



Urban River Basin Enhancement Methods

New techniques for urban river rehabilitation

Specifications for new materials and techniques Improve instream morphology River engineering

Work Package 8

LNEC
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Specifications 8.1

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Summary

In this document, a summary from research on river engineering with particular attention on the application on rehabilitation on urban rivers is presented. Contributions to this document represent findings on experience gained in the analysis of case studies and on the experience of the river engineering practice on the countries of the URBEM partners.

The procedures for re-naturalising flow regimes in urban rivers are divided in two main groups: measures to be practised in the drainage basin (controlling the hydrological processes) and measures to protect, maintain and improve the hydromorphological conditions in stream channels (controlling the hydraulic processes in bed and banks).

The first document of a set of specifications, Specifications 8.1, deals with the river engineering, using classical methods of intervention, although taking into account the specific case of urban river rehabilitation.

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1. Introduction

1.1 General introduction

One of the specific technical and scientific objectives of the URBEM research project is "*to develop innovative urban watercourse rehabilitation techniques for use in future schemes*". This objective is covered by Work Package 8 - New techniques for urban river rehabilitation (WP8).

The procedures for *re-naturalising flow regimes* in urban rivers, in the first work document prepared in WP8, are divided in two main groups: measures to be practised in the drainage basin (controlling the hydrological processes) and measures to protect, maintain and improve the hydromorphological conditions in stream channels (controlling the hydraulic processes in bed and banks). The two groups are divided in different types of measures.

The recommendations on *incorporation of wetlands, floodplains and sustainable drainage methods into urban schemes* are the second work document prepared in WP8. The recommendations are divided into five chapters, namely, Wetlands in rivers, Characterisation of floodplains in rivers, Influence of urban drainage systems on rivers, Procedures to define urban schemes near rivers and Recommendations on incorporation of wetlands, floodplains and sustainable drainage methods into urban schemes.

The specifications of new materials and techniques are mainly dedicated to the interventions on the rivers itself, namely to improve instream morphology (by classical river engineering and by soil bio-engineering), to interventions in drainage basin or to protect the flood in the river valleys.

The design of sustainable urban drainage facilities, and the interventions in drainage basin, is not primarily a technical problem but more of an institutional concern, basically the cooperation between different departments in a city's administration. However, it is included in the specifications.

The specifications are prepared for three main domains related to the rivers: the instream interventions, the river valley interventions and drainage basin interventions. The first are also divided in two types of interventions: the classical river engineering and the soil-bioengineering.

Considering that division of interventions they are prepared four specifications documents, each one for one of the types previously defined.

The Specifications 8.1 deals with the river engineering, using classical methods of intervention, although taking into account the specific case of urban river rehabilitation.

The Specifications 8.2 deals with soil-bioengineering instream interventions.

1.2 Introduction for the improvement of instream morphology using river engineering

The improvement of instream morphology using river engineering shall be based in well sound application of river hydraulic knowledge. It is a specialised scientific domain, and when this is neglected the success of the intervention is low.

From the knowledge of hydrological regime, the discharges for different time and space situations, it is possible to characterise the flow conditions in the river channels.

The characterisation of channel flow processes should include the characterisation of bed and banks and the hydraulic structures. The only way to collect the required data is to survey the site. For important structures the design documents should be referred to, where hydraulic computations may be included.

The hydraulic computations using the available data may be relatively heavy, involving skilled human resources, appropriated models, and for good results, calibrations. It is very easy to make large errors when calibration is not done. The results of hydraulic computations are very sensitive to some input data, such as bed slope, and mainly to the roughness coefficients. There is no good method for using the right values for coefficients, unless a calibration is done or an experienced team is involved. For the alluvial rivers the difficulties are increased. The characterisation of river bed sediments should be always included.

The characterisation of river flow processes should be done for the appropriate situations, being included in most cases, at least: 1) the flood events, where the river channels are small to convey all water, 2) the full bank where the beginning of flood occurs, 3) an average discharge situation, representing the more frequent situation and 4) low flow situations. For certain rivers the discharge decreases to zero, remaining, however, in most cases, sub superficial flows, and small stagnant water bodies.

The computations, supported by calibrations, should deliver for the chosen cross sections, the water flow characteristics for the cases referred to above; water levels, velocities, singular flow behaviour (for instance changes of flow type, subcritical or supercritical), 2D or 3D features (lateral currents, vortex).

The hydraulic characterisation may advance the sediment transport and water quality characterisation.

The degree of comprehensiveness of the hydraulic characterisation depends of the importance of the study. As the hydraulic computations are in general heavy they should be included, certainly, in large studies, but may be simplified accordingly the size of the problem. If we are dealing with an intervention on short reaches of small rivers it should be enough to do simple computations with a minimum of calibration procedures and light site surveys.

The modifications encountered in the river channels situated in urban areas may vary from insignificant to large deviations. Similarly to the hydrological modification analysis the knowledge of the time evolution of the urban occupation is the basis for the characterisation of the previous conditions, and a reference situation shall be found. It may correspond to a situation where no urban occupation was present, or alternatively a light occupation existed. The choice is as previously referred to, pure arbitrarily.

To achieve the “good ecological potential” of urban streams a new approach is required. A more natural approach needs to be taken to manage and design channel form and function. In the past, many rivers were stabilised and hardened with concrete and steel in order to accommodate navigation and to protect urban uses from flooding and erosion. River shorelines were typically designed for a single purpose. Today there is a growing support for ecology and multiple uses as well as an interest in using “soft engineering” of shorelines at appropriate locations. Such an approach incorporates flood conveyance concerns, aquatic habitat, riparian habitat, water quality, recreation and aesthetics.

