HYDROECOLOGICAL CHARACTERIZATION OF ARROYO ALAMAR, TIJUANA, BAJA CALIFORNIA, MÉXICO

PROJECT NUMBER: NR-02-01

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NARRATIVE SUMMARY
The Municipality of Tijuana has among its current projects the rehabilitation of Arroyo Alamar, a tributary of the Tijuana river. The project will satisfy a host of urban-planning needs, such as the preservation of riparian areas, flood management, planned land use, recreation, landscaping, a green corridor, replenishment of groundwater, improvement of water quality, and compliance with federal stream zoning restrictions.

The project encompasses the 10 kilometer (km) reach of Arroyo Alamar, located between the bridge on the toll road to Tecate and the channelized reach near the confluence with the Tijuana river. The objective of the project is to rehabilitate the Arroyo Alamar and its flood plain to encourage planned land use and preserve primary hydroecological functions.

The Municipality of Tijuana has developed a preliminary land-use plan that includes a diversity of uses such as agricultural, industrial, urban, recreation, and flood prevention and mitigation. A hydrological study to determine design flood magnitudes was completed by the principal investigator in a FY2000 SCERP-funded project. For return periods of 2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years, the flood discharges are: 280, 530, 680, 930, 1,140, 1,310, 1,420, 1,600, and 1,720 cubic meters per second (m^3/s), respectively.

This report continues the hydrological study to its next logical step—the development of a hydroecological characterization aimed at determining flood levels that are congruent with the proposed land uses. The work includes close consultation with cognizant federal agencies to determine applicable stream zoning restrictions.

Tijuana's city planners envision the rehabilitation of Arroyo Alamar to have the essential character of a green corridor, with multiple land uses in tune with the primary flood-mitigation, aquifer-replenishment, and riparian-habitat functions. In a city with few large tracts of greenery, the hydroecological rehabilitation of

Arroyo Alamar is a highly desirable project. The concrete-channel alternative used in the development of the first, second, and third Phases of the Río Tijuana is no longer a viable alternative, given the marked negative impacts of the landscape and environment. Thus, this project assists the Municipality of Tijuana in furthering the goals of rehabilitating the Arroyo Alamar with an ecologically sound approach.

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INTRODUCTION

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RESEARCH OBJECTIVES

The specific objectives of this project are the following:

1. To determine the channel properties compatible with primary hydroecological functions. These include the cross-sectional geometry, longitudinal slopes, bank protection, and percolation to groundwater. The study encompasses the preservation and enhancement of existing riparian corridors, the rehabilitation of degraded riparian areas where warranted, and the selection of alternative land uses.
2. The determination of the flood frequencies to be implemented in the characterization and the hydraulic design of the hydroecological channel to convey the selected flood flows.

RESEARCH METHODOLOGY

The research method/approach consists of the following steps:

1. Assemble land-use information, including existing and planned developments, riparian, agriculture, industry, recreation, tourism, and other areas.
2. Consultation meetings with officials of the Comisión Nacional del Agua in Mexicali and Mexico City to establish appropriate flood frequencies to be used in the design.
3. Hydrological and ecological design of the rehabilitated channel and its flood plain. This includes the modeling of flood flows using the standard U.S. Army Corps of Engineers Hydrologic Engineering Center—River Analysis System (HEC-RAS) model, Version 3.0. The ecological design includes the selection and establishment of riparian, agriculture, industry, recreation, and other multi-purpose areas within the project site.
4. To establish the need, where appropriate, to stabilize the stream channel by means of bank protection, grade control, and other suitable means, with the objective of sustaining the design flood flows.

Preliminary appraisal based on Mexican hydrological practice indicates that the federal frequency should be at least 10 years and the project design frequency should be 1,000 years. The characterization encompasses the entire length of the Arroyo Alamar rehabilitation project, from its upstream end at the bridge over the Tecate toll road to its downstream end about 10 km downstream, to connect with the second phase of the Río Tijuana. This includes three distinct sections:

- From the bridge at the Tecate toll road to the bridge at Boulevard Héctor Terán Terán
- From the bridge at Boulevard Terán Terán to the bridge at Boulevard Manuel J. Clouthier

- From the bridge at Boulevard Clouthier to the end of the Second Phase of the Río Tijuana

Several site visits were carried out with the objective of ascertaining the parameters, including riparian areas, friction coefficients, land use, and other influences on the characterization.

The hydraulic modeling was performed using 500 cross sections, each every 20 m. This was necessary to ensure stability and accuracy of the backwater computation, enabling a precise delineation of the design flood stages.

The hydroecological characterization is based on the principle of mixed use of the stream channel, including riparian, agriculture, light industry, recreation, tourism, and water quality management. The cross-sectional design reflects the mixed uses and different flooding risks associated with those uses. A two-frequency compound channel is envisioned, with federal and soft-use zones. The federal zone is left to convey the regulation flood (10-year frequency); the soft-use zone houses riparian, recreation, and ecotourism zones (1,000-year frequency).

PROBLEMS/ISSUES ENCOUNTERED

The researchers used the 5 meter (m) topographic information to develop the hydroecological characterization. Detailed topographic information to 1 m resolution, which is required for final design, remains to be developed. The hydroecological design is to be taken as the level of feasibility study, pending more detailed studies when the detailed topographic information is developed.

RESEARCH FINDINGS

Gabion-Lined Channel Systems

To remain stable and satisfy its intended use, a hydroecological channel requires some type of bank protection. Gabions are usually considered as a compromise between concrete lining, riprap, or natural vegetation. A gabion system is wire-enclosed riprap consisting of mats or baskets fabricated with wire mesh, filled with small riprap, and anchored to a slope. Wrapping the riprap enables the use of smaller stone sizes for the same resistance to displacement by water energy. This is a particular advantage when constructing rock lining in areas of difficult access. The wire basket also allows steeper (up to vertical) channel linings to be constructed from commercially available wire units or from wire-fencing material.

Due to their high shear strength, gabion systems provide a highly effective way to control erosion in streams, rivers, and canals. They are normally designed to sustain channel velocities of 15 fps or higher. Gabions are constructed by individual units that vary in length from 6 feet to nearly 100 feet (gabion mats); therefore, applications can range anywhere from small ditches to large canals.

Gabion channels are a compromise between riprap and concrete. When the same-size rocks are used in gabions and riprap, the acceptable velocity for gabions is at least three to four times that of riprap. Unlike concrete, gabions can be vegetated to blend into the natural landscape.

Gabion channels with vegetation have several advantages. They:

- Allow infiltration and exfiltration
- Filter out contaminants
- Are more flexible than paved channels (Figure 7)
- Provide greater energy dissipation than concrete channels (Figure 8)
- Improve habitat for flora and fauna
- Are more aesthetically pleasing
- Have lower cost to install, although some maintenance is required

The Manning's n, or roughness coefficient, for gabion channels with vegetation depends primarily on the type of vegetation and the size of the stones being used. There is no specific formula for the roughness coefficient for gabion channels with vegetation. The roughness coefficient can be derived by knowing other values of Manning's n and relating them to the specific case. For gabions without vegetation, Manning's n ranges from 0.025 to 0.03. Manning's n for vegetated channels also vary depending on the type of soil, the amount of cover, resistance and retardance. Manning's n for vegetative channels is given by the following formula:

$$n = \frac{R^{1/6}}{C + 19.97 \log(R^{1.4} S^{0.4})}$$

(Eq. 1)

in which R = hydraulic radius; C = retardance coefficient, depending on cover and condition; and S = energy slope (m/m). The retardance coefficient ranges from C = 15.8 for class A vegetation to C = 37.7 for class E vegetation, as shown in Table 1.

Riprap channels have a very large range of Manning's n, depending on the stone diameter and the flow depth. The Manning's n of the composite channel is given by the following formula:

$$n_c = \frac{(P_l n_l^{1.5} + P_b n_b^{1.5} + P_r n_r^{1.5})^{2/3}}{(P_c)^{2/3}}$$

(Eq. 2)

in which n_l, n_b, n_r, n_c= Manning's n of the left side slope, bottom, right side slope 5, and composite channel, respectively; P_l, P_b, P_r, P_c= wetted perimeter of the left side slope, bottom, right side slope, and composite channel, respectively. In gabion channels with vegetation (Figure 11), the value of Manning's n is estimated by experience.

The procedure for placing and filling gabions can be summarized as follows:

- Assembling the individual units before placement (Figure 12)
- Placing and wiring them together and filling the units with rocks (Figure 13)
- Closing and wiring the lids closed (Figure 14)

Gabions can be placed on dry bank (Figure 15) or under water (Figure 16). Linings laid in dry conditions are placed directly on a stable slope that is not too steep as to cause the revetment to slide. The units are normally laid down on the slope of the bank, at right angles to the current. However, the units on the bed itself should be laid in the direction of flow.

When constructing a lining under water, dumping riprap is challenged by the many uncertainties because it is difficult to obtain a uniform distribution of the material over the whole area to be protected. In order to reduce the risk, the amount of rocks dumped has to be increased by 50%. This problem does not arise with gabions because the structure is preassembled and of fixed thickness. The gabions are placed using cranes or pontoons (Figure 17).

The stability of gabion linings depends on the strength of the mesh, the thickness of the lining, and the grading of the stone fill. Once the water velocity is known these parameters can be selected. For longevity of the revetment, the mesh must be protected from corrosion. Gabions are constructed from wires with heavy zinc content and PVC coating.

The two primary elements in channel design are cross-sectional shape and lining (Figure 18). Lining is determined by erosion resistance and drainage requirements. Vegetated linings are appropriate for low velocities. Paved linings may be used for soil-water interfaces where the soil and groundwater conditions are such that the soil may erode under the design flow. Generally, velocities over 1.5 meter per second (m/s) require lined waterways.

For design purposes, uniform flow conditions are usually assumed, with friction (or energy) slope (S_f) equal to average bed slope (S_O). This allows the flow conditions to be defined by a uniform flow equation such as Manning's. Supercritical flow creates surface waves of depth comparable to the flow depth. For very steep channel gradients, the flow may splash and surge; therefore special considerations for freeboard are required.

Once the basic hydraulic and physical characteristics of the channel have been determined, the selection of the lining and stability analysis can be made. Generally, a 10-year to a 100-year storm (1,000-year storm in Mexico) is used to determine capacity, while the two-year storm is used for channel stability. After vegetation is fully developed, the channel is considered stable and capacity becomes more critical.

Channels should be designed so that the flow velocity does not exceed the permissible velocity for the type of lining used. It is also important to check outlets for stability. Excessive velocities or grade changes may require protective or stabilizing structures, transition sections, or energy dissipaters to prevent erosion or scour.

Hydrological Design of Arroyo Alamar
To perform the hydrological design of the rehabilitated channel includes the determination of flood discharges for selected design frequencies and the calculation of water-surface profiles. The U.S. Army Corps of Engineers Hydraulic Engineering Center-River Analysis System (HEC-RAS) model was used to calculate the water-surface profiles.

A hydrological study to determine design flood discharges for two-year to 1,000-year frequencies has been performed by Ponce (2000). The results are shown in Table 3.

The 1,000-year frequency is used by the Comisión Nacional del Agua to design flood control channels in urban environments. To determine the freeboard, there is a need to go beyond the 1,000-year frequency. According to USDA Natural Resources Conservation Service (NRCS) methodology, for urban flood control projects such as the Arroyo Alamar rehabilitation the freeboard hydrograph should be designed to safely pass the Probable Maximum Precipitation (PMP). There is no PMP determination for Mexico. In places where it does not exist, the PMP is commonly approximated as the 10,000-year frequency.

With the two-year to 1,000-year frequency floods determined by mathematical modeling, the Gumbel method was used to calculate the 5,000-year and 10,000-year flood discharges. Figure 19 shows the Gumbel fitting and Table 4 shows the estimated discharges.

To perform the HEC-RAS modeling, the design channel alignment was obtained from Tijuana officials. The project has a total channel length of 9880.849 m. The upstream point, with invert elevation of 80 m, is at the bridge over Cañón del Padre on the toll road to Tecate (Figure 20). The downstream point, with invert elevation of 40 m, is at the beginning of the concrete-lined reach of Arroyo Alamar, near the confluence with the Tijuana river (Figure 21). This provides an average channel slope of 0.004048.

The project reach of 9880.849 m was subdivided into reaches at an equidistance of 20 m, for a total of 494 reaches and 495 cross sections. The small reach interval (20 m) was adopted to ensure the accuracy of the water-surface profile computation. River stations are numbered from 001 to 495.

A prismatic channel of a chosen cross-sectional geometry was adopted for design. The channel consists of a main channel and left and right overbank channels (flood plains). The bottom width of the main channel is 40 m, and the main channel depth is 3.8 m. The side slopes of the main channel are two horizontal to one vertical.

The overbank channels are 20 m wide each, with a channel depth of 3 m and side slopes 2 H:1 V. The overbank channels drain into the main channel with a 1% transversal slope. Figure 22 shows the channel design.

In HEC-RAS, cross-sectional data is entered from left to right, looking in the downstream direction. The left channel bottom x-coordinate was specified as 100 m and the corresponding cross-sectional coordinates were calculated using a spreadsheet. The x-coordinate left overbank limit is 92.4 m, and the x-coordinate right overbank limit is 147.6 m.

Several types of loss coefficients are used by HEC-RAS to evaluate energy losses. These are the Manning's n for friction (boundary) loss, contraction and expansion coefficients to evaluate transition loss, and bridge and culvert loss coefficients. At the present level of approximation, all secondary energy-loss coefficients have been neglected.

Appropriate values of Manning's n are significant to the accuracy of the calculated water surface profiles. The Manning's n value depends on a number of factors, including surface roughness, amount and type of vegetation, channel irregularities, channel alignment, scour and deposition, presence of obstructions, size and shape of channel, stage and discharge, seasonal changes, temperature, and bed material load.

Manning's n values for inbank channel flow was estimated at 0.035, and for overbank flow at 0.075. These values are consistent with established practice. The values of Manning's n recommended by HEC-RAS for natural streams are shown in Table 5.

The boundary condition is necessary to establish the starting water-surface elevation at either end of the channel system. Since the flow is subcritical, the boundary condition is specified at the downstream end. The average channel slope S_O= 0.004048 has been specified as the downstream boundary condition in the present study.

Flood discharge information is required at each cross section in order to compute the water-surface profile. The flow value is entered at the upstream end of the reach, and it assumes that the flow remains constant until another flow value is encountered with the same reach. The flood discharges corresponding to 10-, 50-, 100-, 500-, 1,000-, 5,000- and 10,000-year return periods were used to calculate water-surface profiles with HEC-RAS. In addition, the flood discharge of

550 m^3/s, estimated as the 10-year flood by Comisión Nacional del Agua, was also considered.

The HEC-RAS model results are shown in Table 6. Flow depths vary from 3.278 m to 6.779 m; inbank flow velocities vary from 3.6 m/s to 6.04 m/s; overbank flow velocities vary from 0.77 m/s to 1.56 m/s. The design flow velocity for inbank gabion lining is that corresponding to the 1,000-year flood: 5.45 m/s. For the 1,000-year design flood discharge, the freeboard is 1.117 m.

Ecology and Flora of Arroyo Alamar
The Arroyo Alamar is part of the Tijuana River Watershed. Therefore, its physical and biological characteristics are similar to the majority of the watersheds and river basins located in the northwestern part of Baja California and Southern California. According to the degree of disturbance, the various arroyos that form part of the watershed are divided into three classes:

- Disturbed in urban areas
- Disturbed in suburban areas
- Undisturbed in natural areas

River channelization is accomplished to reduce the risk of catastrophic flooding. However, it reduces riparian habitat, segmenting the local ecology and vegetation. Riparian vegetation is characterized by rapid colonization, high productivity, good dispersion properties, a lowering of species numbers, and a dominance of woody species, specially the willows.

Ecologically, these areas have been classified as riparian, that is, the biological communities that lie along the streams and washes. Biodiversity refers to the variety of biological species and its life forms within an ecosystem. The term "undisturbed" implies a process that significantly alters the patterns of structure and form of an ecosystem, and is usually applied in reference to human activities.

Hydrologic, climatic, and substrate factors determine the composition and, therefore, the structure and function of the riparian vegetation. The riparian ecosystems are protected from strong winds and extreme dry summers. However, this causes the destruction of some vegetation and the creation of new sites for the establishment of new vegetation (Gregory, et al. 1991).

From an ecological perspective, the Arroyo Alamar can be divided into three zones:

- Zone I, from the concrete channelization to the Cañón del Padre bridge
- Zone II, from the Cañón del Padre bridge to the city of Tecate
- Zone III, from the city of Tecate to its headwaters in eastern San Diego County and the municipality of Tecate

Zone I lies within the urban limits of the city of Tijuana. It is the most disturbed and polluted of the three zones, and it features many irregular human settlements. The riparian environment and its ecology are heavily impacted by the trash and debris dumps, as well as by stagnant polluted water. It can be divided into three areas:

1. From the concrete channelization to the Manuel J. Clouthier Boulevard: human settlements, deposits of trash and debris, and polluted surface water. This zone represents a great public health hazard. Several water wells function to provide water for agriculture and recreation.
2. From Manuel J. Clouthier Boulevard to Terán Terán Boulevard: a few human settlements and trash and debris dumps, stagnant water, mining of sand and gravel, and agriculture.
3. From the Terán Terán Boulevard to the Cañón del Padre bridge: some trash and debris, brick manufacturing facilities, agriculture and grazing. This is the better-preserved area in terms of riparian vegetation (Figure 25).

Zone II shows water pollution from Arroyo Tecate; its vegetation and riparian environments do not show great human impact. Zone III is subject to very little pollution and its riparian environment is largely unaffected by human activities.

The biological communities are described in terms of their floristic components and biological forms. The floristic component is assessed by listing all the plants found in a region or area; the biological forms are either trees, shrubs, or grasses. The flora of Arroyo Alamar has a great diversity of native plants and quite a few introduced plants. The latter are characteristic of disturbed environments, principally in Zone I. According to the listings of flora in the official Mexican NOM-059-2001, there are no endemic plants, rare plants, or plants in danger of extinction. Table 7 lists the floristic component of Arroyo Alamar.

The climax vegetation of Arroyo Alamar is of the riparian corridor type. It is dominated by deciduous trees, which help reduce soil erosion and provide habitat for other biological communities.

For many years, ecologists have referred to wide-leaf riparian species such as *Populus, Salix, Fraxinus, Platanus* and others, as obligatory riparian species. These and other terms such as facultative and pseudoriparian have been applied to diverse riparian species. The U.S. Fish and Wildlife Service has adopted the following terms: “true riparian” for the obligatory riparian, and “pseudoriparian” for the facultative riparian (Reichenbacher 1984). However, some riparian plants are greatly dependent on the surface water and others on the subsurface water, being quite distinct from the phreatophytes (Smith, et al. 1991).

In Zone I, the native vegetation has disappeared almost completely. It was formed by species of trees such as willows (*Salix* spp.), poplars (*Populus fremontii*), and alder (*Platanus racemosa*). These species have almost disappeared, except a few species of willows and a few individuals of poplars and alders along the river banks.

The climax vegetation of this arroyo would be an association of willows and poplars. The willows have a high degree of colonization in Zone I, where it can cover up to 100%. This response of the willows may be due to the large anthropogenic disturbance and to the large deposits of organic matter and nitrate. On the other hand, Zones II and III do not present large populations of these species.

At the present time, the vegetation of Arroyo Alamar in those areas where there is good coverage of vegetation consists of three strata: trees, shrubs, and grasses. In addition, there are also some aquatic and semiaquatic plants.

- Trees: Dominated first by a type of willow (Salix goodingii) and secondly, by *Salix lasiolepis*. These are native species, with heights varying from 4 m to 15 m, located along the water course and in contact with it.
- Shrubs: Dominated by two native shrubs, *Baccharis glutinosa* and *Baccharis sarothroides*, growing principally outside the main channel on top of accumulations of sand.
- Grasses: This strata varies with regard to native and introduced plants, the latter being favored due to the altered environment.
- Aquatic and semiaquatic plants: Plants that are located in the main channel, under water, or in lagoons in the surroundings.

The most frequent species in aquatic and semiaquatic ecosystems are: *Azzola filiculoides, Anemopsis californica, Callitriche orcutti, Cyperus laevigatus, Cyperus lanceolatus, Eleocharis acicularis, Eleocharis geniculata, Eleocharis palustris, Eleocharis parishii, Epilobium adenocaulis* var. *parishii, Juncus acutus, Juncus bufonius, Juncus sphaerocarpus, Juncus rugulosus, Juncus xiphioides, Lemna trisulca, Lemna valdiviana, Lemna gibba, Lilae subulata, Marsilia fournieri, Mimulus gutatus, Nasturtium officinale, Ophioglossum californicum, Pilularia americana, Ranunuculus cymbaralia, Sagittaria cuneata, Sagittaria greggi, Scirpus acutus, Typha dominguensis, Typha latifolia,* and *Zannichella palustris*. There are also introduced reeds *Arundo donax* and *Phragmites australis*.

