$)	0.24 - 1.07	0.15 - 0.27	0.24 - 1.10
Depth (m)	0.30 - 0.91	1.35 - 2.6	0.8 - 3.0
Recommended flows ($m^3\ s^{-1}$)	Dry season 37.12 Rainy season 55.67	Dry season 40 Rainy season 64	

Discusión

The Tennant method adapted to the tropical areas of Mexico is consistent when it considers: 1) a minimum flow of 20% for dry season and 30% for rainy period and 2) the historic analysis of the variations in the flow of the river under study, in order to be able to reproduce the patterns of the natural flows. This method is easy and fast and may be used at the early stages of an integral and adaptive management of a basin.

Phabsim´s simulation of the physical habitat and the criteria of habitat suitability for *Dorosoma smithii* indicate a rapid increase in the potentially usable areas as habitat for the species when the river flow increases to between 20 and 64 $m^3\ s^{-1}$. This relationship is equivalent to filling the main channel of the river that is characterized by pronounced slopes and a greater number of niches in the rainy season, which favors the migration of *D. smithii.*

Many organisms are sensitive to changes in current velocity that are related to a resuspension of food. Others respond to temporal variations in the flow, as this may change the structural conditions of the river, favor an increase in mortality, and modify the availability of resources and the interactions among species (Bayley and Li, 1992). The inhabitable area decreases when the flow is 100 $m^3 s^{-1}$. This corresponds to the filling of the main channel of the river, causing a loss of habitat and niches due to high current velocities in the central area of the river that results in sediment, organic matter and fish being carried away.

A second smaller increase in the habitat-flow relationship (between 160 and 210 $m^3 s^{-1}$) was related to the overflow of the river and the creation of a shallow water area with a soft slope, plant cover and submerged vegetation along the river margins and flood plain, that increase the habitats and niches that are adequate for the development, nursing, feeding and refuge of different fish species throughout the flooded area. Díaz-Pardo, *et al*. (1993), MacLeod, *et al*. (1995) and Jungwirth, *et al.* (2000) pointed out that the presence of vegetation in the flood plain changes the flow regime downstream and represents a factor that is related to the migration of fish communities that flee the elevated flows in the main channel of the river, as occurs in the Santiago river.

Cole (1994) indicated that riparian vegetation is also an important factor in the regulation of light and temperature in rivers. Changes in depth in the Santiago river may also reduce the intensive predation by bigger fish, for which reason these areas are used as nursery areas by many species and this favors an increase in species richness and diversity. Flooding areas have been widely recognized as highly productive habitats, particularly in the case of threatened or endangered species (Spence, *et al*. 1996).

Schiemer (2000) and Arthington *et al.* (2006) mentioned that the ecological quality of a river does not depend only on its structural properties, but also on the interrelationship between its geomorphology and hydrology. Variations in the level of the water generate a continuous change in the location of microhabitats, and determine the availability, connectivity and quality of the refuges in each microhabitat.

The multivariate analyses indicated the importance of insuring the presence of three types of environments:

- Shallow areas with submerged vegetation necessary for small (poecilids) and detritivorous or omnivorous species that migrate to shallow and flooding areas with low to moderate current velocities, high sedimentation rates and presence of allochthonous food.
- Deep rocky areas for predatory, nest-forming and territorial species that prefer areas with abrupt walls and rocky substrates, as well as high contents of oxygen and dissolved solids that favor the establishment of planctonic communities and surface insects.
- Shallow sandy areas with high current velocities and constantly suspended organic matter, or areas with fast currents.

A drastic reduction in river flow may modify the abundance of one or more species if the flooding areas and riparian vegetation decrease or disappear. A constant decrease in river flow may reduce rocky areas and affect the big predatory and territorial species that prefer the deep areas with rocky substrates as nursery and nesting areas. A sudden and uncontrolled increase in the flow of the river may erode the substrate and wash away the invertebrate community that constitutes the main food source of the fish. Also affected is the plant cover that is important for different fish activities, resulting in a change in abundance and diversity (González-Villela, 2007). Fraser (1972), Ward and Tockner (2001), Bunn and Arthington (2002) indicated that the relationship between river flow and species diversity is characteristic of flooding areas.

Increases and decreases of water in the Santiago river are related to the rainy seasons. The lowest flows occur during the Winter with a dominance of sub-superficial hydrologic processes and a maximum fragmentation of the habitat. The greatest flows occur during the Summer with a dominance of hydrologic processes, with greater inputs at the surface and in shallow areas, and an increase in temperature, particularly in flooded areas and zones with scarce terrestrial plant cover. This contrasts with temperate rivers where the main source of water is melting ice and the greatest increase in flow occurs at the start of Spring (González-Villela, 2007).

The multivariate approach applied to the physical evaluation of rivers provides an integrative perspective of the ecological functioning of riparian systems and aids in the study of ecological processes, both of which are essential aspects for the generation of management and conservation strategies (Verdonschot, 2000).

