

SUSTAINABLE ARCHITECTURE OF ARROYO ALAMAR, TIJUANA, BAJA CALIFORNIA, MÉXICO

PROJECT NUMBER: W-03-16

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NARRATIVE SUMMARY

A methodology for the sustainable architecture of Arroyo Alamar, in Tijuana, Baja California, México, is presented. Sustainable river architecture enables a seamless interaction between diverse stream functions and uses, including flood mitigation, groundwater replenishment, compliance with federal stream zoning regulations, preservation of riparian corridors, enhancement of water quality, and multipurpose land use such as agriculture, light industry, sports and recreation, and urban aesthetics.

Topographic, hydrological, hydroecological, hydraulic, vegetation, and land-use data were assembled to accomplish the sustainable architectural design of Arroyo Alamar. In addition, a socioeconomic study was performed to develop the appropriate basis for design.

The flood conveyance channel is designed to carry the 10-year flood without restrictions and the 1000-year flood with some restrictions. Above the 10-year flood level, the 1000-year flood plain is allocated to soft uses, including recreation. Users of these features would move out of harm's way in the event of an unusual flood. The floodway is stabilized using gabion systems and natural vegetation. The sustainable architectural design considers three parks in one: recreational, sports, and ecological. The 10-kilometer reach of Arroyo Alamar is designed to reflect these uses.

Sustainable river architecture successfully reconciles hydroecological laws and economic interests. It provides a clear societal benefit such as the inclusion of the river and its flood plain into the city's footprint.

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INTRODUCTION

The Arroyo Alamar, in Tijuana, Baja California, is being considered by the Municipality of Tijuana for rehabilitation. The objective of the project is to enable a seamless interaction between diverse stream functions and uses, including flood mitigation, groundwater replenishment, compliance with federal stream zoning regulations, preservation of riparian corridors, enhancement of water quality, and multipurpose land use such as agriculture, light industry, sports and recreation, and urban aesthetics.

The project encompasses a 10-km stretch of Arroyo Alamar, between Puente Cañón del Padre and its confluence with the Arroyo Las Palmas, in the city of Tijuana. Upstream of Arroyo Alamar, Cottonwood Creek and Tecate Creek join together in Marron Valley, just north of the U.S.-Mexican border, to form the Tijuana River. In turn, the Tijuana River takes the name of Arroyo Alamar as it enters México and flows for about 5 km past Puente Cañón del Padre. Immediately downstream of the project site, Arroyo Alamar joins the Arroyo Las Palmas to again form the Tijuana River, which flows back into the United States and discharges into the Pacific Ocean at Imperial Beach, California.

Due to its close proximity to the United States, the project site is of strategic binational importance. Over the past several years, lack of proper planning and disdain for regulation have produced an environment where irregular settlements abound, and where the unregulated stream uses, including encroachment on the flood plain and illegal trash dumps, constitute a veritable flood risk and a public health hazard.

Thus, there is an urgent need to rehabilitate the Arroyo Alamar, not only to restore its natural functions, but also to enable a planned and effective use of the stream to reduce the flood risk while maximizing the use of the flood plain. This leads to the concept of "sustainable river architecture," which refers to the design of the stream channel and its flood plain to conserve their natural functions, while at the same time recognizing their socioeconomic role and relationship to urban society. The term entails the design of the stream channel to convey the 10-year flood without restriction (i.e., no artificial obstructions allowed), and the 1000-year flow with some restrictions. The restrictions to the 1000-year flood channel, perched above the 10-year flood channel, allow only soft uses, where people can get out of harm's way in the event of a major flood, and where

property damage would be minimal because only temporary structures would be allowed on the flood plain.

While the concept of "sustainable river architecture" is decidedly novel, it has already been tried in several places with a great measure of success. To the writers' knowledge, the best example in México of planned, mixed architectural use of a river and its flood plain is in Monterrey, Nuevo León, on the Santa Catarina River. In this project, a stretch of 7.5 km of river adjacent to downtown Monterrey has been recently rehabilitated following the principle of sustainable river architecture. The river and its flood plain have remained a visible and useful part of the city, while the flood control, groundwater replenishment, sports and recreation, and other sustainable development objectives have been properly addressed (Figure 1).