The species *Nicotiana glauca* and *Salsola kali* var. *tenuifolia* establish themselves quite readily in agricultural and urban areas. Other species occupy areas that have been disturbed; among these are *Baccharis sarothroides, Baccharis glutinosa, Erodium cicutarium, Brassica campestris, Haplopappus venetus, Taraxacum officinale, Xanthium strumarium, Ambrosia psilostachya, Cirsium vulgare, Sonchus oleraceus,* and *Datura discolor*.

Design Velocities for Vegetated and Gabion-Lined Channels

The flow velocity in watercourses has a direct relation to boundary roughness and bank stability. When all other variables are held constant, the boundary roughness decreases as the velocity increases. When the velocity increases, the shear stress increases on the bed and bank material. In turn, this increases the rate of erosion and sediment transport.

There are several ways to protect the stream channel against bed and bank erosion. The bed and banks can be protected directly by using different types of lining, made from both artificial and natural materials. Artificial linings include concrete, gabions, and dumped rock. Natural linings include lawns, vegetated mattresses, and bundles of wood. Table 8 shows a comparison between vegetated and gabion-lined channels.

Stabilization with Gabions
Gabions consist of mesh baskets filled with small riprap. A gabion structure can consist of several baskets (Figure 3). Since the riprap is enclosed within a wire mesh, it has high stability against erosion. Vegetation can be planted and is able to grow between the gabion's layers (Figures 26, 27, and 28). Planting vegetation in gabions provides habitat, decreases the flow velocity during storm events and increases their aesthetic appeal.

Natural Bank Stabilization
In bank stabilization using natural vegetation, attention must be paid to the temporal wetting zones to assure habitat sustainability. The temporal wetting zones are: permanently wetted, intermittently wetted, and event wetted, or flood plain.

In permanently wetted zones, wattle and fascines are used in various types of assemblies, as shown in Figure 29. The wattles are staked 30 cm to 50 cm into the ground and the stakes are braided with flexible strong brushwood. The height of the wattle assembly is 30 cm to 80 cm.

Fascines can be built as sausages or rolls. The fascine sausages are cylindrical bodies of willow rods with a length of 10 m to 20 m and a diameter of 0.10 m to 0.15 m. They are manufactured from flexible brushwood with a length of 2.5 m to 3.0 m, and anchored with stakes of 4 cm to 5 cm thickness and length of about 1 m (Figures 30, 31, and 32).

The fascines rolls are in structure similar to the fascine sausages, with a diameter of 0.25 m to 0.40 m, and 1/3 to 2/3 of their thickness placed under the average baseflow level. Weighted fascines are cylindrical bodies with a diameter of 0.80 m to 1.20 m. They consist of a 0.15 m to 0.20 m thick coat of brush wood and a core of rough gravel or crushed rock (Figure 33).

Cattails are placed in the intermittently wetted zone. In the event-wetted zone, the natural building materials used are finished lawn and grass seeding. The lawn pieces are square turf sods with an edge length of 25 cm to 30 cm and a thickness of 3 cm to 8 cm, imported into place. Lawns are laid flat or in stacks.

Flat lawns use bank slopes of 1.5:1-2:1, with 3:1 being rarely used (Figures 35 and 36). Areas with high shear stress should be anchored with stakes 20 cm to 30 cm in length. Stacked lawns use bank slopes of 0.75:1 for flowing water bodies and 0.3:1-1:1 at walls (Figure 37).

For lawn rolls, the principle is the same as that of flat lawns. Lawn rolls can be handled over larger surfaces, and they can be grown beforehand on special surfaces.

Lawn seeds are disseminated by wet or dry means (Figure 40). Young seedlings can be protected against removal by means of fiber mattresses or by mixing with a biodegradable adhesive during seeding (Figure 41).
Vegetative bank stabilization consists of individual components of 2 m x 6 m and a thickness of 0.2 m. The materials are a mixture of gravel, plastic mesh, biodegradable geotextiles, and endemic riparian vegetation. The building materials are combined and spread in layers. The assembly can usually withstand large shear stresses (Figure 42).

To stabilize with wood parts, staking woody debris are collected during the winter. These stakes are assembled in either brush mattresses, live staking, or small trees and shrubs. Brush mattresses are anchored to the ground with fascines or wire mesh (Figures 43 and 44). Slopes of 1:1 or flatter may be required to withstand high shear stresses. Water velocities up to 3.5 m/s may be used with brush mattresses.

Live staking uses root-able branch ends with length of 1.0 m to 2.5 m and thickness of 4 cm to 6 cm. They are inserted as shown in Figure 45. Small trees and shrubs are placed above the baseflow (Figure 50). They are able to sustain flooding for several days when mature. They are typically used in combination with other measures such as lawn pieces and/or weighted fascines. They provide the following functions:

- Stabilization of the bank against erosion
- A mature canopy will provide shading to a good portion of the bank
- Shading reduces the temperature of the water
- For tropical and mid-latitudinal climates, this temperature reduction will improve water quality by discouraging the growth of algae and other nuisance species
- This creates a niche habitat for a particular community of flora and fauna

Hydraulic Design
The critical velocity v_c and the critical shear stress τ_c are used in the analysis of the stability of the bottom and the banks of rivers against erosion. The stability can be determined by comparing the actual velocity to the maximum allowable velocity or critical velocity v_c based on the bed and bank material. The following Manning equation can be used:

$$v = (1/n)\, R^{2/3} S^{1/2}$$

in which is v = velocity (m/s), n = Manning's n, R = hydraulic radius (m) and S = slope (m/m).

The critical velocity must be determined by experiments or empirically derived from information in the literature. The critical velocity is that at which erosion of the bed and/or bank material begins. The criterion for stability is:

$$v < v_c$$

Typical values of critical velocity are shown in Table 9. The critical shear stress τ_c is a measure of the stability of the bed and banks of a river against erosion. The bottom shear stress can be calculated as follows:

$$\tau_o = \gamma R S$$

in which is τ_o = the bottom shear stress (N/m^2), γ = specific weight of water (N/m^3), R = hydraulic radius (m) and S = slope (m/m).

For wide channels, i.e., those with a top width T ≥ 10 R, the flow depth h is substituted for R:

$$\tau_o = \gamma h S$$

The critical shear stress τ_c must be determined by experiments or empirically derived from information in the literature. The critical shear stress τ_c is that at which erosion of the bed and/or bank material begins. The criterion for stability is:

$$\tau < \tau_c$$

Typical values of critical shear stress are shown in Table 9.

The variety of vegetation cover available in nature implies that there is also a wide variation in resistance to flow. Flow resistance is dependent on whether vegetation is completely or partially submerged. The controlling factor is the height of the canopy in relation to the water depth. The three general cases are (Figure 54) short, average, and tall vegetation.

Short vegetation is that which is short in relation to the flow depth, its height being on the same scale as the absolute roughness. The velocity distribution in the cross section resembles that due to absolute roughness. Average vegetation occurs when the plant height is, on the average, the same as the flow depth. It varies between full and partial submersion. The behavior of the resistance to flow demands a special attention to the flow conditions. This is because average vegetation is susceptible to forceful submission (i.e., tilting) when the stream power overcomes the static resistance of the stems. For average vegetation, there is a definite relationship between vegetative resistance and the ratio of plant height to flow depth. Tall vegetation is that which is tall in relation to the flow depth. This definition excludes plants that bend such that their height is decreased below the water surface. Several examples of roughness coefficients for vegetated channels are shown in Table 10 and Figures 55 through 59.

For conceptually based calculations, the Darcy-Weisbach formula can be used:

$$v = (1/ f^{1/2}) (8 g R S)^{1/2}$$

with

$$f = [(4 A_{p,i}) / (a_x a_y)] c_{w,i}$$

for nearly horizontal flood areas, and

$$f = [(4 A_{p,i} \cos \alpha) / (a_x a_y)] c_{w,i}$$

for hillslope flood areas, with

$$A_{p,i} = h_i d_{m,i}$$

The geometric characterization and the equivalent diameter are shown in Figures 60 and 61.

For an individual specimen, the coefficient of resistance $c_{w,i}$ is equal to that of a circular cylinder for which $c_w = 1.2$.

For groups of trees or bushes, the following formulas can be used:

$$f = [(4 A_p) / (a_x a_y)] c_{w,r}$$

$$f = [(4 A_p \cos \alpha) / (a_x a_y)] c_{w,r}$$

with $c_{w,r}$ between 0.6 and 2.4, with mean value $c_{w,r} = 1.5$.

Riparian Husbandry

Different vegetative species are expected to require different location and flow conditions. All of them are expected to provide vegetative cover to minimize the possibility of channel or bank erosion. For wood, the following practices are recommended:

- Remove old and sick wood, particularly when they are an obstacle to the flow
- With existing vegetation, thin elements positioned in untypical locations
- If hydraulically insignificant, leave vegetative debris to encourage habitat (Figures 62, 63, and 64)

Sedges and shrubs should be cut only when hydraulically necessary. For lawns, the following practices are recommended:

- Mow lawn of embankment once to twice per year
- During mowing, attention should be payed to bird eggs
- Some areas should be kept unmowed to conserve biodiversity

Design of Horizontal Alignment
The design of the horizontal alignment of Arroyo Alamar has been accomplished following the current location of the streambed. It is understood that the stream will have a tendency to change its alignment with time. The proposed stream rehabilitation fixes the streambed in order to define the external limits of the project (Figures 65 through 70).

Design of Vertical Alignment
This document contains an approximate calculation of the volume of granular materials (sand and gravel) that could be extracted from the Arroyo Alamar project if the channel were to be lowered. The rational for lowering the channel has several purposes:

- To increase the channel conveyance
- To extract sand and gravel and commercialize it to support the project development
- To enhance the aesthetics of the channel design

Figure 71 shows the horizontal alignment of the channel design in Arroyo Alamar. A vertical bed-level profile was obtained with AutoCAD, and used to calculate the volume of cut (removal of sand and gravel) from the bed (Figure 72). Three cases were considered:

1. A uniform slope linking upstream and downstream end points (From Puente Cañón del Padre to Primera Etapa del Rio Tijuana)
2. A uniform slope at a depth of 1 m below the slope at a
3. A uniform slope at a depth of 2 m below the slope at a

Table 11 summarizes the results of the analysis. An analysis has been performed to calculate volumes of sand and gravel mining as a result of rehabilitation of Arroyo Alamar. Results indicate that up to 2.7 million cubic meters can be obtained from the channel bed of Arroyo Alamar by lowering it 2 m.

Documentation of Present Conditions
This study has performed a photographic documentation of the present conditions in Arroyo Alamar. Currently, Arroyo Alamar has a mixed use of irregular housing, recreation, light industry, agriculture, garbage dumps, and other uses. The collection of 108 photographs portray the present conditions in the Arroyo Alamar on September 2002. The rehabilitation will change the look of the channel; therefore, it is necessary to document the present (baseline) conditions to establish the measure to which channel improvements have been accomplished at the conclusion of the project (Figure 73).

CONCLUSIONS
The following conclusions are obtained from this study:

- A hydroecological design has been accomplished for the Arroyo Alamar. The design used the U.S. Army Corps of Engineers' HEC-RAS model to determine design flow depths, mean velocities, Froude numbers, and freeboards for a typical cross-section featuring a compound prismatic channel with left and right overbank side channels (Figure 4)

- Gabion systems are a compromise between riprap and concrete channels, and are applicable to the hydroecological rehabilitation of Arroyo Alamar
- The ecology and flora of Arroyo Alamar has been described and documented for project use
- Vegetative and gabion-lined systems have been documented for project use
- Horizontal and vertical design alignments have been accomplished; the use of the streambed of Arroyo Alamar as source of borrow materials (sand mining) has been examined
- The present conditions of Arroyo Alamar have been documented for use as baseline data on which to base future assessments of channel rehabilitation and restoration
- A website (http://proyectoalamar.org) has been developed to inform interested persons and the public at-large about project developments

Recommendations for Further Research

Arroyo Alamar should be developed in a sustainable way. For this purpose, the principles of sustainable river architecture should be taken into account. According to this principle, efforts should be made to design the flood plains for soft uses such as recreation, sports education, parking, and so on, following examples already available in Mexico (such as Atoyac River in Oaxaca and Santa Catarina River in Monterrey).

Every effort should be made to discourage, at all levels of government, the implementation of hard solutions such as concrete lining of the flood channel. This type of solution degrades the natural and social environment and negatively impacts a host of other channel uses, such as groundwater replenishment, riparian ecosystem health, biodiversity, and water quality. All over the world, streams and rivers are being restored, to the extent practicable, to their natural conditions. Therefore, any solution based on concrete channelization will represent a serious setback and cause irreparable harm to the local environment.

Research Benefits

The research has identified a practical and effective way to rehabilitate and restore the Arroyo Alamar following sound hydroecological principles. Over the course of several years, institutional neglect has allowed the Arroyo Alamar to degrade to such a serious state that attention is now of the essence. Currently, Arroyo Alamar is both an eyesore and a public health hazard, not to mention it being a haven for substandard settlements, severe risk of flood damage to life and property, and illegal trash dumping. The focus is currently on the rehabilitation, which will enable Arroyo Alamar to become a green area within Tijuana’s city limits, a resource sorely needed for the social and economic well-being of the local population.

The research has provided the technical elements to persuade local officials and stakeholders to pursue the Arroyo Alamar rehabilitation along the principles of sustainable development. The research findings specifically discourage any solution based on concrete channelization, and encourages the hydroecological approach to river channelization. The latter is based on sound ecological and social principles, since in this way the river and its natural resources are preserved for the use and enjoyment of the local population, instead of being held hostage (not accessible for use by the local population) through a concrete channelization scheme.

ACKNOWLEDGEMENTS

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APPENDIX FIGURES

Figure01_Ponce.jpg

Figure 1. Arroyo Alamar

Figure02_Ponce.jpg

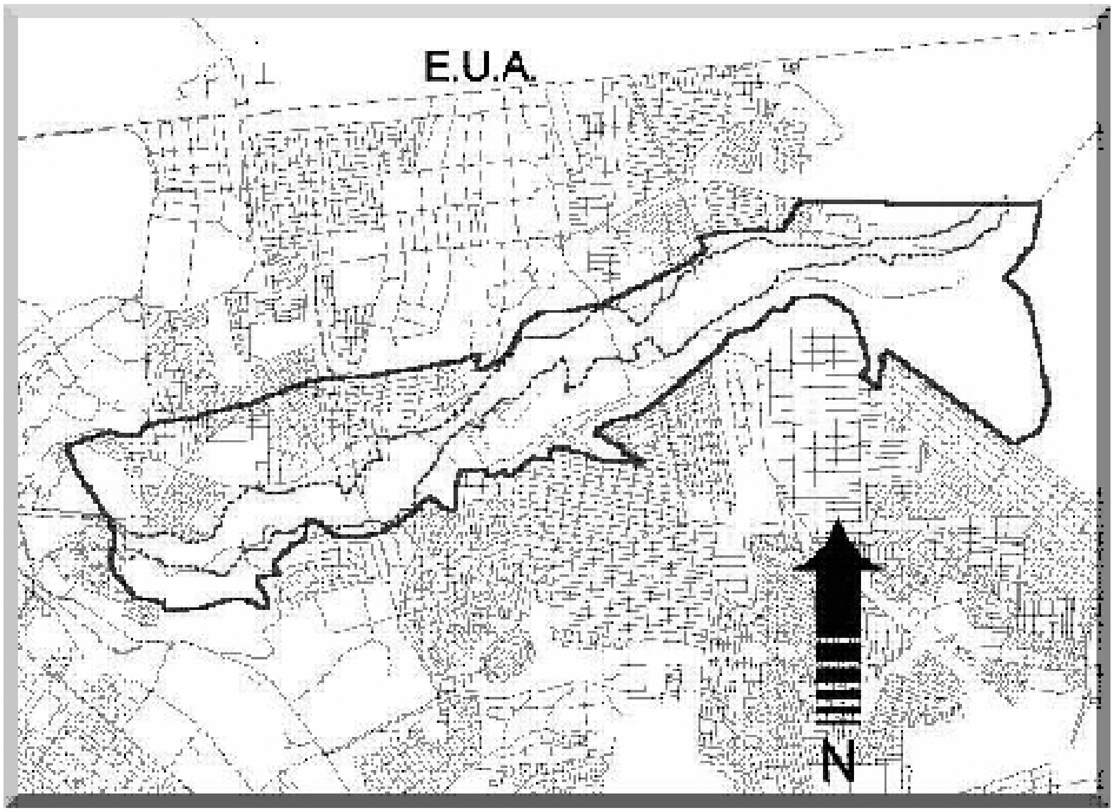

Figure 2. Project site along the northeastern portion of the city of Tijuana; outside (solid) lines delimit project area; inside lines delimit federal zone.

Figure03_Ponce.jpg

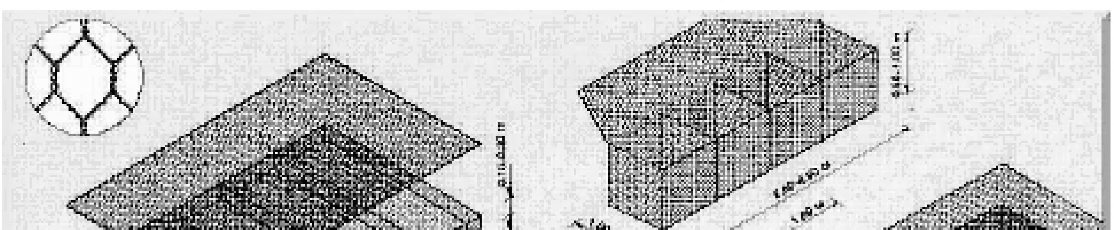

Figure 3. Layout and dimensions of gabion boxes and mattresses.

Figure04_Ponce.jpg

Figure 4. Example of vegetated gabion channel.

Figure05_Ponce.jpg

Figure 5. Example of vegetated gabion channel.

Figure06_Ponce.jpg

Figure 6. Example of vegetated gabion channel.

Figure07_Ponce.jpg

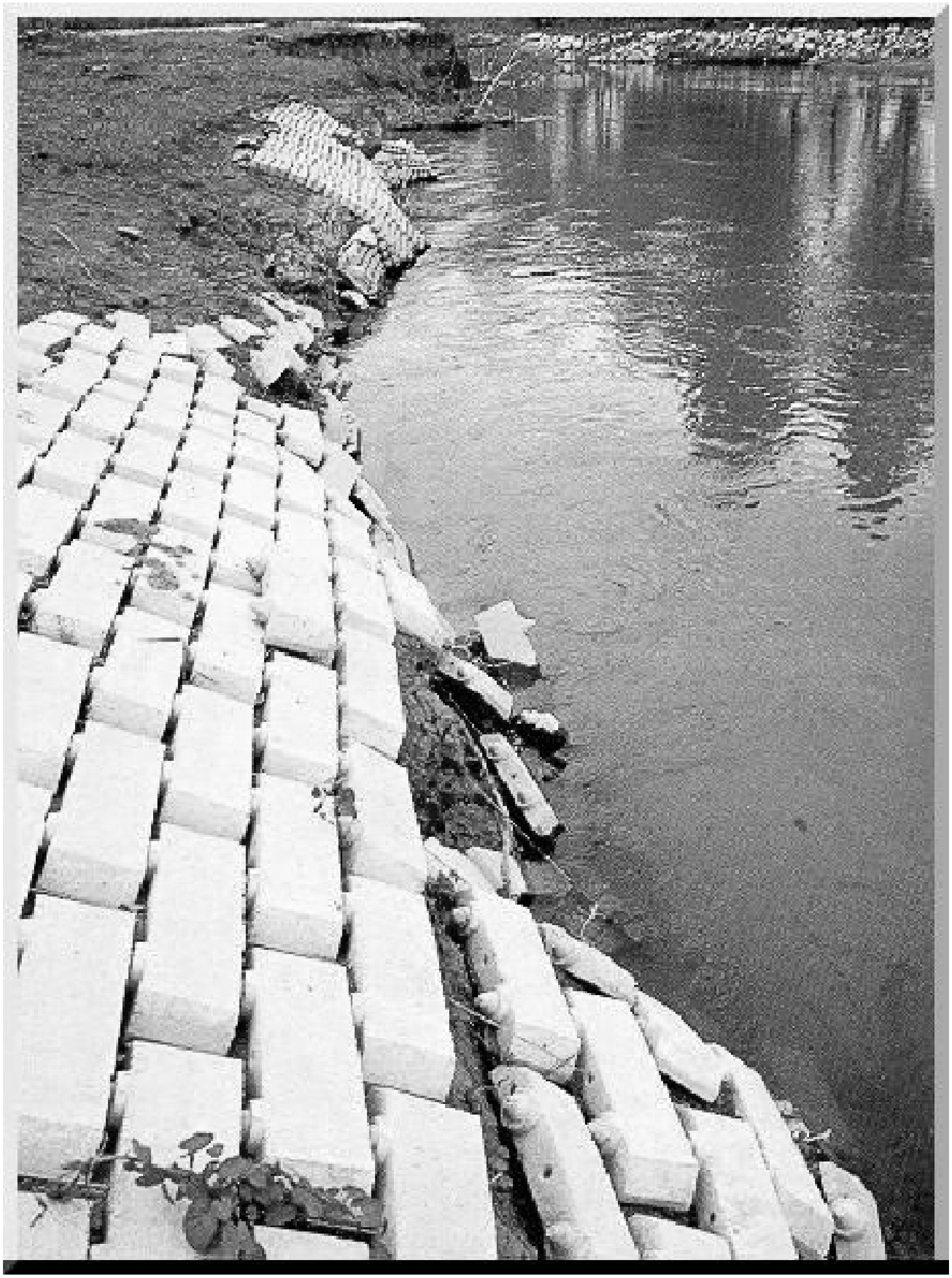

Figure 7. Failure of paved channels due to lack of flexibility.