The flow requirements for fish, the water quality and the simulation of the availability curves to predict changes in microhabitats when the river flow changes, as well as the present and historic hydrological conditions in the Santiago river, were used to recommend a flow regime for the management of the Aguamilpa dam as follows:

- A stable average monthly flow of 64 m^3 s^{-1} during periods of management and regulation (October-February) is required as the minimum optimum flow for a general pattern of post-regulation flows.
- Minimum flows of 40 m^3 s^{-1} during the March-May dry season, particularly when the resource is limited.
- Flows of 200 m^3 s^{-1} during June and July to conserve the flood plain.
- Flows of 350 to 500 m^3 s^{-1} during August-September (peak rainy season) as maximum flows to maintain and conserve the structure of the river and flood plain (particularly when the climatic conditions and the hydroelectrical production require the dam to be drained quickly). This flows are estimated as ecological or environmental during some seasons of the year (August-September), may remove sediment and excessive vegetation accumulated on the bottom. This is sometimes necessary to conserve the shape of the river and flood plain, as well as the vegetation along the river. However, this flow regime should be implemented in a flexible way so as to make it possible to carry out necessary adjustments for the best operation of the reservoir (González-Villela and Banderas, 2007).

Conflict around the insufficient availability of water has increased worldwide, particularly in cities, industries and hydroelectric plants, although at the same time there is a greater consciousness about the need to use part of river water to maintain lakes, rivers and aquifers that benefit communities and economies. Governments need to generate methods for an integrated and efficient management of aquatic resources to favor the development of human populations and to protect and restore natural ecosystems (TNC, 2006).

Measuring river flows provides decision makers the information they need to determine how much of the remaining flow can be used by populations, and what percentage of the alteration to the natural flow patterns of the rivers has been caused by human consumption. Thus, river flows need to be measured in order to be able to plan a sustainable use of water as a resource (Davis and Hirji, 2003).

No method for the determination of river flows, out of more than 200, has been used at the regional level for management of aquatic resources. Many authors have indicated that holistic methods are more appropriate than habitat simulation methods, particularly in the case of developing countries as a result of the need to focus on the protection of resources at the ecosystem scale, the strong dependence on the resource for subsistence, and the goods and services provided by aquatic ecosystems, and they consider that holistic methods incorporate advanced techniques, other types of predictive models, hydraulics and tools for habitat modeling, and multiple components of the ecosystem that provide more information (Bunn and Arthington, 2002; Dyson *et al*, 2003; Tharme, 2003 and Arthington *et al,* 2006).

Conclusions

The modified Tennant method, the habitat simulation model and the multivariate analyses indicated that the distribution and abundance of species in the stretch of river under study may be explained by the environmental variations in the current velocity, the substrate, the depth and terrestrial vegetation, variables that are susceptible to natural variations in rivers and/or artificial variations caused by the management of the water flows discharged from dams.

The complexity of ecosystems makes it important to include ecological aspects in the administration of rivers.

The application of various methodologies for the flow environmental analysis is very useful because the habitat analysis differ with respect to the purpose of study, the way information is obtained, the methods of analysis that are applied and the variables that are involved. The complexity of the methods varies according to the aspect that is important and the scales of approximation, and the information that is provided is useful at different levels. The determination of river water flows should become an iterative process in which the actions adopted by the water administrator (restoration flows) are evaluated and monitored to generate recommendations that may change through observation, testing and evaluation, in adaptive and integral ways.

Management policies should adequately evaluate social, political, economic and environmental problems in order to avoid generating conflicts among the users of the resource.

Acknowledgements:

The authors thank Dra. Andrea Raz-Guzman for the translation of the manuscript and for valuable suggestions, to M. en C. Marco Antonio Mijangos Carro for the Santiago river study area map, and Dr. Polioptro Martinez Austria, Director of the Instituto Mexicano de Tecnología del Agua for the support of this study.

References

Arthington, A., S. Bunn, L. Poff & R. J. Naiman, 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications, 16(4): 1311-1318.

Álvarez, J., 1970. *Peces Mexicanos* (Claves). Sec. Ind. Com. Direc. Gral. de Pesca e Ind. Conexas. 166 pp.

Bayley, P. B. 1995. Understanding large river-floodplain ecosystems. *BioScience* 45(3):154-163.

Bovee, K. D., 1986. *Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology*. National Ecology Center. Division of Wild and Contaminant Research. Fish and Wild Service. US Department of the Interior. Washington, DC. 233 pp.

Bunn, S. E. & P. M. Davies, 2000. Biological processes in running waters and their implications for the assessment of ecological integrity. *Hydrobiologia* 422/423: 61-70.

Bunn, S.E. & A.H. Arthington, 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30(4):492-507.

Castro-Aguirre, J. L., 1978. *Catálogo sistemático de los peces marinos que penetran a las aguas continentales de México, con aspectos zoogeográficos y ecológicos.* Dirección General del Instituto Nacional de la Pesca. Serie Científica No. 19 a 29. México.