RESEARCH OBJECTIVES

This project builds upon two previously funded Southwest Consortium for Environmental Research and Policy (SCERP) projects. The first project, funded in the year 2000-01, was titled "Flood hydrology of the binational Cottonwood Creek - Arroyo Alamar, California and Baja California." This project calculated flood discharges in Arroyo Alamar for return periods of two to 1000 years. A primary objective was to model event rainfall-runoff in the watershed of Arroyo Alamar, a binational watershed covering 1387 km², 86 percent of which lies on the U.S. side of the border. Another was to use the routing model to estimate the volume of groundwater replenishment that would be lost to channel lining, which would satisfy only a flood control objective.

The second project, funded in the year 2002-03, was titled: "Hydroecological characterization of Arroyo Alamar, Tijuana, Baja California, México." The project characterized the Arroyo Alamar in terms of a host of hydroecological and socioeconomic functions, which included flood mitigation, groundwater replenishment, preservation of riparian corridors, compliance with federal stream zoning regulations, and multipurpose use of the flood plain. A primary objective involved designing the channel cross-section to convey the 10-year flood in a lower portion and the 1000-year flood in a much wider, upper portion. The U.S. Army Corps of Engineers' HEC-RAS model was used for this purpose. Other goals were to define horizontal and vertical alignments for the rehabilitated channel within the perceived constraints of stream mechanics, hydroecology, hydrogeology, and socioeconomic use of the flood plain.

Given the background of hydrological and hydroecological studies, the next logical step is to design the elements of sustainable architecture that are particularly suited to the Arroyo Alamar. The specific research objective encompasses the spatial design of the 10-kilometer reach of Arroyo Alamar, seeking a compromise between the natural and anthropogenic functions of the stream. The natural functions include flood mitigation, groundwater replenishment, and preservation of the riparian corridor. The anthropogenic (i.e., socioeconomic) functions include the need for parks, areas for sports and recreation, landscaping, and aesthetics.

In the framework of stream rehabilitation, the concept of sustainable architecture comprises the hydrological, ecological, architectural, and socioeconomic aspects that contribute to the spatial design of the stream and its flood plain. The ultimate goal is to design a channel that will foster an environment that floods, plants, animals, and humans can share with harmony, in accordance with the principle of sustainable development (Figure 2).

RESEARCH METHODOLOGY / APPROACHES

The research methodology/approach consists of the following steps:

- (1) Data collection
- (2) Development of GIS
- (3) Involvement of stakeholders
- (4) Sustainable architectural design

The project has collected topographic, hydrological, hydroecological, hydraulic, vegetation, socioeconomic and land-use data to accomplish the sustainable architectural design of Arroyo Alamar. The topographic data includes digital images of the project site. The hydrological data was collected as part of the project entitled "Flood hydrology of the Binational Cottonwood Creek - Arroyo Alamar, California, and Baja California." Flood discharges for the two-, five-, 10-, 25-, 50-, 100-, 200-, 500-, and 1000-year return period were established in this study.

The hydroecological data was collected as part of the project entitled "Hydroecological characterization of Arroyo Alamar, Tijuana, Baja California, Mexico." The series of flood discharges was extended to 5000- and 10000-year using the Gumbel method (Ponce 1989). Using standard floodway design concepts, the 10000-year design discharge is used to size the freeboard. In other words, the floodway should pass this flood peak using the available freeboard (The 10000-year frequency is equivalent to the concept of Probable Maximum Flood, or PMF, in the United States). The project calculated design flood stages (hydraulic data) using the U.S. Army Corps of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS) model.