Figure08_Ponce.jpg

Figure 8. Failure of paved channels due to lack of flexibility.

Figure09_Ponce.jpg

Figure 9. Failure of paved channels due to lack of flexibility.

Figure10_Ponce.jpg

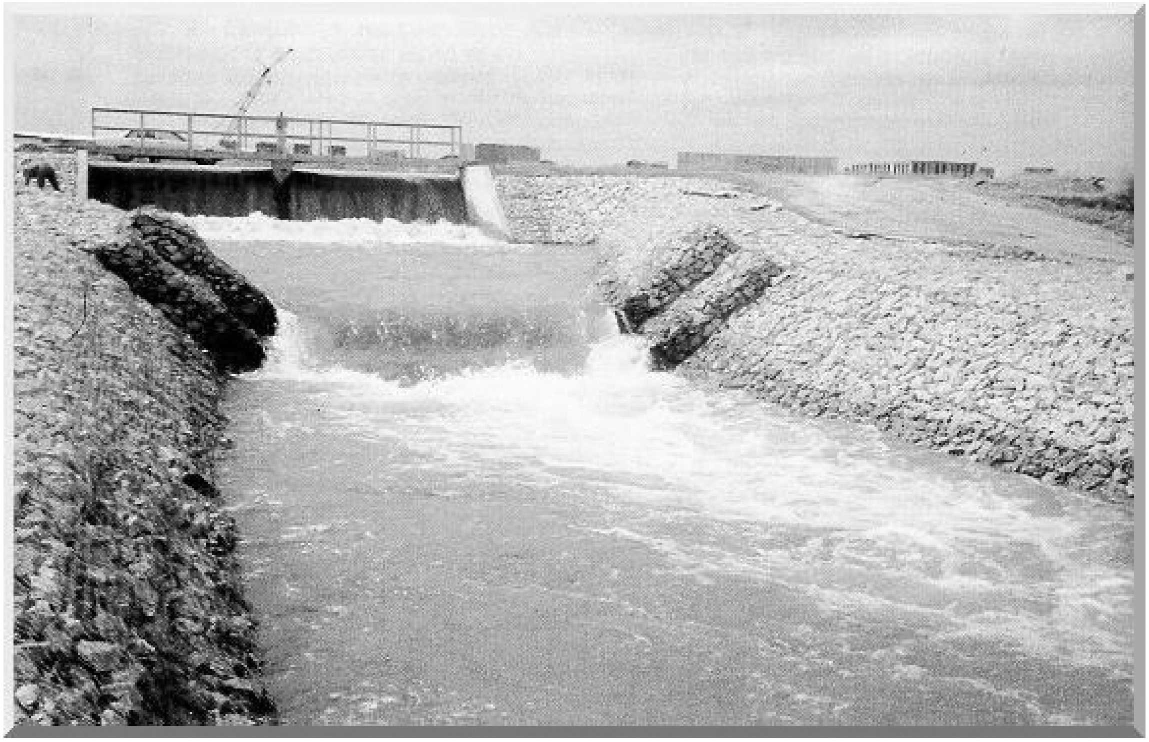

Figure 10. Gabion-lined spillway provides energy dissipation.

Figure11_Ponce.jpg

Figure 11. A gabion channel with vegetation
(Source: Maccaferri, Inc).

Figure12_Ponce.jpg

Figure 12. Assembling the individual units before placing.

Figure13_Ponce.jpg

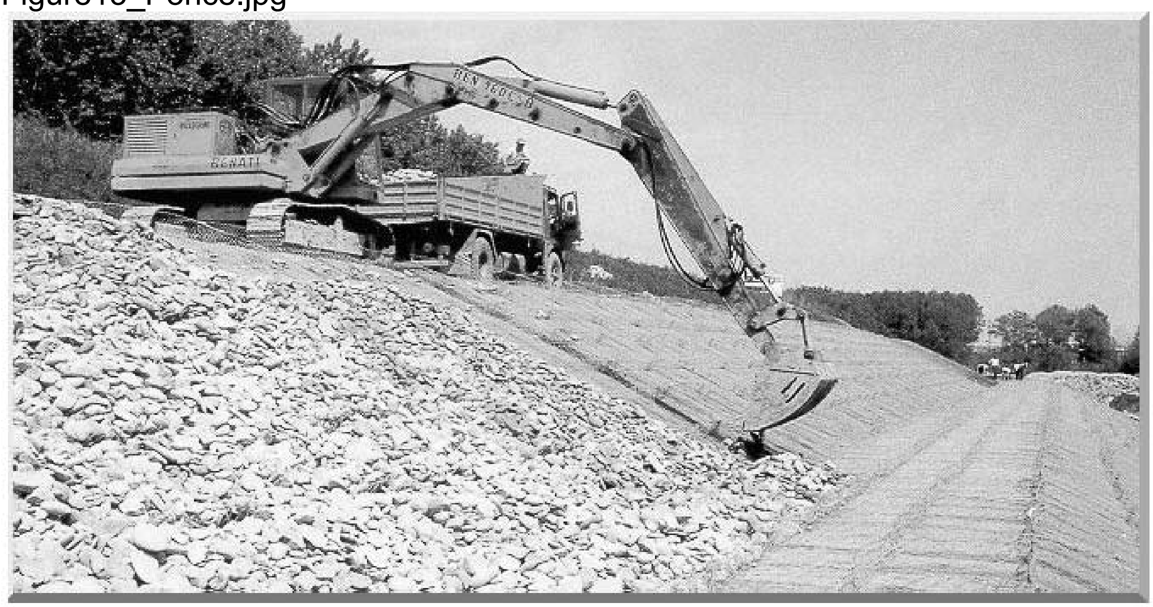

Figure 13. Filling the units with rocks.

Figure14_Ponce.jpg

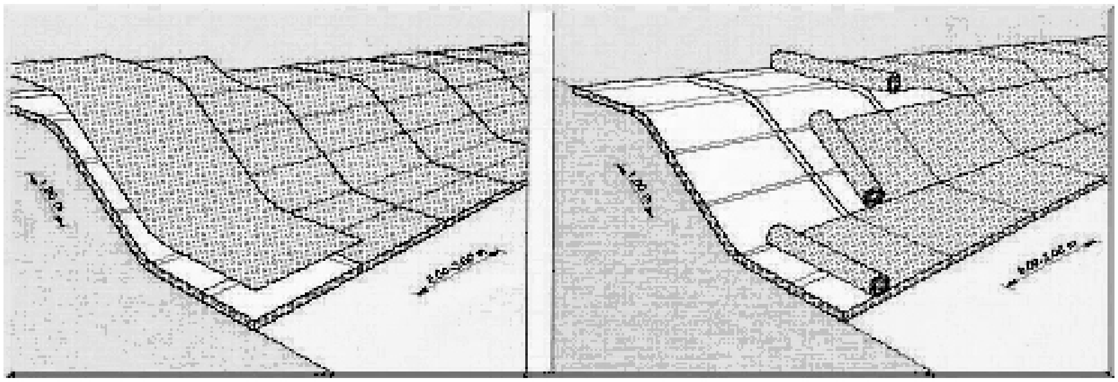

Figure 14. Closure of gabions using single lids or mesh rolls.

Figure15_Ponce.jpg

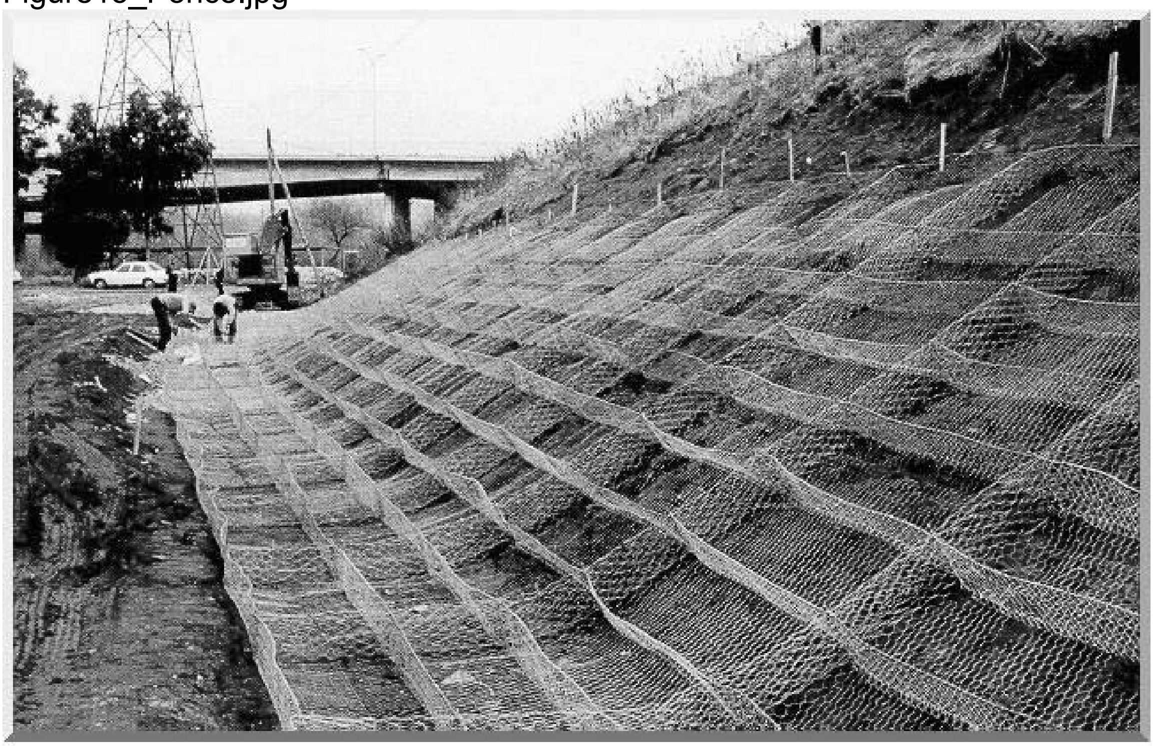

Figure 15. Placing gabions on dry banks.

Figure16_Ponce.jpg

Figure 16. Placing gabions under water.

Figure17_Ponce.jpg

Figure 17. Using a pontoon to place the gabion mattress.

Figure18_Ponce.jpg

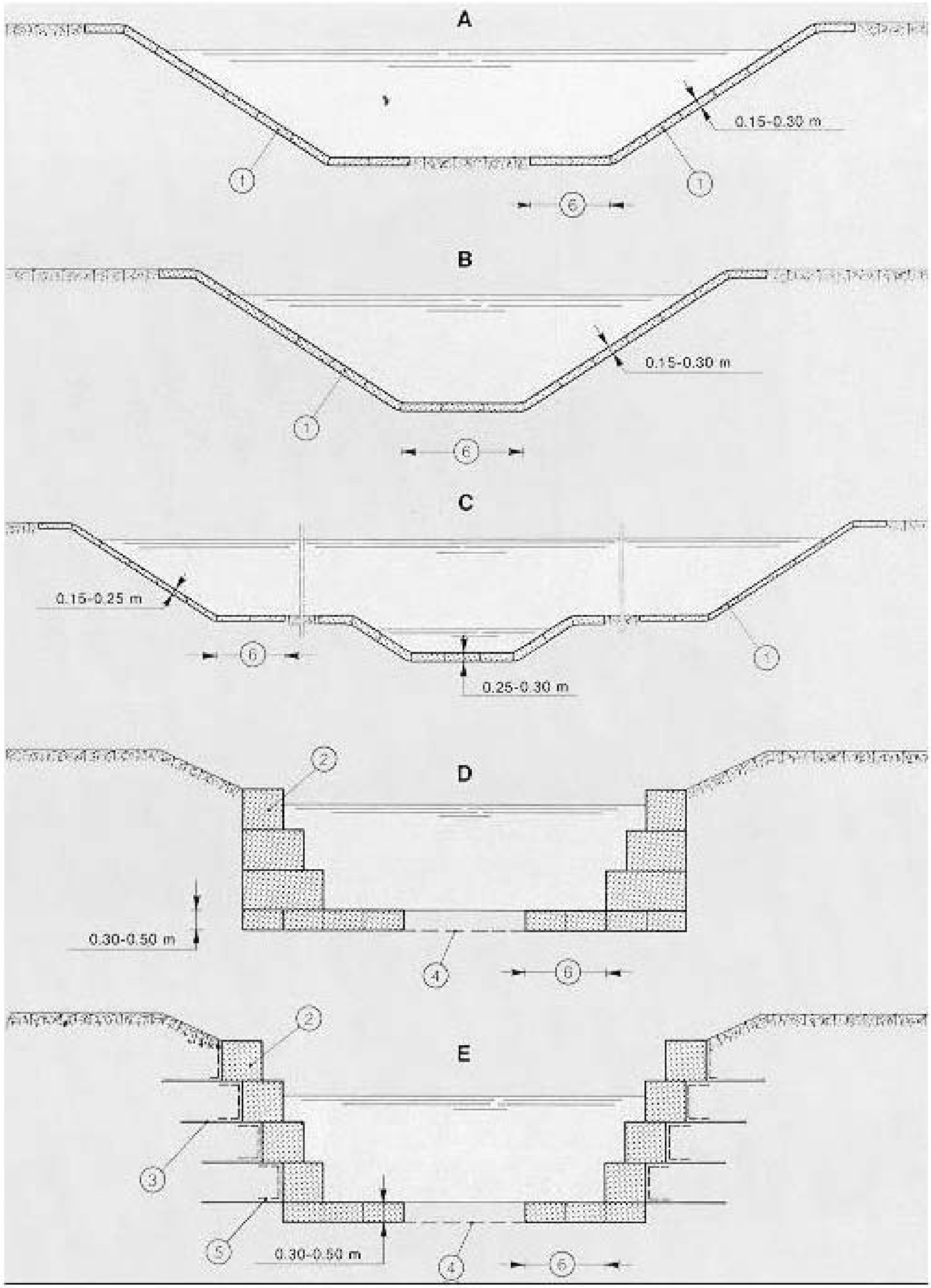

Figure 18. Usual types of channel linings in gabions and gabion mats.

Figure19_Ponce.jpg

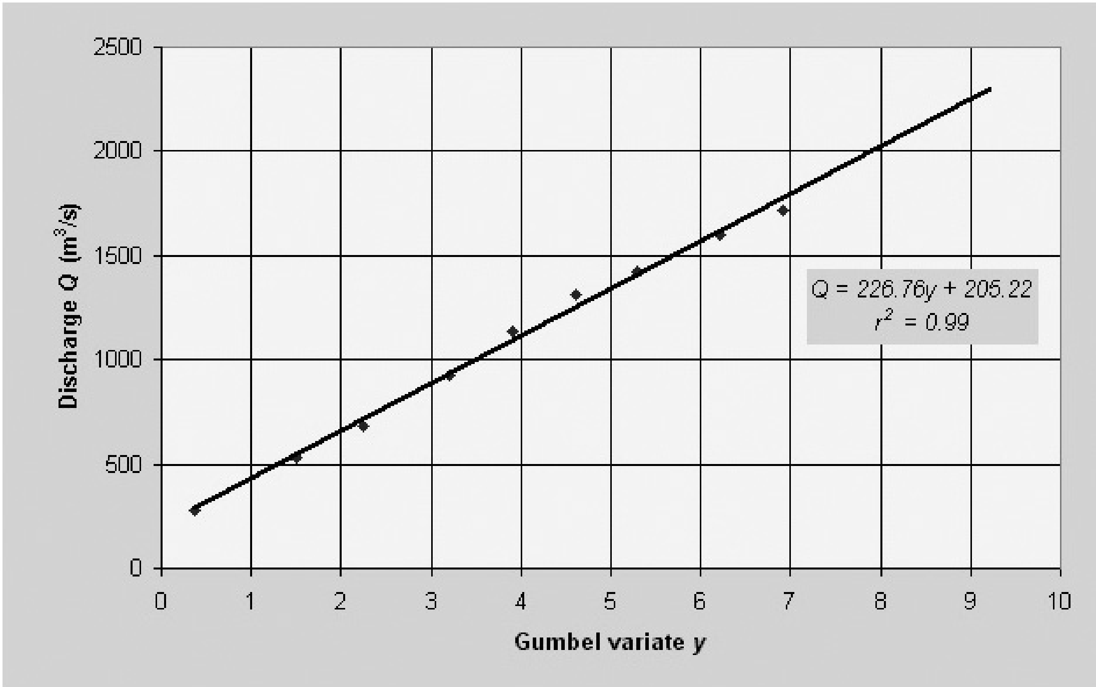

Figure 19. Gumbel fitting for Arroyo Alamar 5,000-yr and 10,000-yr flood discharges.

Figure20_Ponce.jpg

Figure 20. Upstream end of Arroyo Alamar rehabilitation project, at Puente Cañon del Padre.

Figure21_Ponce.jpg

Figure 21. Downstream end of Arroyo Alamar rehabilitation project, at the beginning of the concrete-lined reach, near the confluence with the Tijuana river.

Figure22_Ponce.jpg

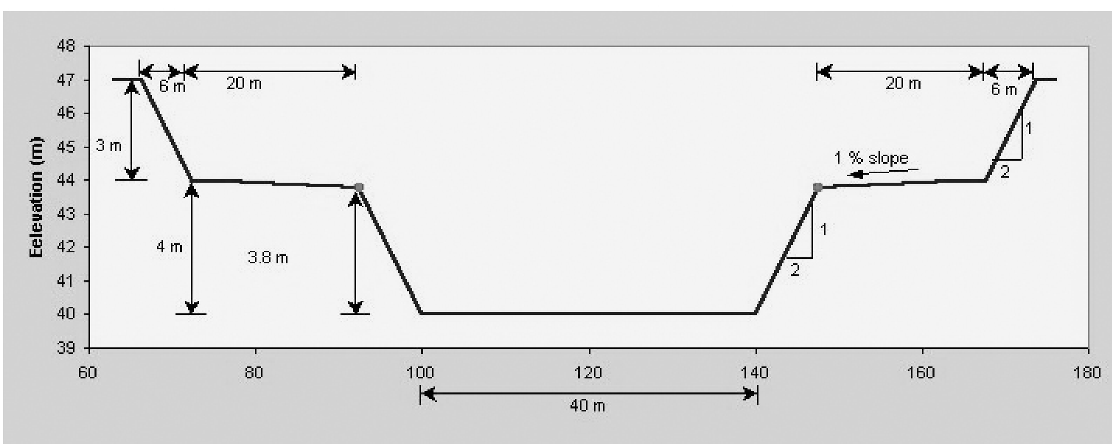

Figure 22. Arroyo Alamar channel design.

Figure23_Ponce.jpg

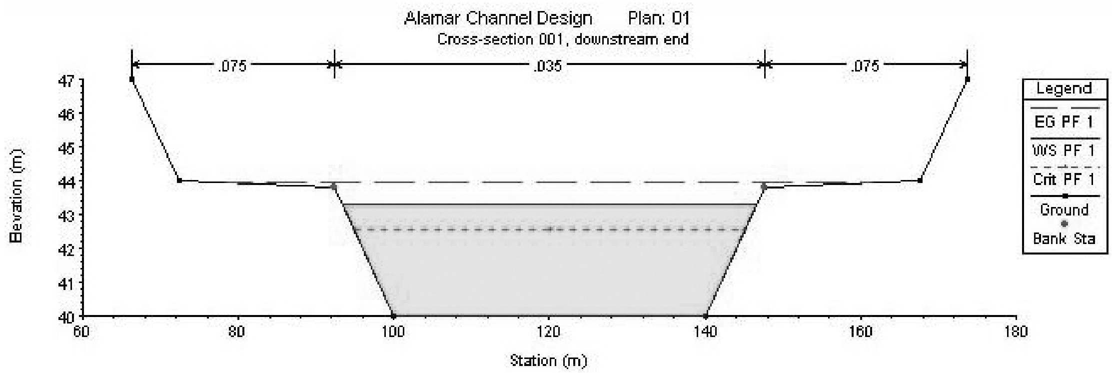

Figure 23. Result generated by HEC-RAS for the flood discharge of 550 m³/sec at cross section 001.