Cole, G. A., 1994. *Textbook of Limnology*. 4^{th} ed. Waveland Press. Prospect Heights. Illinois. USA.

Comisión Nacional del Agua, 1994. *Archivos de información actualizada a 1994 de estaciones hidrométricas y entradas a las presas*. CONAGUA. México.

Davis R. & R. Hirji, 2003. *Water Resources and Environment Technical Note C.1. Environmental Flows: Concept and Methods.* Series Editions. The World Bank, Washington, D.C.

Díaz-Pardo E., J. Paulo-Maya & E. Soto-Galera, 1996. *Monitoreo de la ictiofauna posterior a la construcción de la PH. Zimapán*. Informe final.

Dyson, M., G. Bergkamp & J. Scanlon, 2003. *Flows*. Editorial UICN. Reino Unido.125 p.

Fischer, S. & H. Kummer, 2000. Effects of residual flow and habitat fragmentation on distribution and movement of bullhead (Cottus gobio L.) in an alpine stream. *Hydrobiología* 422/423: 305-317.

Fraser, J.C., 1972. Regulated discharge and stream environment. In: *River Ecology and Man*. (Eds): Oglesby, R.T., C.A. Carlson & J.A. McCann. New York. p. 26-82.

Galat, D. L. & R. Lipkin, 2000. Restoring ecological integrity of great rivers: historical hydrographs aid in defining reference conditions for the Missouri River. *Hydrobiologia* 422/423:29-48.

García, R. E., R. González-Villela, P. Martínez A., J. Athala M. & G. A. P. Soldán, 1999. *Guía de aplicación de los métodos de cálculo de caudales de reserva ecológicos en México.* Colección Manuales. Instituto Mexicano de Tecnología del Agua. México. 190 p.

González-Villela, R., 2007. Cálculo de caudales para la conservación del hábitat en ríos regulados por presas. In: *Bases Teóricas y Prácticas del Manejo Limnológico de las Presas Mexicanas: Hacia un Manejo Sustentable del Agua.* (Ed.). Arredondo, F. J. L. Editorial. AGT.

González-Villela, R. & A. Banderas Tarabay, 2007. Curvas de preferencia de hábitat para el cálculo de caudales en ríos regulados por presas. Caso de estudio: Río Santiago, Nayarit, México. In: *Las Aguas Interiores de México*. (Eds). De la Lanza E. G. & J. L. Calderón. Editorial AGT.

Gustard, A., 1992. Analysis of River Regimes. (Eds) Calow and Petts. *The Rivers Handbook*, Vol. I. J. Wiley & Sons.

Jungwirth, M., S. Muhar & S. Schmutz, 2000. Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. *Hydrobiologia* 422/423:85-97.

King, J. & C. Brown, 2006. Environmental flows: stiking the balance between development and resource protection. *Ecology and Society* 11(2): 26-47.

Instituto de Biología (IBUNAM), 1992. *Estudios específicos de la fauna de la zona del embalse del proyecto hidroeléctrico Aguamilpa, Nayarit.* Universidad Nacional Autónoma de México. pp 94-95.

Lowe-MacConnell, R. H., 1975. *Fish communities in tropical freshwater*. Academic Press. New York XVII. London, Longman. 337 pp.

MacLeod, W. D., C. K. Minns, A. Mathers & S. Mee, 1995. *An evaluation of biotic indices and habitat suitability scores for classifying littoral habitats. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2334*. Minister of Supply and Services Canada. 26 p.

Moog, O. & A. Chovanec, 2000. Assessing the ecological integrity of rivers: walking the line among ecological, political and administrative interest. *Hydrobiologia* 422/423: 99-109.

Rodríguez Gutiérrez, M., 1992. Técnicas de evaluación cuantitativa de la madurez gonádica en peces. AGT Editor, S.A. México. 79 p.

Rosgen, D. L., 1996. *Applied river morphology*. Wildland Hydrology, Colorado, USA.

Tennant, D. L., 1976. *Instream flow regimens for fish, wildlife, recreation and related environmental resources*. U.S. Fish and Wildlife Service, Montana, U.S.A.

Tharme, R. E., 2003. A global pespective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19: 397-441.

The Nature Conservancy (TNC), 2006. Ecological limits of hydrologic alteration. Integratin environmental flows with regional water management. Sustainable Waters Program. Boletín. 1 – 4 p.

Schiemer, F., 2000. Fish as indicators for the assessment of the ecological integrity of large rivers. *Hydrobiologia* 422/423:271-278.

Schreck, C. & P. B. Moyle, 1990. *Methods for fish biology.* American Fisheries Society. Bethesda Maryland. 684 p.

Spence, B. C., G. A. Lomnscky, R. M. Hughes & R. P. Novitski, 1996. An ecosystem approach to salmonid conservation. Mantech Environmental Research Service Corp. Corvallis, Oregon. USA.

Ward, J. V. & K. Tockner, 2001. Biodiversity: towards a unifying theme for river ecology. *Freshwater Biology* 46: 807-819.