In addition to the flood stages, the hydroecological project defined the following objectives:

- Document present conditions, to serve as baseline for future comparisons (Figure 3)
- Establish bank protection using gabions, which are a reasonable compromise between channel lining to provide channel stability on one hand, and the perceived need to keep the lining porous enough to encourage groundwater replenishment on the other hand
- Calculate, using HEC-RAS, design velocities for both in-bank (10-year) and over-bank (1000- and 10000-year) flows

- Identify the floristic component of Arroyo Alamar, to make possible the enhancement of the native riparian corridor
- Identify other natural ways to stabilize the banks and provide additional flood protection
- Establish the horizontal alignment of the proposed channelization
- Study various alternatives for vertical alignment, to analyze the possibility of artificially lowering the flood channel to enhance landscaping and aesthetics, while making possible the extraction of much needed sand and gravel for commercial purposes

The GIS defines spatial management units. These units contain socioeconomic data, such as income, years of schooling, quality of housing, and characteristics of the infrastructure and environment; these final two units will specify biological species, soil types, terrain slopes, and hydrologic information. The GIS makes it possible to:

- Define the land use within the framework of the Arroyo Alamar sustainable architecture project
- Provide the Municipality of Tijuana with a spatial data base of Arroyo Alamar and environs
- Develop a social management program, designed to incorporate local stakeholders in the decision making process

The Citizens Involvement Program seeks to gather stakeholders' input through questionnaires and information meetings. Input will be continuously considered during the design stage. Feedback from local stakeholders is considered absolutely necessary in order to involve them effectively in the sustainable development of the river.

The design methodology encompasses the entire length of Arroyo Alamar, from its upstream end at the bridge at Cañón del Padre to its downstream end 10 km (actually, 9.88 km) downstream, to connect with the Second Phase of Río Tijuana. This includes three distinct reaches (Figure 4):

- (1) From the bridge at Cañón del Padre to the bridge at Boulevard Terán Terán
- (2) From the bridge at Boulevard Terán Terán to the bridge at Boulevard Clouthier
- (3) From the bridge at Boulevard Clouthier to the end of the Second Phase of Río Tijuana

Reach 1 is currently a mix of agricultural and industrial uses; reaches 2 and 3 are primarily make-shift urban. Garbage dumps and irregular settlements dot the Arroyo Alamar landscape.

The research methodology includes the review of several river rehabilitation projects that have been completed, particularly in México. In the Atoyac River, in Oaxaca, the concept of river architecture, including groundwater replenishment, preservation of riparian vegetation, flood mitigation, landscaping, and recreation was successfully implemented in 1996. The Río Santa Catarina and the Río La Silla, in Monterrey, are two other

successful projects of sustainable river architecture. Insights gained by the review of these projects is used in the formulation of the sustainable architectural design of Arroyo Alamar.

PROBLEMS / ISSUES ENCOUNTERED

The research team encountered no major problems or issues during the period of performance. The project held monthly meetings in Tijuana, México, to coordinate the work performed by the various members (Figure 5). Ana Elena Espinoza coordinated the work of the Tijuana staff. The field survey was contracted to Instituto Nacional de Estadística Geografía e Informática staff in Tijuana. The project hired Ever Castro, a Tijuana architect, as an independent contractor to assist in the digital rendering of the architectural design. Data analysis and modeling was performed by Sezar Ercan. Web design and other web-based work were performed by Flor Perez.

RESEARCH FINDINGS

The following three activities are summarized in this report:

- (1) Review of existing sustainable river architecture projects in México
- (2) Basis for sustainable architectural design of Arroyo Alamar
- (3) Sustainable architectural design of Arroyo Alamar

Review of existing sustainable river architecture projects

The following projects were reviewed:

- (1) Río Atoyac, Oaxaca, Oaxaca, México
- (2) Río Santa Catarina, Monterrey, Nuevo León, México
- (3) Río La Silla, Monterrey, Nuevo León, México

Río Atoyac

The Atoyac River, which crosses the city of Oaxaca, México, was developed in 1996 following the principles of sustainable river architecture. A length of 2 km of river was channelized using a trapezoidal, eight-point cross section, and soft uses were implemented on the flood plain. These included walkways, exercise tracks, basketball courts, skating courts, playgrounds, and other recreational features. The pilot channel (10-year floodway) was lined with gabions, and riparian vegetation was allowed to develop along the river banks. The most important accomplishment was that the river and its environs were effectively incorporated into the city's footprint, while the flood conveyance function was maintained and enhanced. A pictorial documentation is shown in Figures 6-21.