Figure24_Ponce.jpg

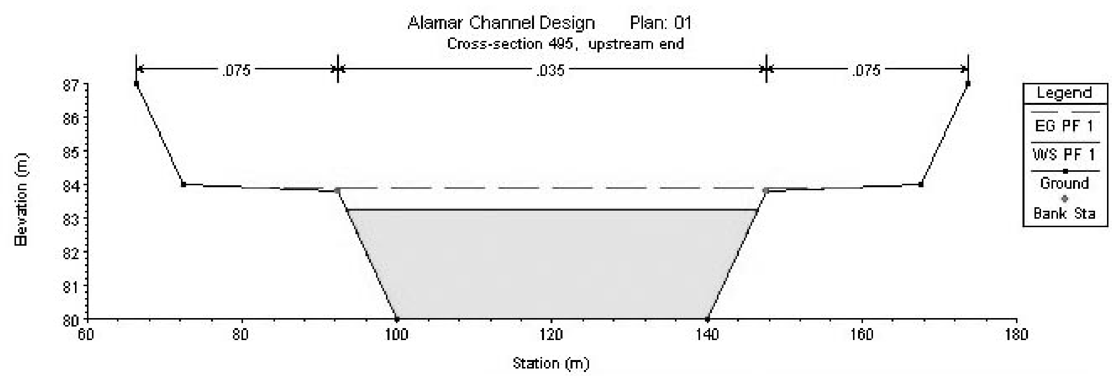

Figure 24. Result generated by HEC-RAS for the flood discharge of 550 m³/sec at cross section 495.

Figure25_Ponce.jpg

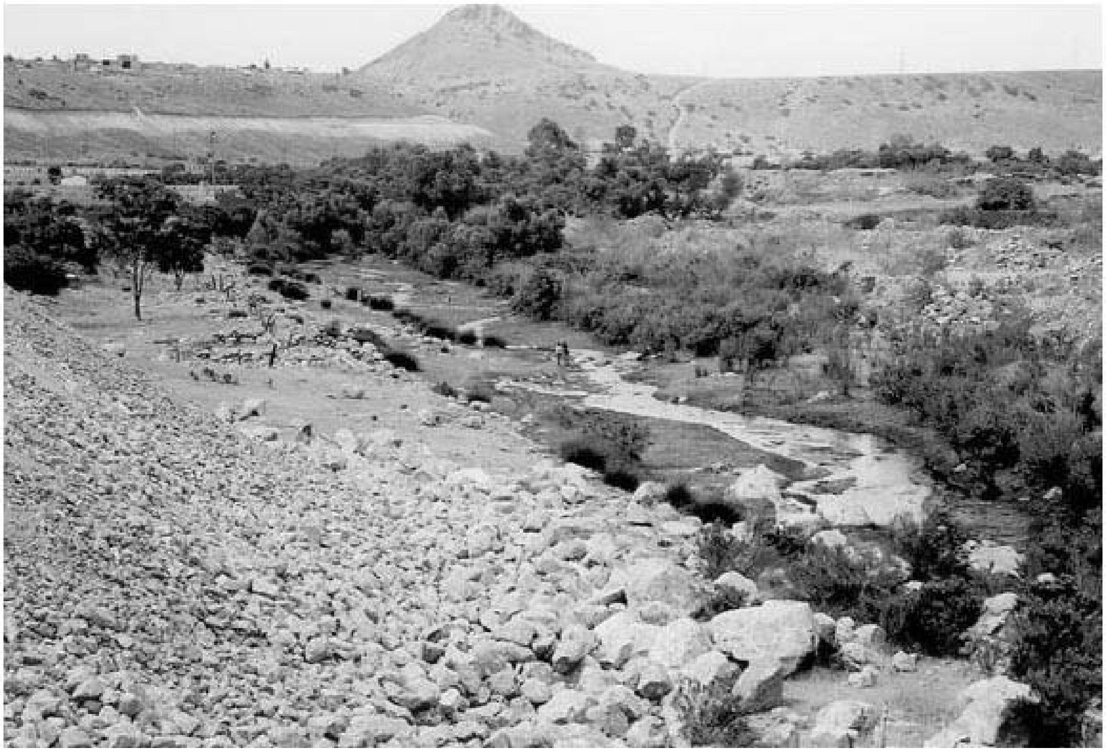

Figure 25. View of Arroyo Alamar immediately downstream of Cañon del Padre bridge.

Figure26_Ponce.jpg

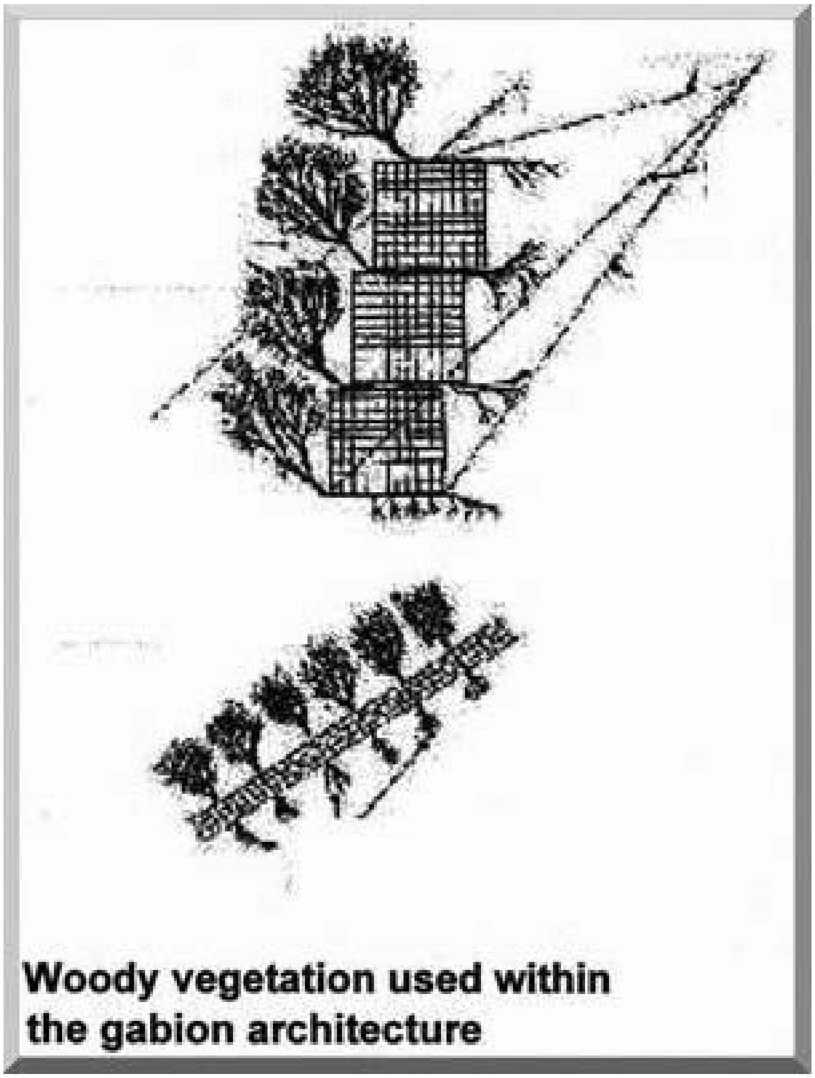

Figure 26. Woody vegetation in gabions.

Figure27_Ponce.jpg

Figure 27. Woody vegetation in gabions.

Figure28_Ponce.jpg

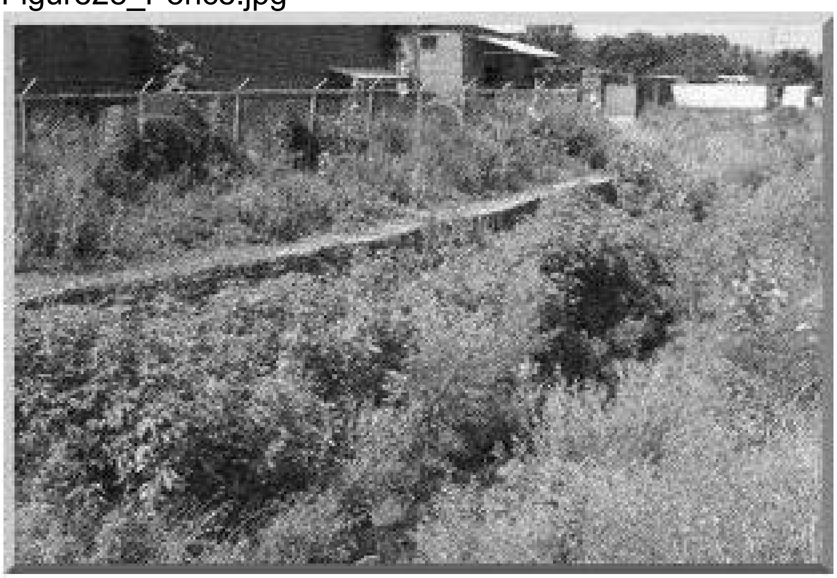

Figure 28. Growth of woody vegetation in gabions.

Figure29_Ponce.jpg

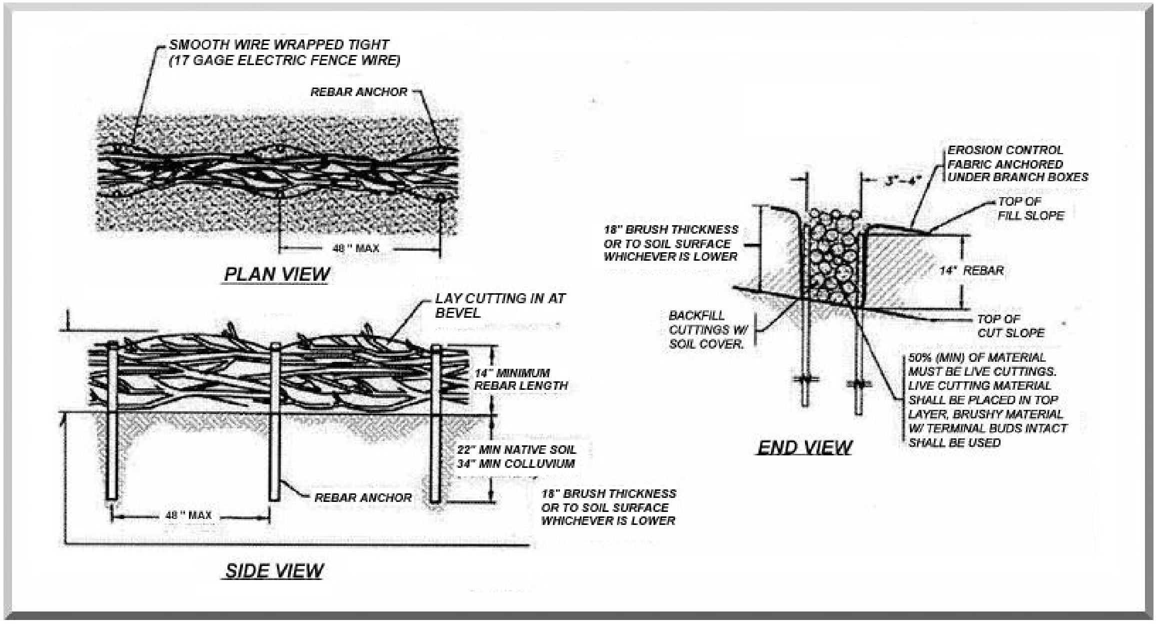

Figure 29. Wattle assembly for natural bank stabilization.

Figure30_Ponce.jpg

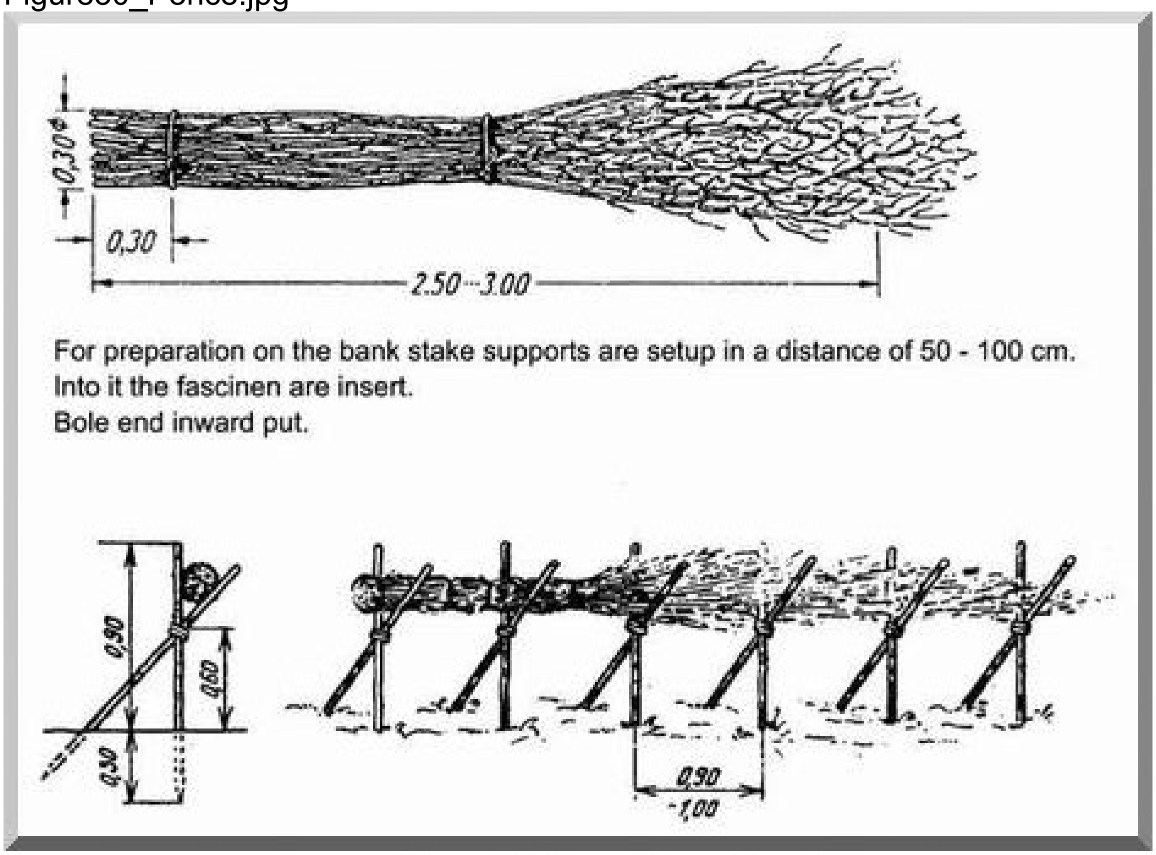

Figure 30. Preparation of fascines.

Figure31_Ponce.jpg

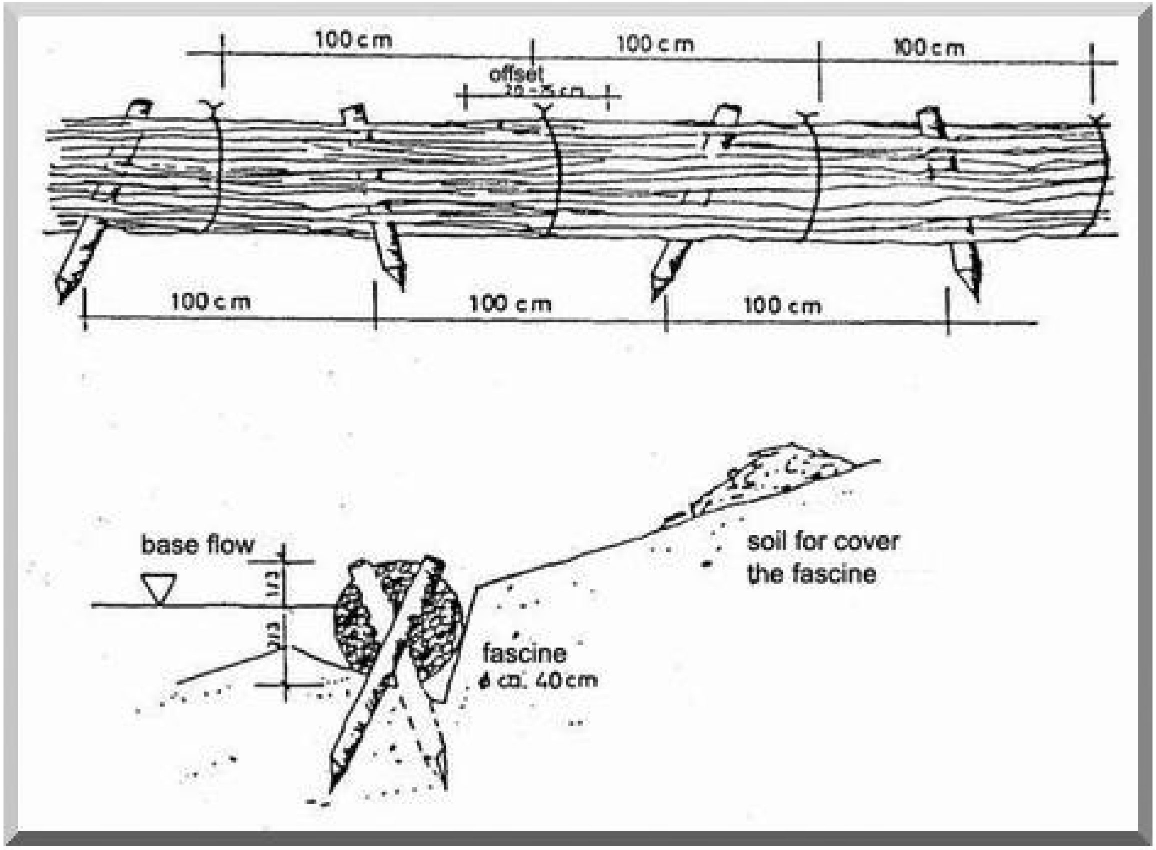

Figure 31. Installation of fascines.

Figure32_Ponce.jpg


Figure 32. Completed fascines.

Figure33_Ponce.jpg

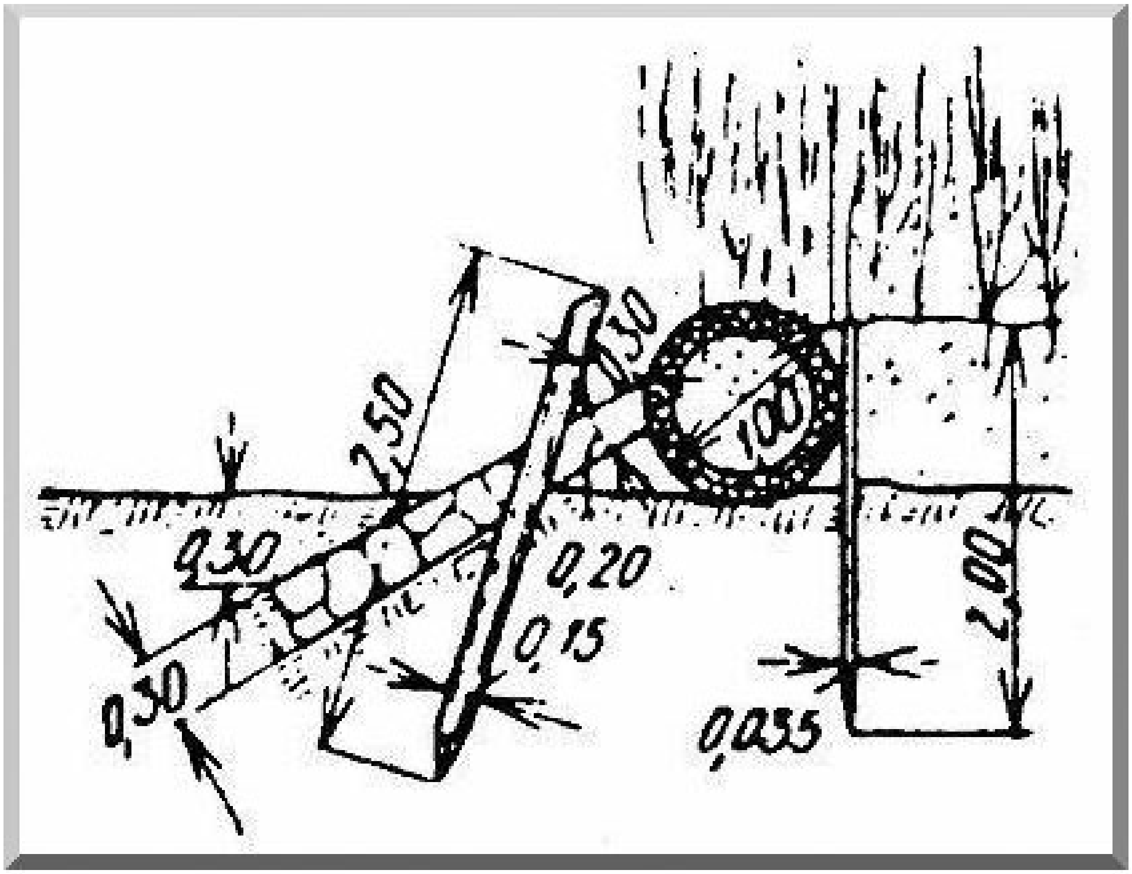

Figure 33. Weighted fascines.