Río Santa Catarina

The Santa Catarina river, which crosses the city of Monterrey, México, was recently developed (2002) following the principles of sustainable river architecture. The project developed 7.5 km of the principal watercourse, lying within the Monterrey city limits, into an ecological, cultural, sports, and entertainment park. The rehabilitation of the river environment and its incorporation into the urban footprint gives the city's population a safer, healthier, visually appealing, and more useful area.

A pilot channel implemented as a floodway was designed to carry the 10-year to 50-year flood. Gabions were used to protect the banks of the pilot channel against erosion. The flood plain was built on the right side of the pilot channel, and designed to carry the 1000-year flood. The plan for the park included facilities for sports such as soccer, basketball, volleyball, a go-kart track, and a temporary building for community entertainment. Flood plain areas are reserved for other temporary uses such as a swap meet and a helicopter pad.

The economic viability of the project was assured with a series of marketing strategies. The external slopes of the channel were leased to advertisers. Flower garden arrangements with commercial motifs are planned on the high river banks (left margin). Cooperative agreements were signed with third parties to develop the flood plain for diverse cultural, sports, and recreational activities. A pictorial documentation is shown in Figures 22-29.

Río La Silla Natural Park

The project "Parque Natural Río La Silla" encompasses a stretch of the Río La Silla (The Chair River), located along the eastern slopes of the Sierra Madre Oriental, in the city of Monterrey, Nuevo Laredo, México. The name "La Silla" originates in a nearby geologic outcrop that has the form of a chair (*silla*, in Spanish). This river crosses the city along a length of several kilometers, until it joins the Río Santa Catarina. A three-kilometer reach of the Río La Silla has been recently developed as a natural park (2002). The

development includes fencing, various structures for sports and recreation, and a park administration building.

The significant accomplishment has been the creation of another park within the confines of the city of Monterrey. The park is being used by the local population as a natural environment, thus the name of "Río La Silla Natural Park." Several recreational activities are permissible, all-the-while actively promoting a culture of environmental stewardship of the park's natural resources. The park has a high biodiversity, with the presence of diverse species such as fish, squirrels, woodpeckers, turtles, sycamores, and ancient sabinos. Sports and recreation features include exercise facilities and a walking fitness course and bicycle path. A pictorial documentation is shown in Figures 30-33.

Basis for sustainable architectural design of Arroyo Alamar

A socioeconomic study was performed with the objective of developing the basis for the sustainable architectural design of Arroyo Alamar. The report considers the following topics:

- (1) Background
- (2) Location
- (3) Field survey (questionnaire)
- (4) Evolution of the settlement
- (5) Age pyramid
- (6) Years of residence
- (7) Place of origin
- (8) Occupation of the economically active population
- (9) Economic strata
- (10) Land ownership
- (11) Distribution of lots by land holding
- (12) Classification of housing in terms of physical components
- (13) Housing with piped potable water
- (14) Housing with sanitary plumbing and sewage drainage
- (15) Housing with electricity
- (16) Population density
- (17) Preference of local inhabitants with regard to recreational activities in the flood plain
- (18) Conclusions
- (19) Proposal for a sustainable architectural design of Arroyo Alamar

A sample of the GIS-based data analysis contained in the aforementioned report is shown in Figure 34.

The conclusions of the report are the following:

- The project area has had three distinct periods in its history of settlement:
 - (1) Beginning of the 1970s,
 - (2) End of the 1980s, and
 - (3) Middle of the 1990s

The more recent period represents a greater settlement activity.

- The majority of the settled population is of productive age, that is, from 20 to 45 years old. The next important group in terms of size is the children, from 0 to 15 years old
- The population of Arroyo Alamar originates predominantly from the northwestern states of Baja California Sur, Sinaloa, and Sonora
- While there are settlers that have been there for more than twenty years, a third of them have arrived in the past six years
- The distribution of income reflects the years of settlement. In the great majority of cases, income was proportional to years of settlement
- Income for the majority of the population is about three times the minimum salary, which is considered an average income. Income for the population of Arroyo Alamar varies between three and four minimum salaries
- The irregular settlements have the lowest salaries (less than three minimum salaries). In this case, the quality of housing is poor
- There are no irregular settlements older than 23 years. The people who have been there more than 23 years are the legal owners of the land
- The lots are rented without regard to their legal condition
- Housing quality is not determined by type of salary or ownership
- Houses that have piped potable water also have sanitary plumbing
- Age of settlement does not determine whether the housing has piped water and sewage. There are new settlements less than 5 years old that have piped water, sewage drainage, and electricity
- Although some houses are connected to the public power system, many others are not. These often take their power in a clandestine fashion (the so-called *diablitos*), endangering neighbors and creating a public hazard
- Population density of Arroyo Alamar is very low, compared to the high density found in the city of Tijuana
- The people of Arroyo Alamar say that there is a lack of recreational space

Based on the socioeconomic study, the project site is divided into three zones or phases, from downstream to upstream:

- (1) Greenhouses, recreational, equestrian, and sports areas.
- (2) Sports and recreational areas.
- (3) Natural (ecological) park.

The proposal is shown in Figure 35.

Sustainable architectural design of Arroyo Alamar

Design philosophy

Rivers are natural entities possessing physical, chemical, and biological properties. They use the force of gravity to convey water, which carries solids (suspended and dissolved, consisting of sediments, humus, nutrients, and other chemical constituents) from uplands to the sea, closing the hydrologic cycle. In addition, they serve an anthropogenic purpose, conveying water to rural and urban settings, where it is used to satisfy various human needs.

Rivers perform a host of natural functions, among which some of the most important are:

- Flood conveyance
- Groundwater replenishment (in arid and semiarid regions)
- Sustenance of riparian corridors
- Enhancement of water quality (through self-purification)
- Preservation of biodiversity

In this era of environmental awareness, societies can no longer afford to treat rivers as mere flood-conveyance systems. Equally important are the other functions identified above. Thus, sustainable river architectural design entails a multidisciplinary approach wherein specific attention is paid to the river's natural functions, tying those together with other identified anthropogenic functions.

In the case of Arroyo Alamar, in addition to serving the aforementioned functions, the river has to serve a land-use purpose, which includes agriculture, light industry, and sports and recreation. Thus, the sustainable architectural design of Arroyo Alamar hinges upon the formulation of the natural and anthropogenic functions of the river to enable a seamless interaction of diverse uses in the spatial and temporal domains.

In essence, it means the design of a flood conveyance channel that can carry the 10-year flood without restrictions and the 1000-year flood with restrictions. It implies that above the 10-year flood level, the 1000-year flood plain can be allocated to soft uses such as sports and recreation. Users of these features would move out of harm's way in the event of an unusual flood. To satisfy the perceived need for groundwater replenishment, the 10-year floodway should be stabilized using natural or some other soft means. Gabion systems are particularly indicated for permeable-surface river bank stabilization (Ponce et al. 2003).

A significant feature of the sustainable river architectural design for Arroyo Alamar is the incorporation of the river and its environs into the city's footprint. This feature provides a host of social and other related benefits that set this solution apart from outdated channel-lining solutions which ostensibly sequester the river from the city. Natural rivers are

aesthetically pleasing live entities. Therefore, the sustainable architectural design must preserve and enhance these natural characteristics.

The design philosophy for sustainable architectural design is in line with recent experiences in the Atoyac River (Figure 36), and the Santa Catarina and La Silla rivers, as documented elsewhere in this report. The common denominator for these projects is the maintenance of natural functions and the effective incorporation of the river and its environs into the city's footprint. Thus, the same design approach is postulated for the Arroyo Alamar.

Horizontal alignment

The design of the horizontal alignment of Arroyo Alamar has been accomplished using the current location of the streambed. It is understood that the stream will have a tendency to change its alignment with time. The proposed alignment fixes the streambed in order to define the external limits of the project. The details of the horizontal alignment are given in Ponce et al. (2003).

Vertical alignment

There are three ways to design the vertical alignment of a river channel.