Figure34_Ponce.jpg

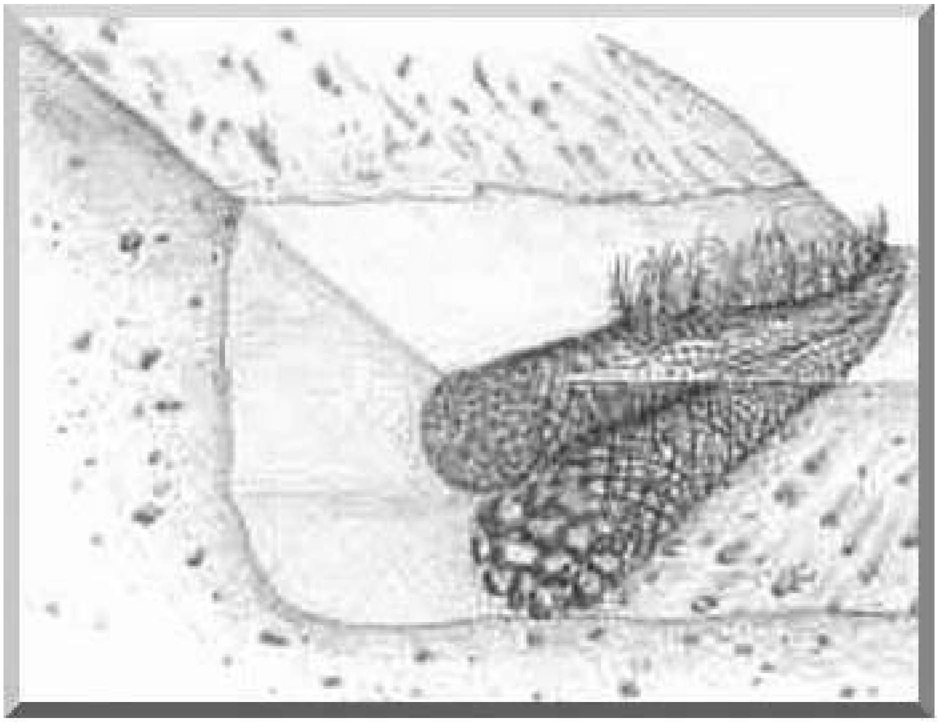

Figure 34. Weighted fascines.

Figure35_Ponce.jpg

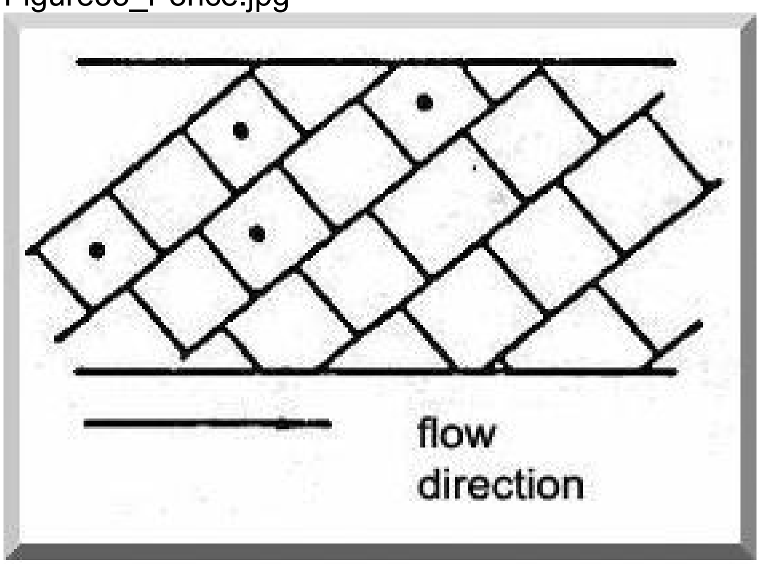

Figure 35. Flat lawns.

Figure36_Ponce.jpg

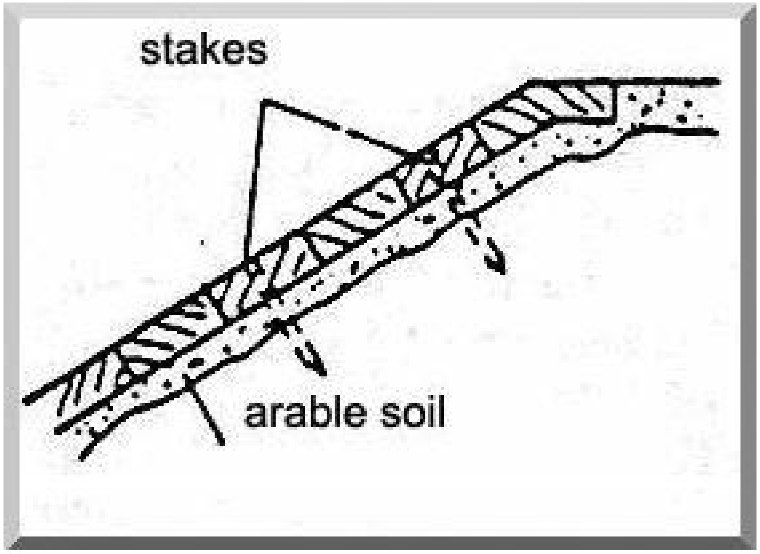

Figure 36. Flat lawns.

Figure37_Ponce.jpg

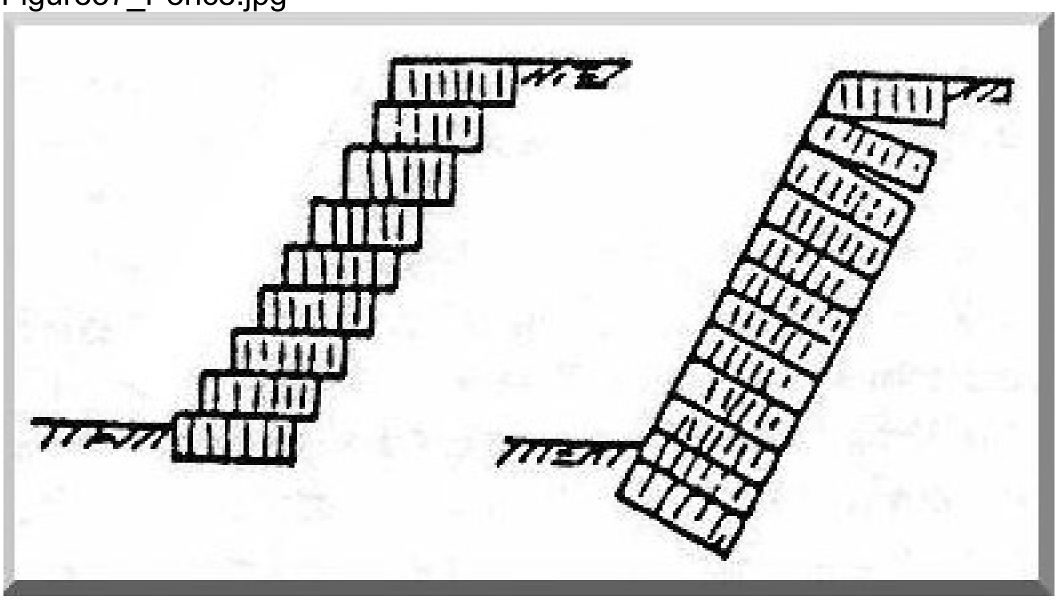

Figure 37. Staked lawns.

Figure38_Ponce.jpg

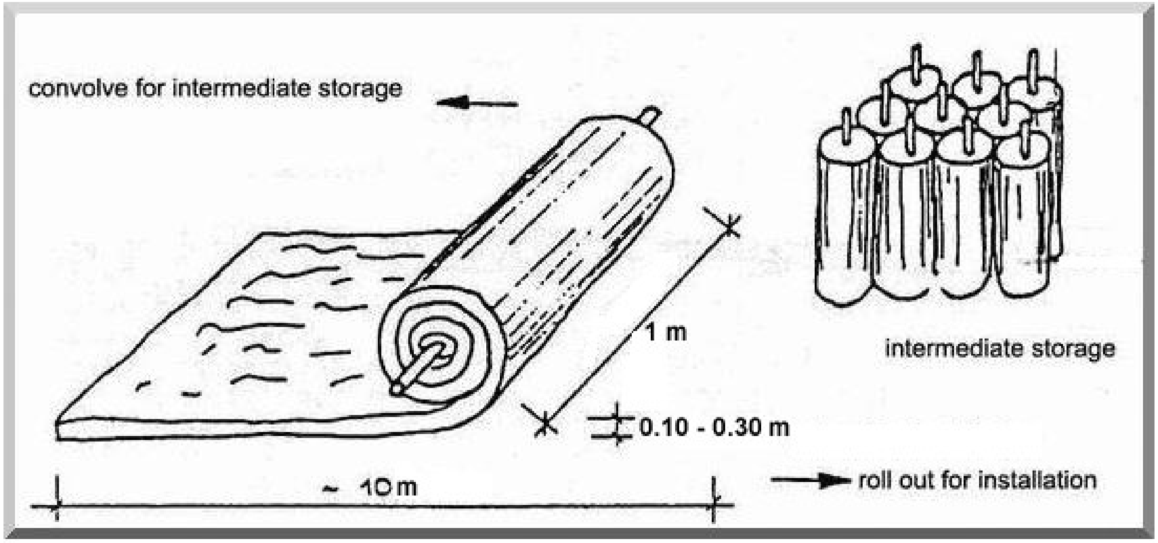

Figure 38. Lawn roll.

Figure39_Ponce.jpg

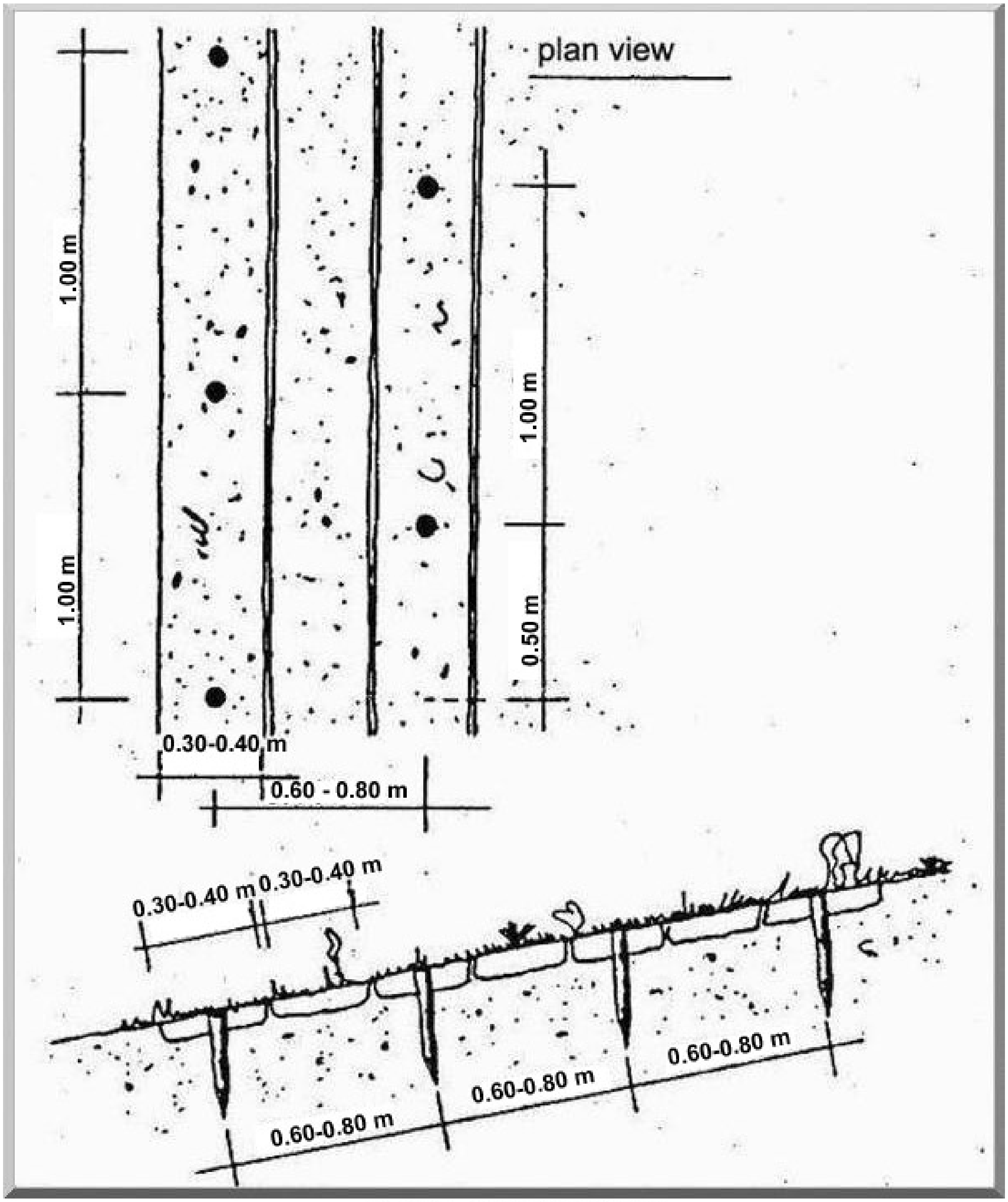

Figure 39. Installation of lawn roll.

Figure40_Ponce.jpg

Figure 40. Lawn seeding.

Figure41_Ponce.jpg

Figure 41. Fiber mattress for protection of seeds.

Figure42_Ponce.jpg

Figure42_Ponce.jpg

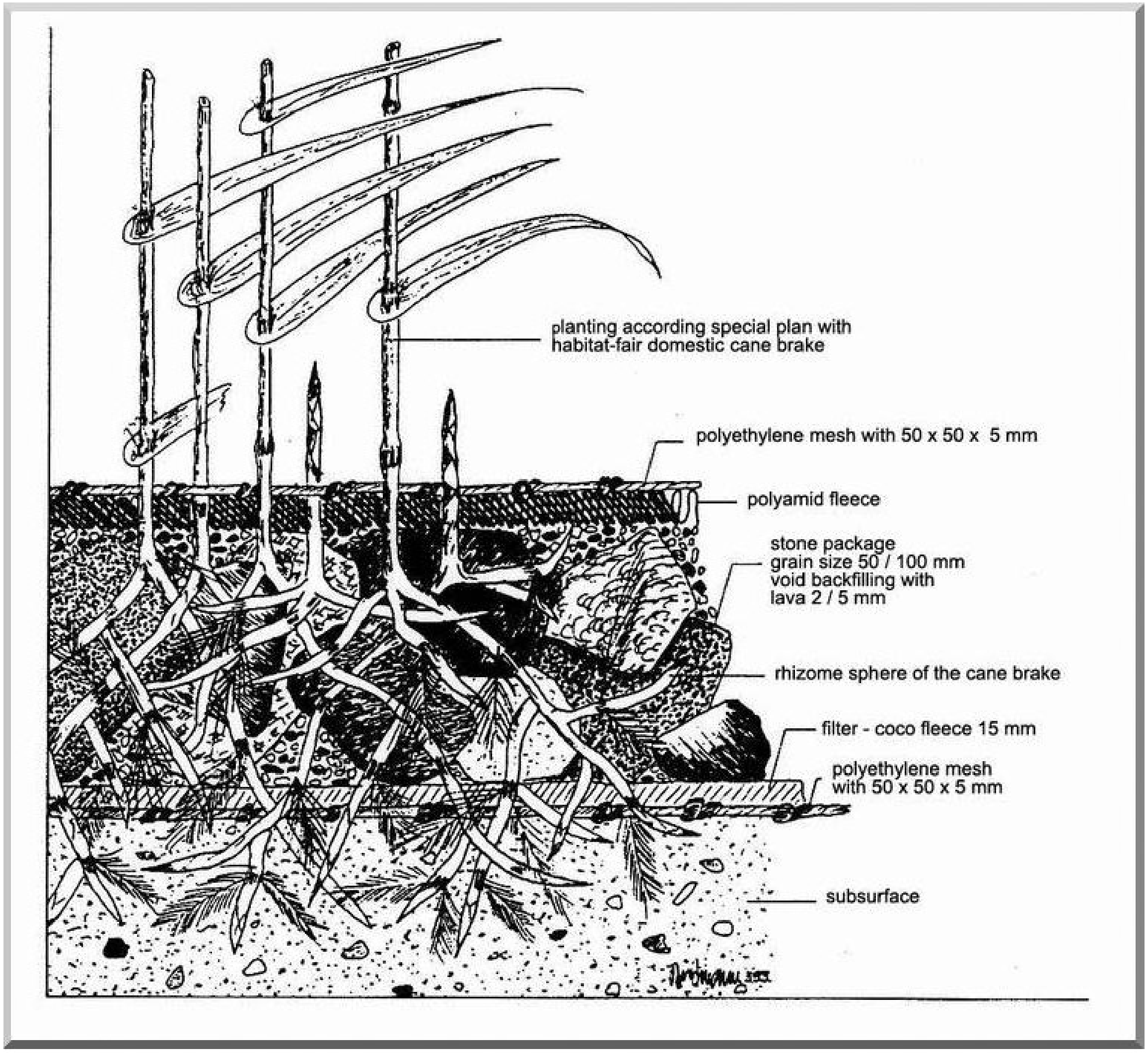

Figure 42. Vegetative bank stabilization.

Figure43_Ponce.jpg

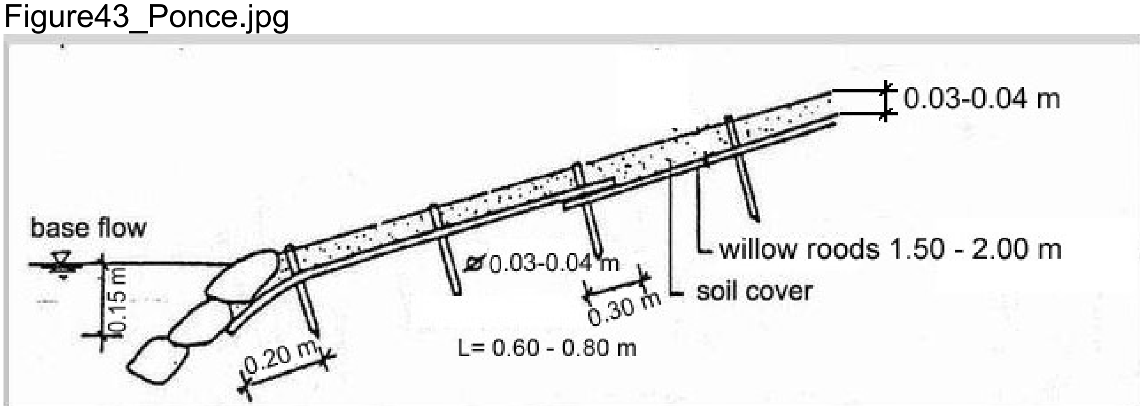

Figure 43. Plan view of brush mattress.

Figure44_Ponce.jpg

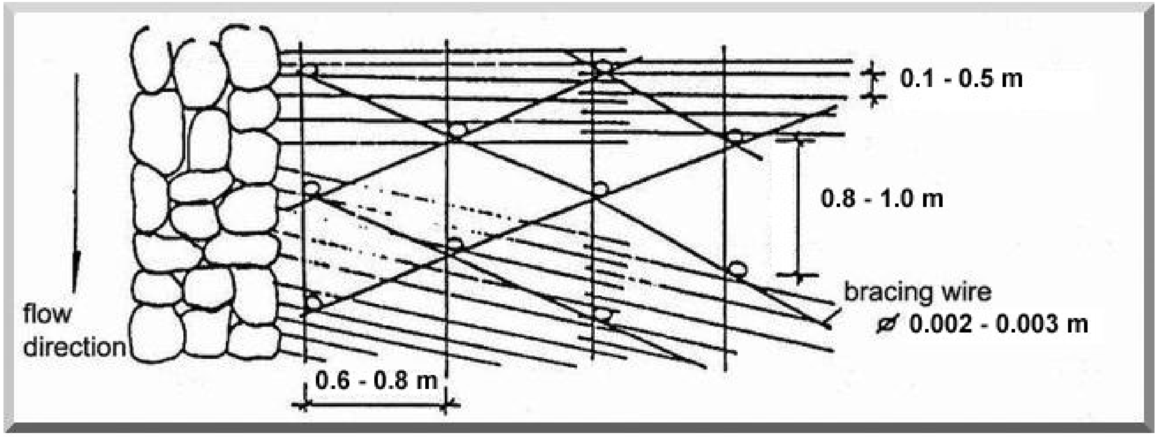

Figure 44. Side view of brush mattress.