- (1) Above ground, with levees, as in the Primera Etapa of Río Tijuana; i.e., a net import of construction materials to build the earthen fill
- (2) By balancing cut and fill to minimize earth movement/borrowing, i.e., with a minimum import/export of materials
- (3) A depressed cross section, with a net export of river bed material

The first solution, the "hold by levee" type, has a number of serious drawbacks, among which some of the most important are:

- It raises the stakes in the case of catastrophic floods, i.e., those with return periods above those used in the design of the levee. Failure remains a possibility in this case, and the water will pour with tremendous force from the levee top
- It hides the river and its flood plain from the local population, effectively sequestering the stream and rendering it inoperable for most other uses except flood control, and this only up to a point. The damage to the quality of life is substantial
- In cases where flooding is necessary to nourish the floodplain ecosystem, the "hold by levee" type of flood control system effectively eliminates nutrient replenishment, becoming unsustainable in the long run

The second solution, the "cut and fill" type, is environmentally appropriate, but it requires a large footprint in order to provide reasonable flood control (100-year or larger design flood).

The third solution, a "depressed channel" type, is a convenient compromise between competing hydroecological laws, anthropogenic uses, and economic interests. In the case of Arroyo Alamar, the depressed channel solution makes sense, particularly because the extracted material (sand and gravel) could be commercialized to help finance the park project. Commercial sand and gravel are at a premium in California and Baja California, with large volumes being annually exported from Baja California to California to satisfy the demand. A report on this subject can be found at Ojos Negros Research Group (2002).

In addition to making economic sense in the region, the "depressed channel" solution makes sense from an aesthetic point of view. Both the Atoyac and Santa Catarina rivers have "depressed channel" solutions, and the landscaping and aesthetic benefits are shown to be quite significant. This same type of solution has been tried in the Tercera Etapa of Río Tijuana, albeit with concrete lining of the floodway. From a hydrological and architectural standpoint, the "depressed channel" is the preferred solution for the vertical alignment of Arroyo Alamar.

To examine the quality of sand and gravel, six exploratory boreholes were dug in the project site. The details of the sampling are given in Ponce et al. (2004a, 2004b). Figure 37 shows the location of the boreholes, and Figure 38 shows the results of grain-size analysis. Five samples (1C, 2A, 3C, 4A and 6C) classify as either SP (poorly graded sand) or SW (well graded sand), and only one sample (5C) classifies as SP-SM (silty sand). For the most part, the bed material of Arroyo Alamar is composed of coarse alluvial material in the sand and gravel sizes, competent to be used as construction materials. Preliminary estimates of the quantities of removed material for several postulated vertical alignments are found in Ponce et al. (2003). The final choice of vertical alignment will require more detailed study and analysis, including detailed topographic maps.

Hydraulic modeling with HEC-RAS

The design flood discharges for Arroyo Alamar have been calculated by Ponce (2001). These flood discharges are used to calculate flood stages in the typical cross section, using the U.S. Army Corps of Engineers' HEC-RAS model. Details of this modeling are given in Arroyo Alamar Sustainable Architecture Design Team (2004).

Table 1 shows the hydraulic data, including discharge, flow depth, inbank flow mean velocity, overbank flow mean velocity, inbank Froude number, total Froude number, and freeboard. It is seen that the designed cross section is able to pass the 10000-year flood peak, which is akin to the concept of Probable Maximum Flood (PMF). The freeboard for the design 1000-year flood is 1.02 m, and for the 10000-year flood (the "freeboard hydrograph") is 0.1 m.

Figure 39 shows the typical cross section in the sustainable architecture design of Arroyo Alamar.

Sustainable architectural design

Based on the socioeconomic study, the sustainable architectural design of Arroyo Alamar was divided into three phases as follows (see Figure 10):

(1) First Phase: Recreational Park

Area A: From the end of the Second Phase of Río Tijuana to the bridge at Boulevard Clouthier.

(2) Second Phase: Sports Park

Area B: From the bridge at Boulevard Clouthier to the bridge at Boulevard Terán Terán.

(3) Third Phase: Ecological Park

Area C: From the bridge at Boulevard Terán Terán to the bridge at Cañón del Padre.

A sample of the design is shown in Figure 40-42. A sample of the digital architectural rendering is shown in Figure 43-45.