Figure45_Ponce.jpg

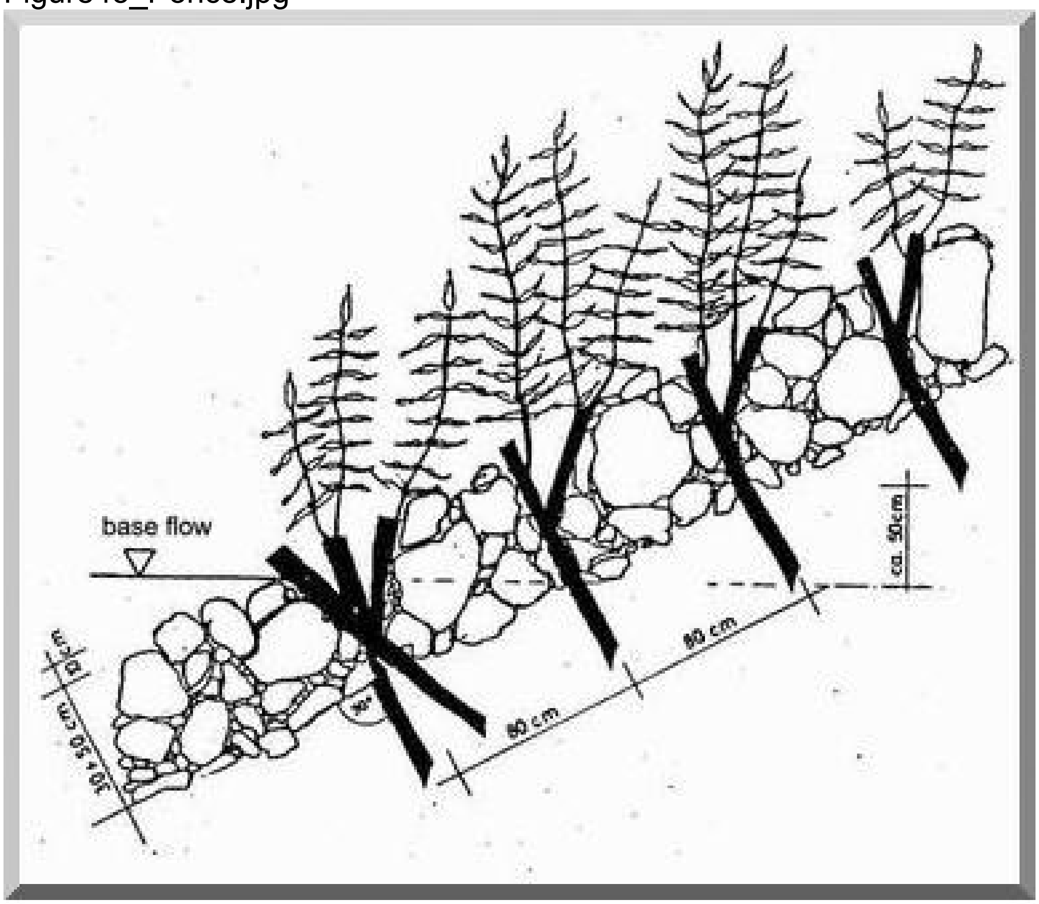

Figure 45. Live staking schematic.

Figure46_Ponce.jpg

Figure 46. Live staking soon after installation.

Figure47_Ponce.jpg

Figure 47. Live staking some time after installation.

Figure48_Ponce.jpg

Figure 48. Live staking 2-5 years after installation.

Figure49_Ponce.jpg

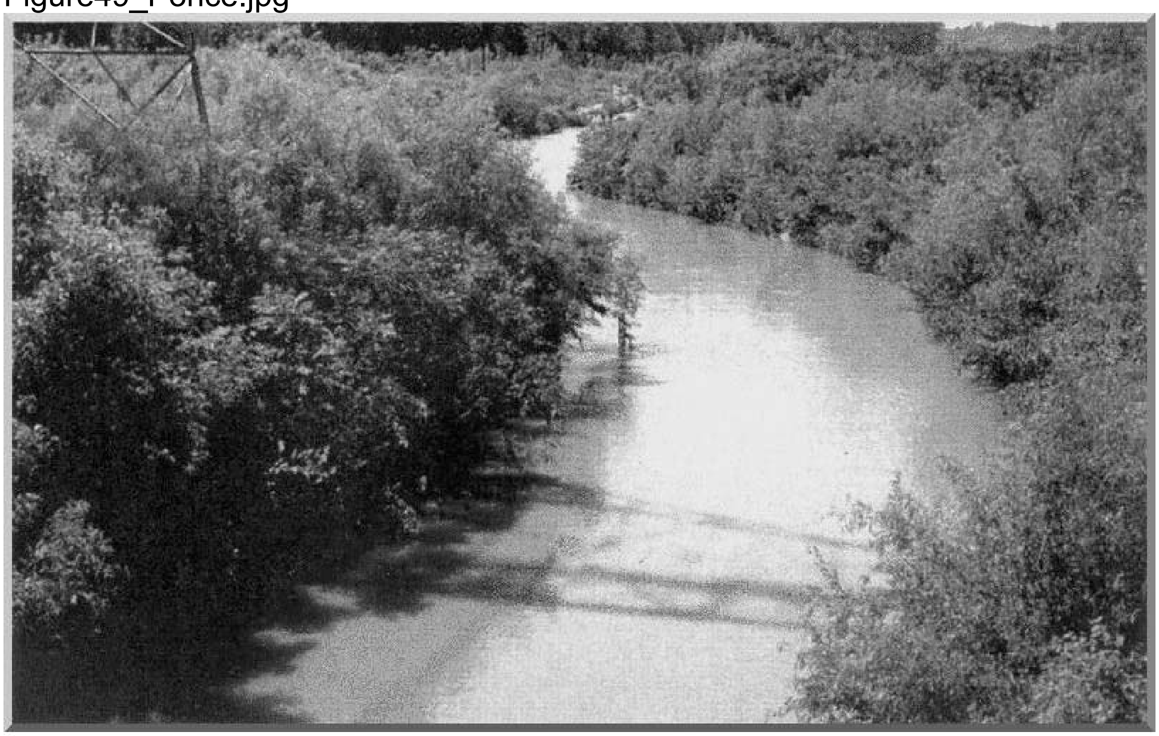

Figure 49. Established live staking.

Figure50_Ponce.jpg

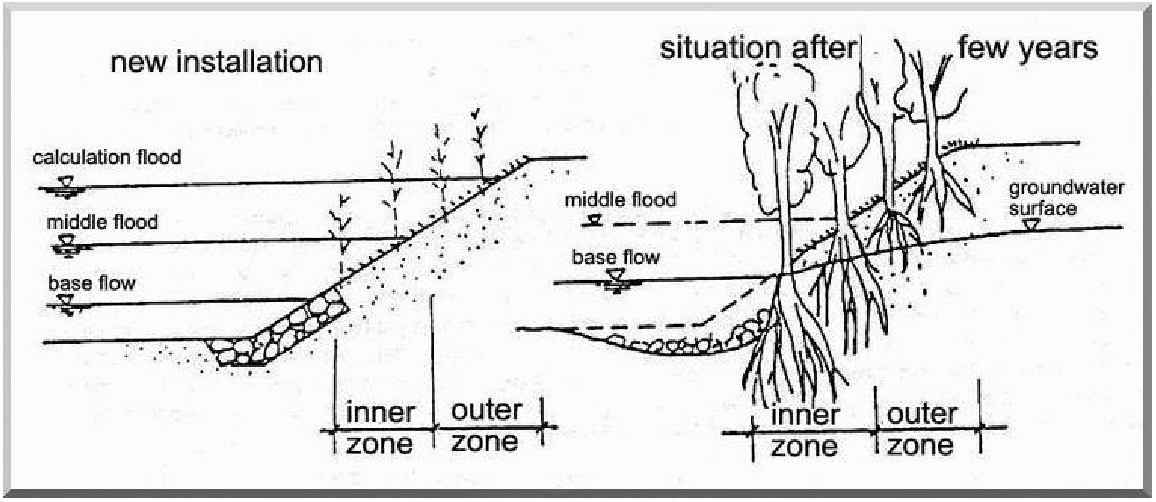

Figure 50. Bank protection with trees and shrubs.

Figure51_Ponce.jpg

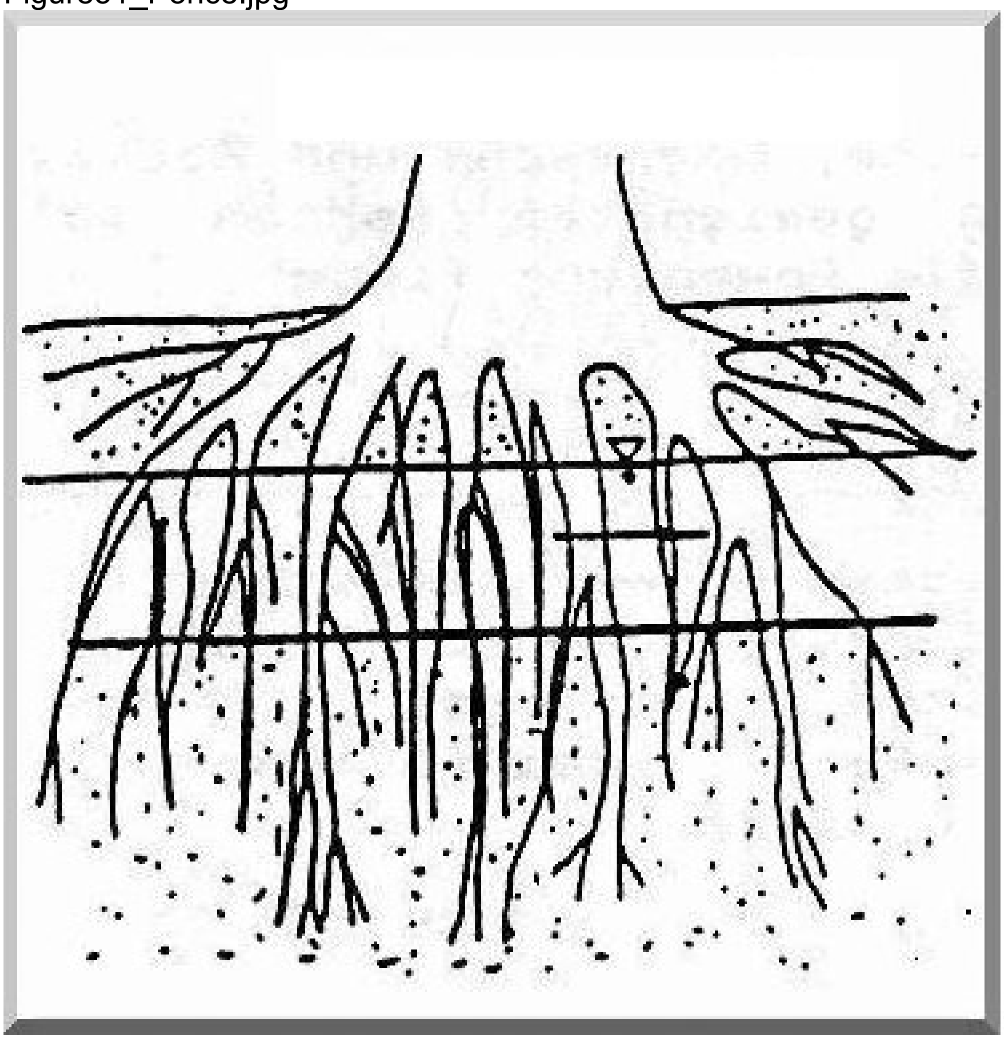

Figure 51. Longitudinal view of bank protection with vegetation.

Figure52_Ponce.jpg

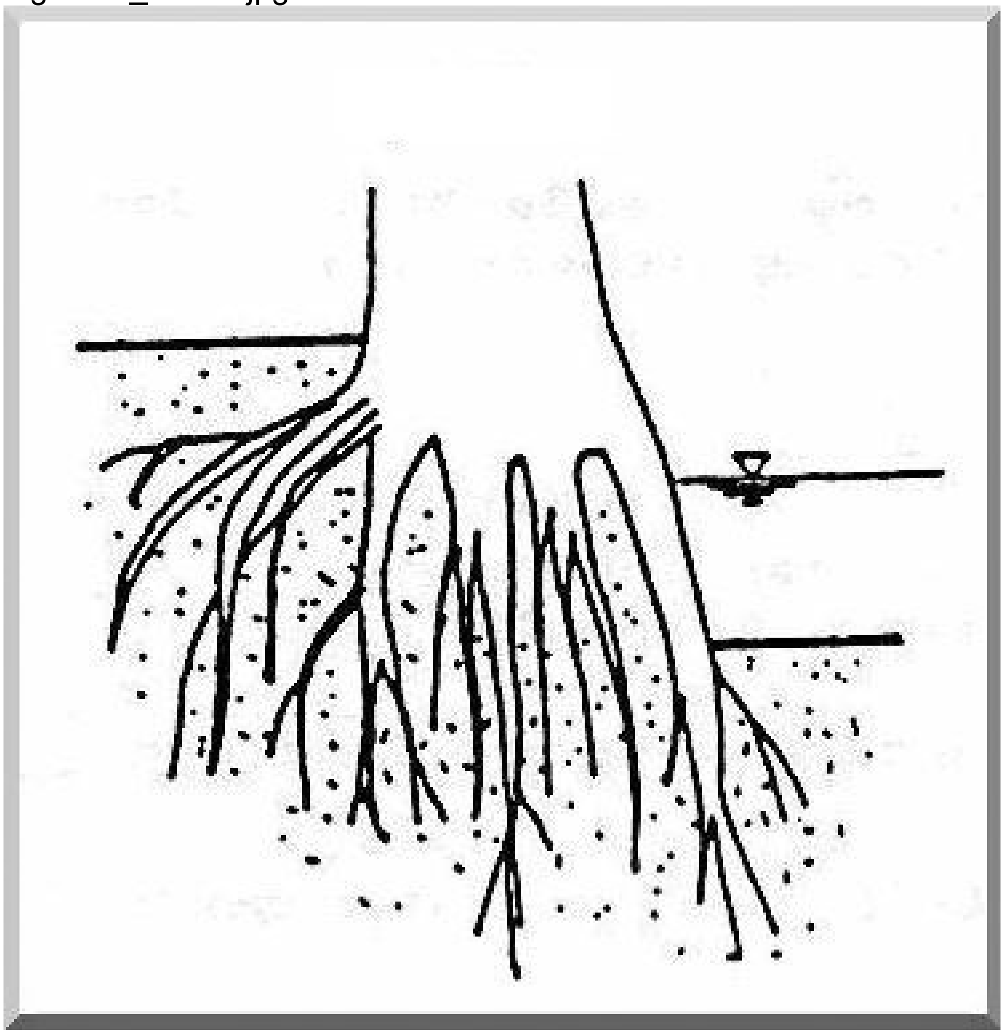

Figure 52. Side view of bank protection with vegetation.

Figure53_Ponce.jpg

Figure 53. Completed bank protection with trees and shrubs.

Figure54_Ponce.jpg

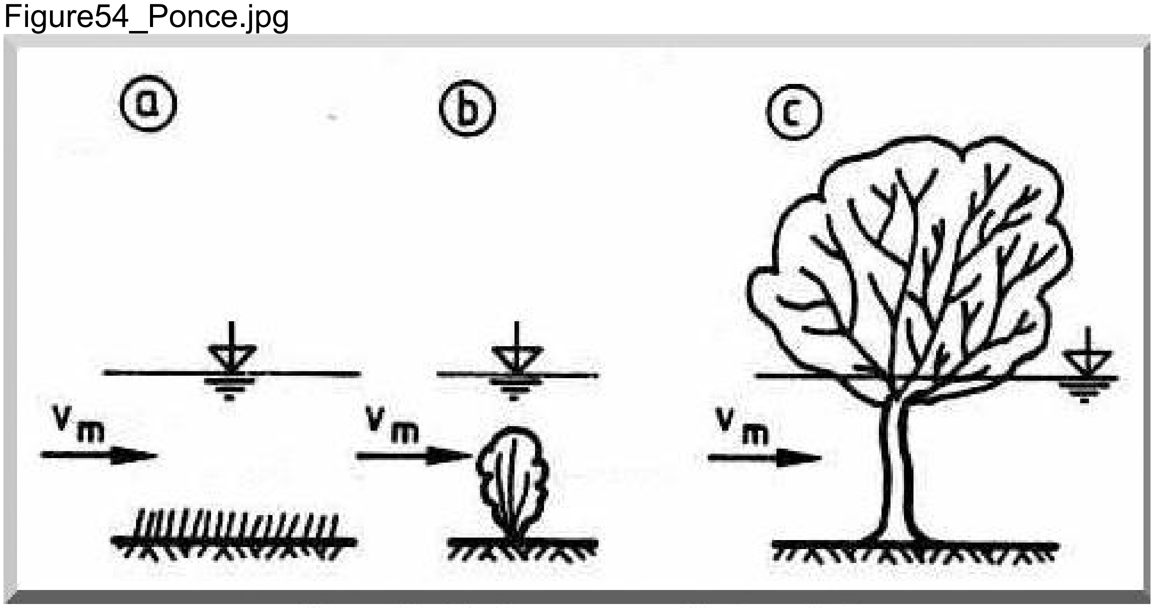

Figure 54. Short, average, and tall vegetation.

Figure55_Ponce.jpg

Figure 55. Irregular flood plains: 0.055 ? n ? 0.083.

Figure56_Ponce.jpg

Figure 56. Herbaceous flood plains: 0.041 ? *n* ? 0.050.

Figure57_Ponce.jpg

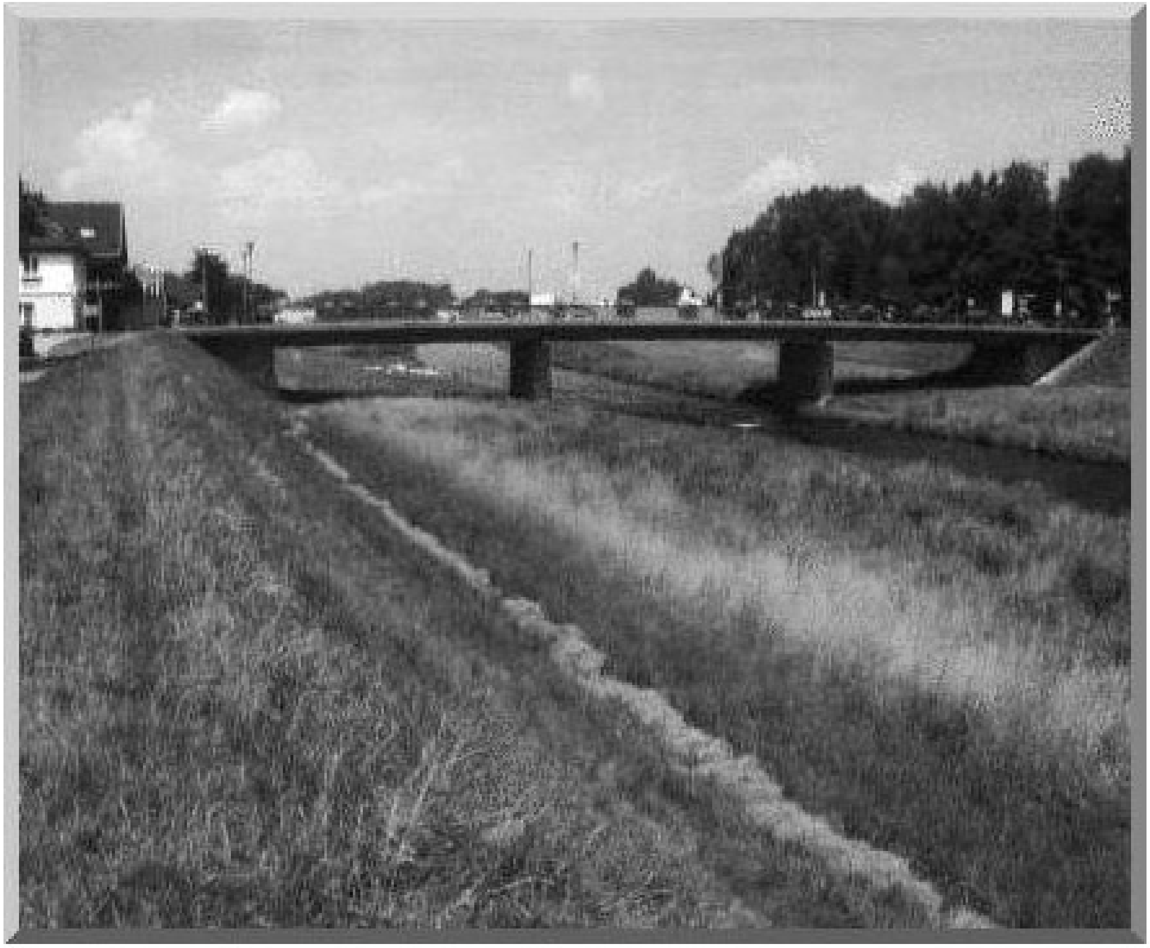

Figure 57. Grasslands flood plains: 0.028 ? *n* ? 0.040.

Figure58_Ponce.jpg

Figure 58. Grasslands flood plains: 0.028 ? *n* ? 0.040.

Figure59_Ponce.jpg

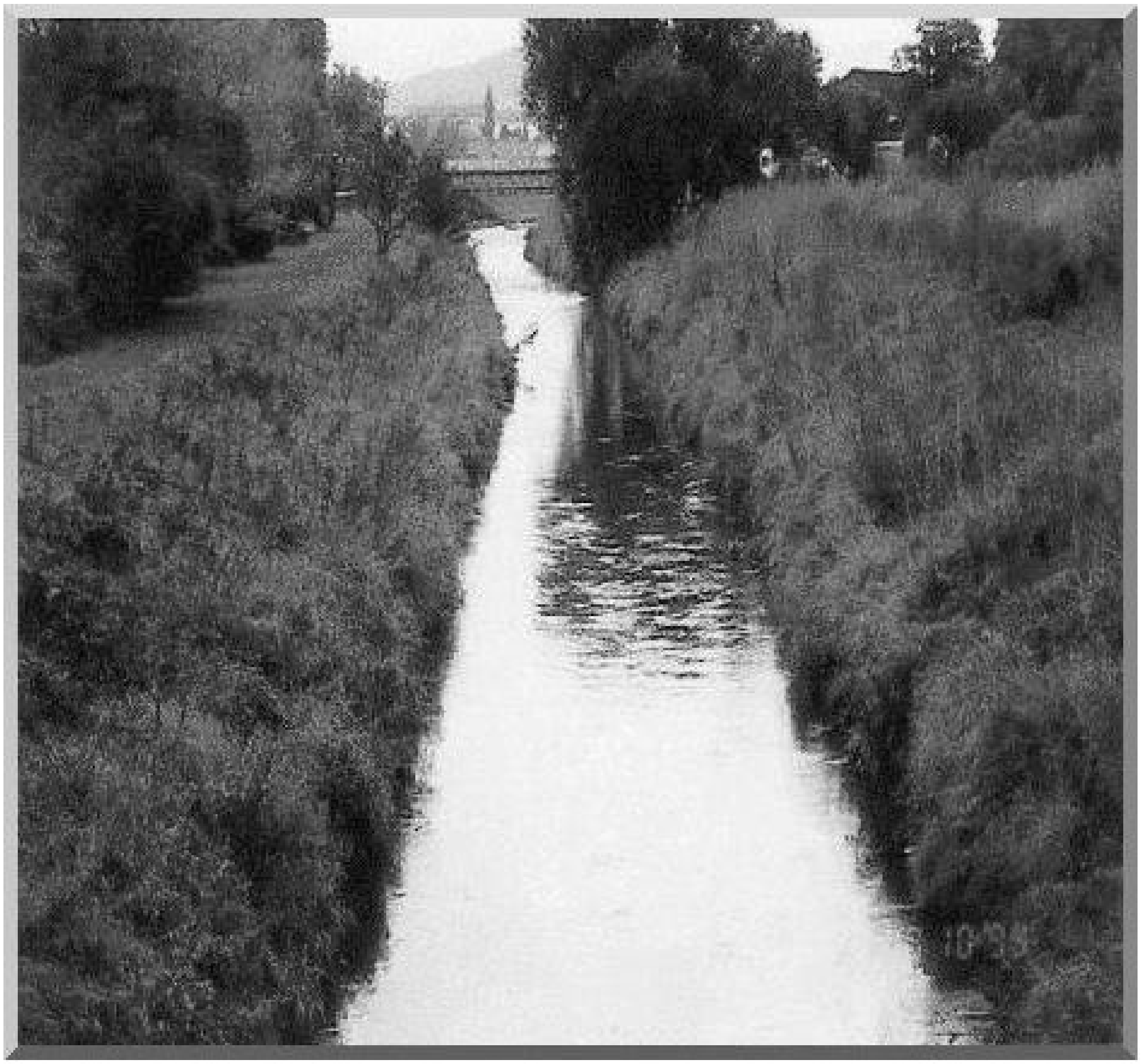

Figure 59. Shrub flood plains: 0.028 ? *n* ? 0.033.

Figure60_Ponce.jpg

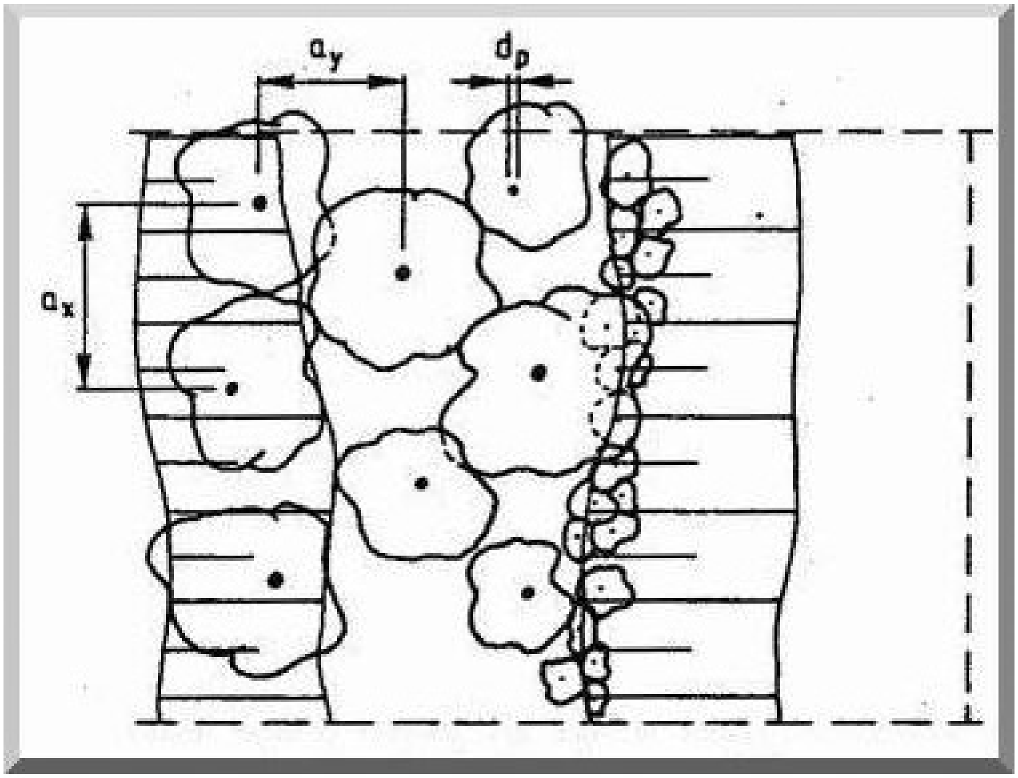

Figure 60. Geometric characterization of tree population density.

Figure61_Ponce.jpg

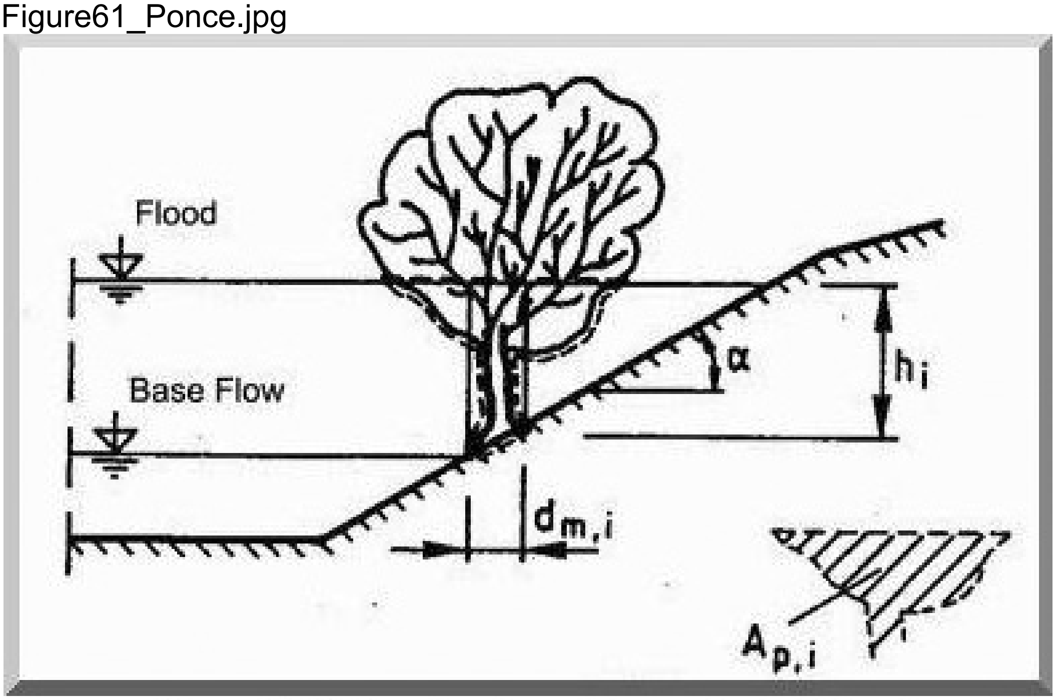

Figure 61. Determination of the equivalent diameter.

Figure62_Ponce.jpg

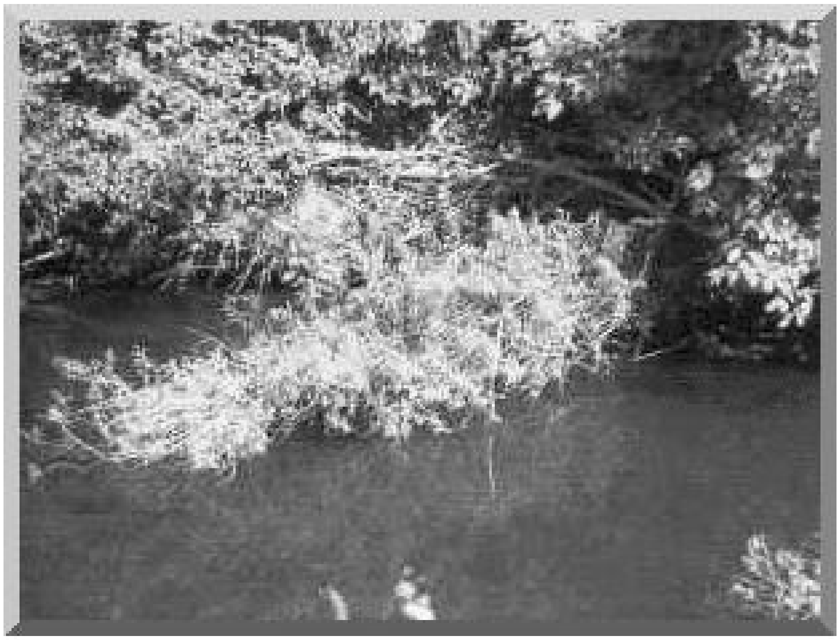

Figure 62. Examples of vegetative debris.

Figure63_Ponce.jpg

Figure 63. Examples of vegetative debris.

Figure64_Ponce.jpg

Figure 64. Examples of vegetative debris.

Figure65_Ponce.jpg

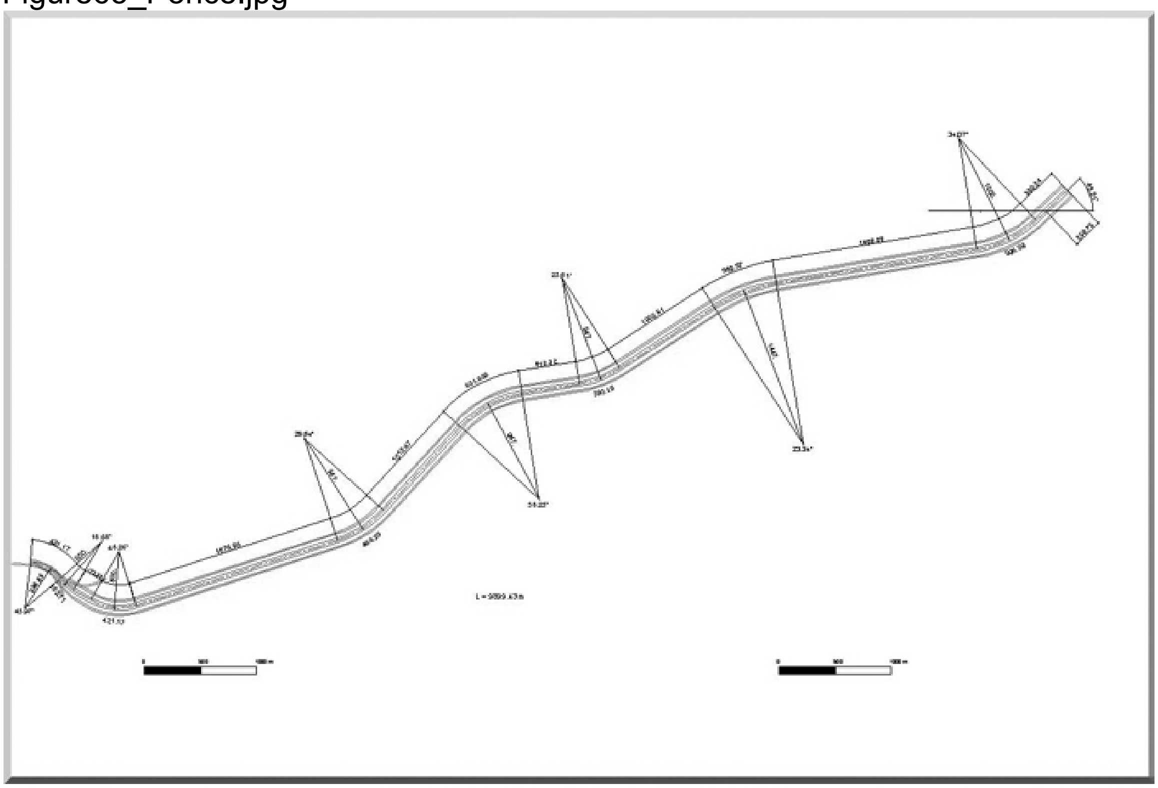

Figure 65. View of the proposed alignment.

Figure66_Ponce.jpg

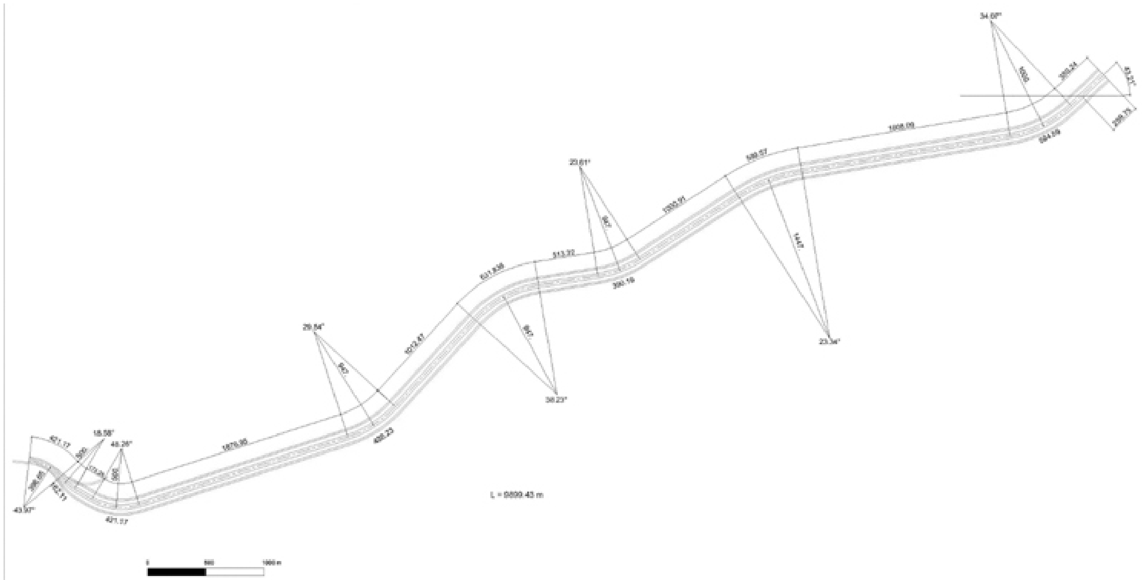

Figure 66. View of the proposed alignment (large scale): A + B + C + D.

Figure67_Ponce.jpg

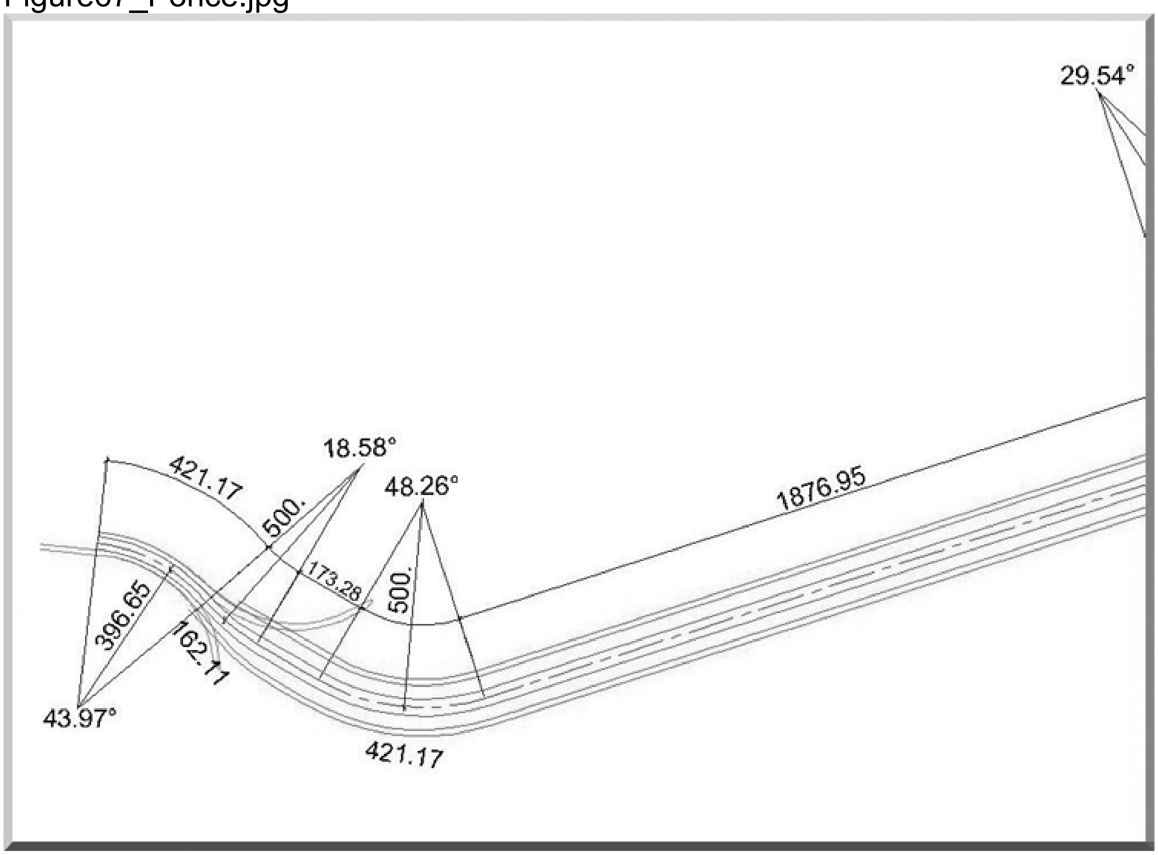

Figure 67. View of the proposed alignment: A.