Implementation

The implementation of a design such as the sustainable architecture of Arroyo Alamar requires a good measure of political will and strong and dedicated leadership. For one thing, there is the issue of where to relocate the current settlers of the flood plain. Areas currently occupied by irregular settlements will have to be cleared to make way for the park project. This will require an organization of stakeholders and government officials committed to seeing the project to completion, despite the odds. Of course, the alternative is to do nothing, but this is unsustainable and bound to make matters worse in the future. In the case of the Arroyo Alamar, the issues of public health and flood risk should be taken seriously.

One way to facilitate the implementation of the project, which has been tried in other places, is to bring in commercial third parties that would be willing to develop the flood plain with temporary uses. This course of action has been used successfully in the Santa Catarina project, where entertainment services companies have been brought in to collaborate with the city in the development of the flood plain. It is also possible to lease space along the river banks to commercial companies for flower gardens and other landscaping projects that advertise established brands. Any of a number of economic incentives can be tried to interest third parties in the flood plain development with soft uses. In this way, everybody wins, and the project can be carried to the implementation stage. The examples reviewed, Atoyac, Santa Catarina, and La Silla Rivers, show that the sustainable architecture alternative for flood plain development makes hydrological,

ecological, economic, and social sense. It is the only holistic way of dealing with flood plain development in urban settings.

CONCLUSIONS

The following conclusions are obtained from this study:

- The sustainable architectural design of Arroyo Alamar has been accomplished.
- The design concept considers a host of river natural functions and several identified anthropogenic uses.
- The river's natural functions include flood mitigation, groundwater replenishment, preservation of riparian corridors, sustenance of riparian corridors, enhancement of water quality, and preservation of biodiversity.
- The anthropogenic uses include agriculture, light industry, sports and recreation, and landscape aesthetics.
- A socioeconomic study, which included a questionnaire and field survey, served as the basis for the spatial design.
- The "depressed channel" type of vertical alignment shows promise in the Arroyo Alamar. The extracted material could be commercialized to help finance the park project.
- The sustainable architectural design consists of three parks in one: (1) recreational, (2) sports, and (3) ecological. The details of the design can be found [online](#) (a collection of 45 images in jpg format).
- An intrinsic component of the design is the digital rendering, which includes the following online features: (1) mobile design, (2) perspectives, (3) virtual cameras, and (4) movies (see Table 2).
- The concept of sustainable architectural design successfully reconciles hydroecological laws and economic interests, while providing additional benefits such as (1) the inclusion of the river and its flood plain into the city's footprint, and (2) enhanced landscape aesthetics.
- Commercial third parties should be encouraged to participate in the development of the flood plain with soft uses. This facilitates project funding and implementation.

RECOMMENDATIONS FOR FURTHER RESEARCH

The following recommendations are offered for further research:

- Three studies have been completed on the Arroyo Alamar rehabilitation project: (1) flood hydrology, (2) hydroecology, and (3) sustainable river architecture. Future studies should address the institutional capabilities of the city of Tijuana to carry out this project to completion. Particular attention should be paid to funding sources and to the formation of stakeholder entities.
- The "depressed channel" type of vertical alignment shows promise. More detailed technical and economic studies are recommended to support this concept for Arroyo Alamar.

- Given the current health hazard and flood risk posed by the Arroyo Alamar, efforts should be directed to implementing the social momentum required to carry out this project to completion.

RESEARCH BENEFITS

The following research benefits have been identified:

- A proposal for a sustainable architectural design of a river and its flood plain (Arroyo Alamar) has been advanced. The proposal is novel because it maintains the river's natural functions. In addition, it incorporates the river into the city's footprint, creating a set of three parks that will contribute to increase the quality of life for all Tijuana residents.
- The proposal replaces the current situation, which represents a decided flood risk and public health hazard. Rehabilitation of the Arroyo Alamar is a must if the city of Tijuana is to make strides to improve its image.
- The research methodologies developed as part of these SCERP-funded studies, including flood hydrology, hydroecology, and sustainable river architecture, are technically and environmentally sound. These methodologies can be applied to other rivers in similar urban settings throughout México, the United States, and the world.

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