Figure68_Ponce.jpg

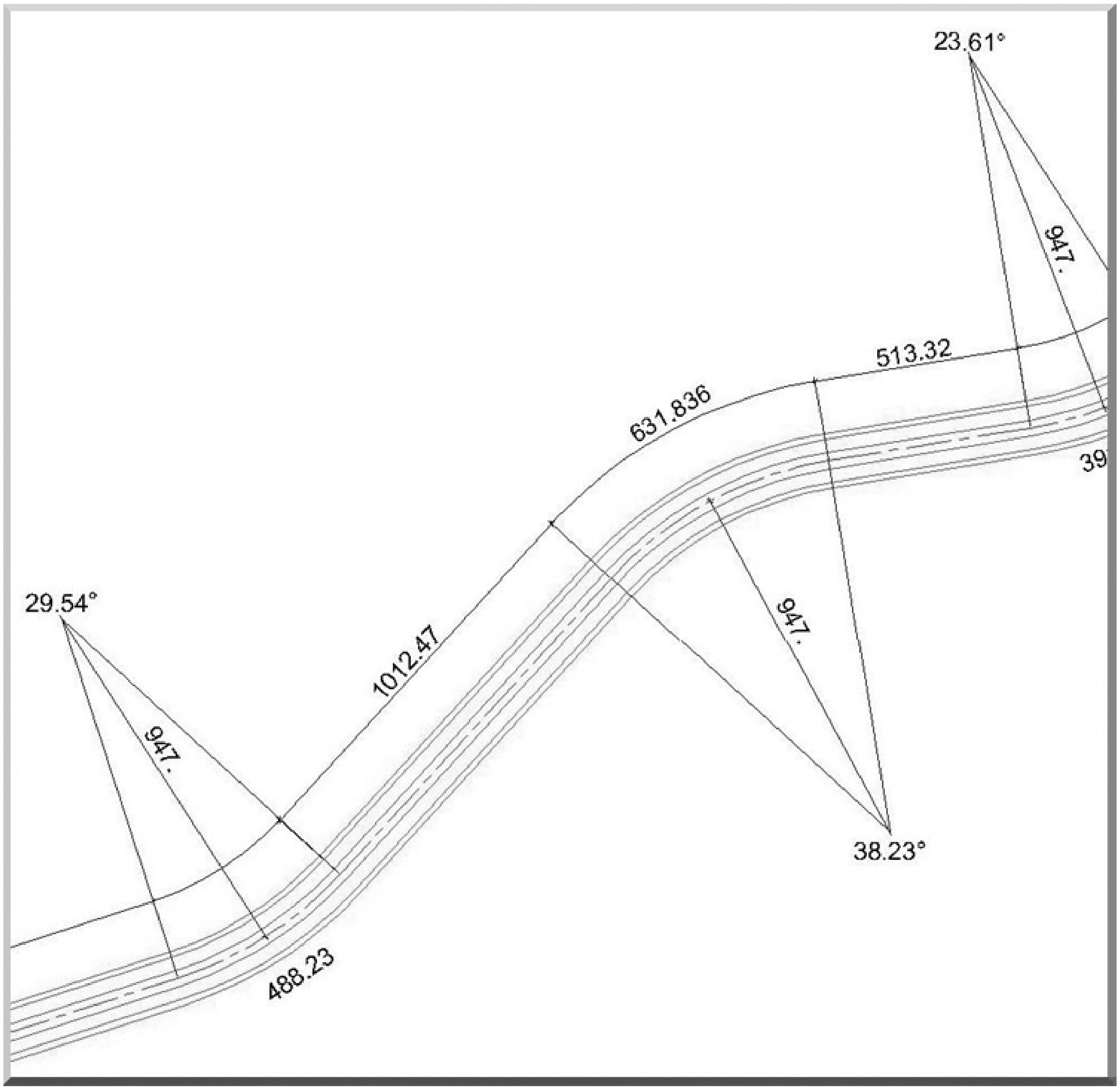

Figure 68. View of the proposed alignment: B

Figure69_Ponce.jpg

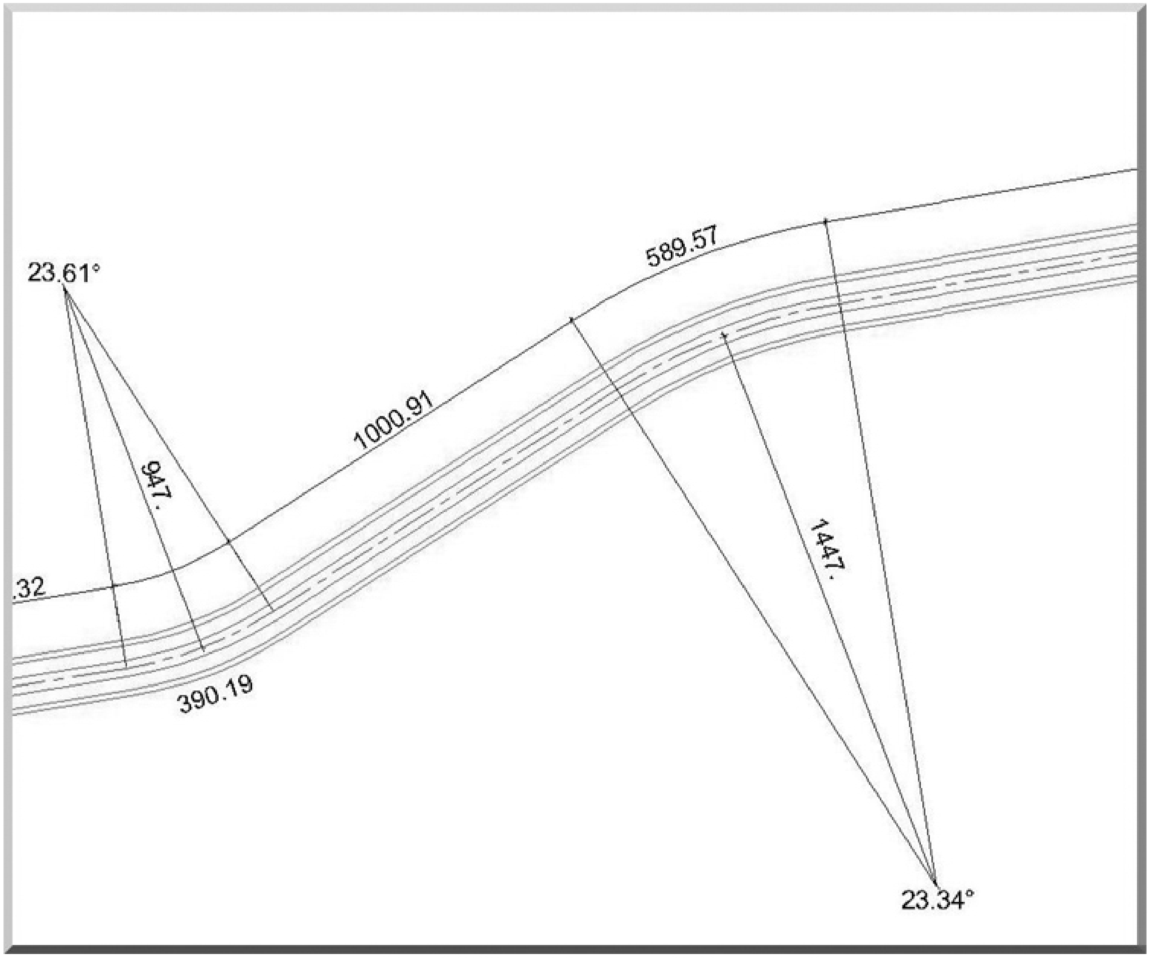

Figure 69. View of the proposed alignment: C

Figure70_Ponce.jpg

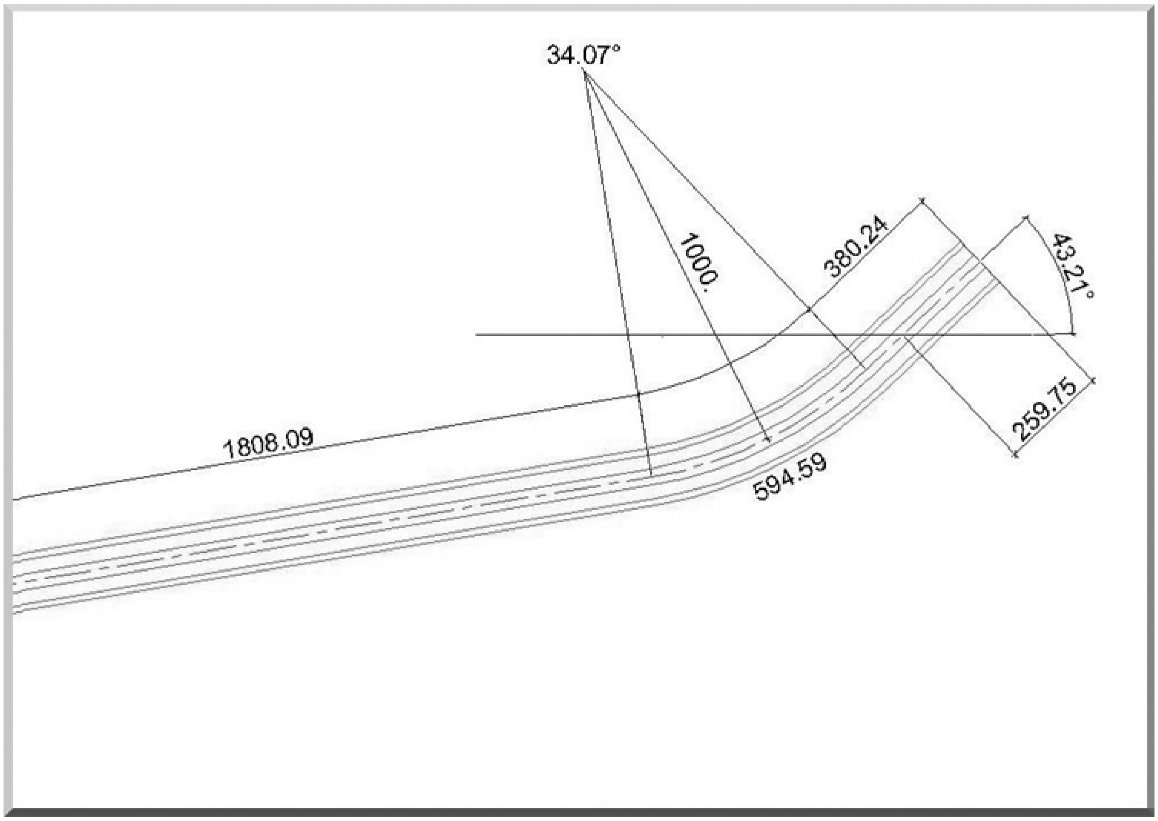

Figure 70. View of the proposed alignment: D

Figure71_Ponce.jpg

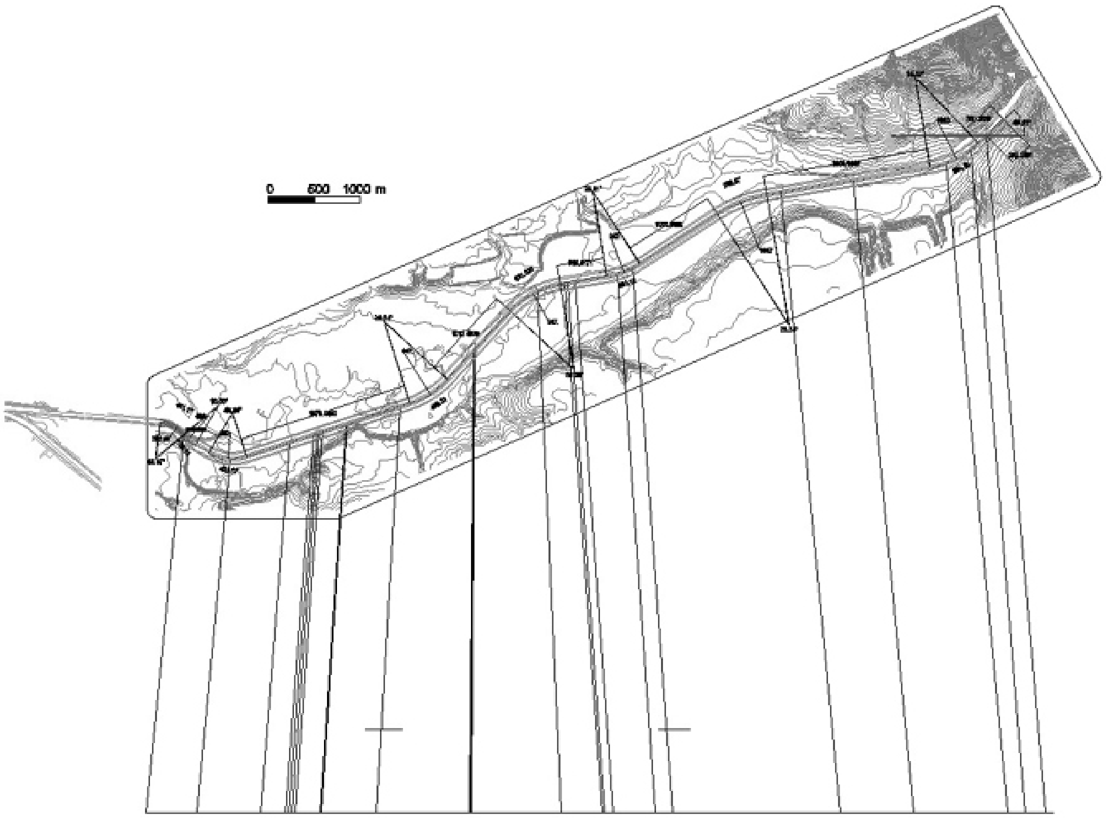

Figure 71. Arroyo Alamar: Horizontal alignment.

Figure72_Ponce.jpg

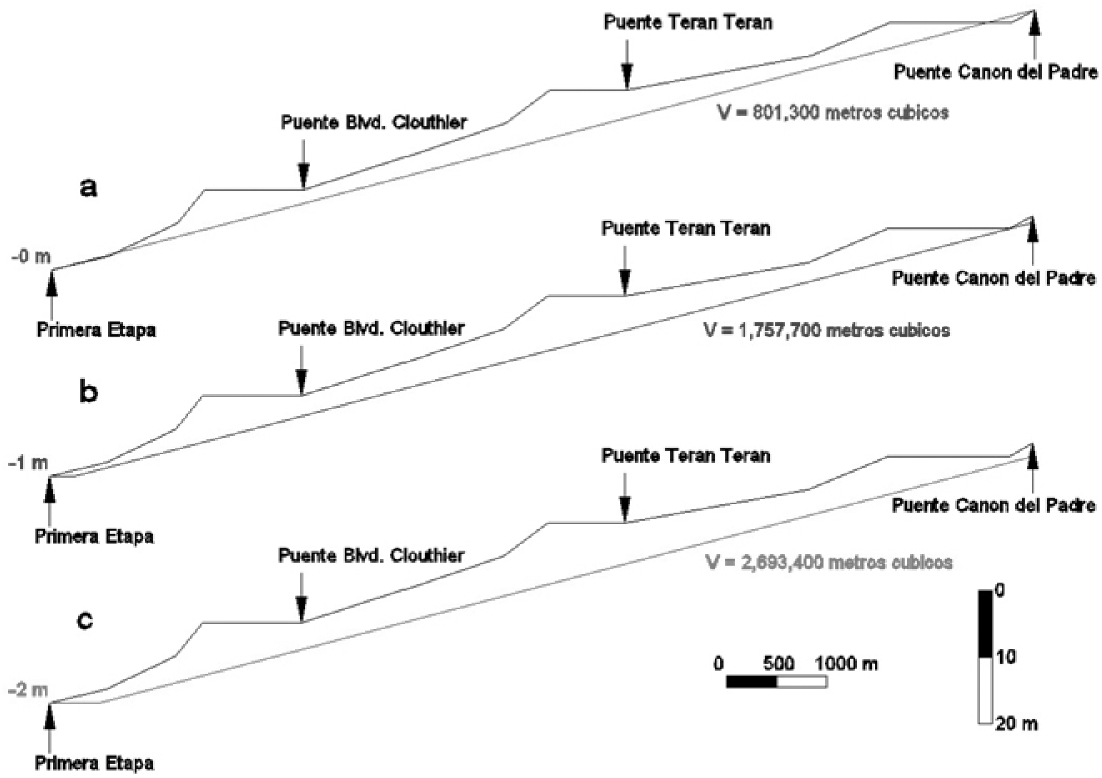

Figure 72. Arroyo Alamar: Vertical alignment.

Figure73_Ponce.jpg

Figure 73. Present conditions in Arroyo Alamar (Click to enlarge and display photos).

APPENDIX TABLES

Table 1. Classification of vegetative cover depending on degree of retardance.

Retardance Class	Cover	Condition	*C* Value
A	Weeping lovegrass	Excellent stand, tall, avg.	15.8
	Yellow bluestem Ischawmum	Excellent stand, tall, avg.	
B	Kudzu	Very dense growth, uncut	23.0
	Bermuda grass	Good Stand, tall, avg.	
	Native grass mixture (mixture of bluestems)	Good stand, unmowed	
	Weeping lovegrass	Good stand, tall,avg.	
	Lespedeza sericea	Good stand, not woody, tall, avg.	
	Alfalfa	Good stand, uncut, avg.	
	Weeping lovegrass	Good stand, unmoved, avg.	
	Kudzu	Dense growth, uncut	
	Blue gramma	Good stand, uncut, avg.	
C	Crabgrass	Fair stand, uncut, avg.	30.2
	Bermuda grass	Good stand mowed, avg.	
	Common lespedeza	Good stand, uncut, avg.	
	Grass-legume summer mixture	Good stand, uncut, avg.	
	Centipedegrass	Very dense cover, avg.	
	Kentucky bluegrass	Good stand, headed,	

		avg.	
	Bermuda grass	Good stand	
	Common lespedeza	Excellent stand, uncut, avg.	
D	Buffalo grass	Good stand, uncut, avg.	34.6
	Grass-legume fall mixture	Good stand, uncut 10 to 13 cm	
	Lespedeza sericea	Cut to 5-cm height	
E	Bermuda grass	Good stand, cut to 4cm	37.7
	Bermuda grass	Burned stubble	

Table 2. Values of Manning's *n* for selected lining materials	
Concrete: Trowel finish	0.012-0.014
Concrete: Float finish	0.013-0.017
Gunite	0.016-0.022
Flagstone	0.020-0.025
Gabions	0.025-0.030
Riprap	0.040-0.070

Table 3. Arroyo Alamar flood discharges calculated using mathematical modeling.	
Return period (yr)	Flood discharge Q (m^3/s)
2	280
5	530
10	680
25	930
50	1,140
100	1,310
200	1,420
500	1,600
1,000	1,720

Table 4. Estimated discharges using the Gumbel method.		
Return period (yr)	Gumbel variate *y*	Flood discharge *Q* (m^3/s)
5,000	8.52	2,140
10,000	9.21	2,29

Table 5. Manning's *n* values recommended by HEC-RAS for natural streams.			
Type of channel and description	**Minimum**	**Normal**	**Maximum**
1. Main channels			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150
2. Flood Plains			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040

2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium dense brush, in winter	0.045	0.070	0.110
5. Medium dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
4. Same as above but with flood stage reaching branches	0.100	0.120	0.160
5. Dense willows, summer straight	0.110	0.150	0.200
3. Mountain streams, no vegetation in channel, banks usually steep, with trees and brush on bank submerged			
a. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070

Table 6. HEC-RAS results showing flow depths, mean velocities, Froude numbers, and freeboard for corresponding return periods.						
Return period (yr)	**Discharge (m^3/s)**	**Flow depth (m)**	**Inbank flow mean velocity (m/s)**	**Overbank flow mean velocity (m/s)**	**Froude number**	**Freeboard (m)**
-	550	3.278	3.60	-	0.68	0.522
10	680	3.706	3.87	-	0.69	0.094
50	1140	4.810	4.70	0.77	0.72	2.190
100	1310	5.147	4.62	1.18	0.73	1.873
500	1600	5.677	5.31	1.17	0.75	1.323
1000	1720	5.883	5.45	1.25	0.75	1.117
5000	2140	6.554	5.90	1.49	0.77	0.450
10000	2290	6.779	6.04	1.56	0.77	0.221

Table 7. Floristic component of Arroyo Alamar.				
Species	**Common name (English)**	**Common name (Spanish)**	**Biological form**	**Origin**
Ambrosia confertiflora	-	-	grass	Nativa
Anemopsis californica	[hierba del manzo]	hierba del manzo	semiaquatic grass	Native
Apium graveolens	celery	ápio	aquatic grass	Introduced from Eurasia
Arundo donax	reed	carrizo	tall-stem grass	Introduced from Europe
Baccharis glutinosa	[huatamote]	huatamote	shrub	Native
Brassica campestris	[moztacilla]	moztacilla	grass	Introduced from Europe
Chenopodium murale	-	-	grass	Introduced from Europe
Chrysantemum coronarium	chrysanthemum	crisantemo	grass	Introduced from Europe
Cotula coronopifolia	-	-	semiaquatic grass	Introduced from Africa
Cynodon dactylon	[zacate pata de gallo]	zacate pata de gallo	grass	Introduced from Africa
Foenicullum vulgare	anise	anís	grass	Introduced from Europe
Helianthemum annum	sunflower	girasol	grass	Introduced from Europe
Heliotropium curassavicum	-	-	grass	Introduced from tropical America
Juncus acutus	rush	junco	small shrub	Native
Marrubium vulgare	[marrubio]	marrubio	grass	Introduced from Europe

Nicotiana glauca	[tabaquillo]	tabaquillo	shrub	Introduced from South America
Platanus racemosa	alder	aliso	tree	Native
Populus fremontii	poplar	alamo	tree	Native
Riccinis comunis	[higuerilla]	higuerilla	small tree	Introduced from Europe
Rorripa nasturtium-aquaticum	watercress	berro	aquatic grass	Native
Rumex crispus	-	-	grass	Introduced from Eurasia
Rumex salicifolius	-	-	grass	Native
Salis lasiolepis	willow	sauce	tree	Native
Salix goodingii	willow	sauce	tree	Native
Scirpus spp.	-	-	grass	Native
Solanum spp.	-	-	grass	-
Tamarix ramossisima	-	-	tree	Introduced from Eurasia
Urtica holosericea	[hortiguilla]	hortiguilla	grass	Native
Xanthium strumarium	-	-	grass	

Table 8. Comparison between vegetated and gabion-lined channels			
Vegetated channels		**Gabion-lined channels**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
• Higher infiltration and exfiltration • Excellent habitat function • Sizable reduction in flow velocity • Aesthetically very pleasing	• Low structural integrity • Protection is usually not immediate after installation	• High stability • Moderate infiltration and exfiltration • Immediate protection after installation • Moderate reduction in flow	

Table 9. Typical values of critical velocity and shear stress		
Material	**Critical velocity (m/s)**	**Critical shear stress (N/m^2)**
Lawn (short-time loaded)	1.8	20-30
Lawn (long-time loaded)	1.5	15-18
Fascine sausage	2.5-3.0	60-70
Fascine roll	3.0-3.5	100-150
Weighted fascine	2.5-3.0	60-100
Brush mattress	2.5-3.5	150-300
Live staking in riprap		>140
Willows/alder		80-140
Gabions	1.8-6.7	80-140

Table 10. Roughness coefficient for vegetated channels.			
Surface structure	**k**	**K_{St}**	**n**
	(m)	**($m^{1/3}$/s)**	**[Fig. 34]**
Lawn	0.06	40	0.025
Grass; field without cover	0.2	30	0.033
Grassland; rocky forest soil	0.25	25	0.040
Grass with shrubs	0.3	24	0.042
Herbaceous vegetation	0.4	22	0.045
Field with arable crop	0.6	21	0.048
Irregular flood plains	0.8	15	0.067
Highly irregular flood plains	1	12	0.083