However, the “soft engineering” has limitations and the classical river engineering shall be also considered in the instream interventions.

In the following sections a few main type of interventions are presented, taking into consideration the characteristics of the river channel parts.

2. Planning of instream interventions

2.1 Introduction

The instream interventions to improve the morphology of river in urban rivers shall comply with the EU Water Framework Directive (WFD). In this it is expected to improve water quality and the ecological conditions of rivers within Europe, but for that purposes it is also needed to have the appropriate hydromorphology of the river, river bed and river banks. This is applicable either natural rivers or “Heavily Modified Rivers”.

The main objective of the instream interventions is to achieve good ecological conditions by combining water resources management and city planning, hence improving the quality of life. The interventions shall be done with the “best practicable technology” and the present specifications are made to guide cities how to achieve good ecological potential in its urban rivers.

The rehabilitation of urban rivers shall result of a planning process that may start a few years leading to the implementation of measures involving stakeholders that define goals and objectives and setting quantifiable targets that can be monitored.

2.2 Identification of stream type

The identification of stream type is primary step to choose the intervention on urban rivers. One way to identify is to use the stream classification system by Rosgen (MNR, 1994). This classification expresses physical attributes of the channel such as slope, sinuosity, width-to-depth ratio, particle size of sediments in bed and banks, stream entrenchment ratio, landform features by stability class and others. It offers a morphological tool for the classification of rivers by type.

This classification system for the hydromorphological features of a river is based on the natural rivers, and includes the main parameters to be obligatory considered in the conception of the rehabilitation, and on the design of the interventions.

It is not obligatory necessary to consider this classification, but it helps to check the needs in data and the parameters of the technical interventions in the stream channel.

The classification is to be used in the existing conditions of the urban river, that are usually in a modified state, some times strongly different from the previous natural conditions

The classification of river type shall be done by stream section (or reaches). The reaches are to be defined in function of the variations encountered along its length.

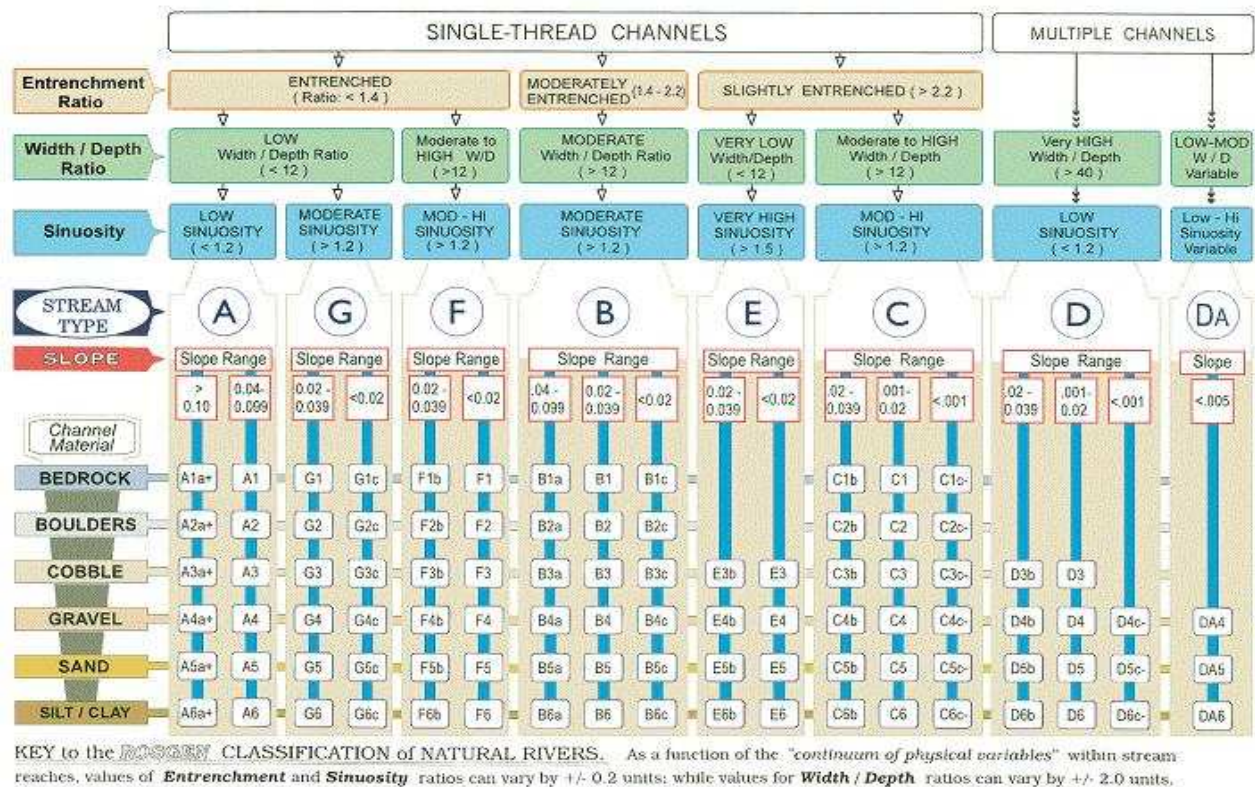


Figure 2-1 – Classification of rivers, Rosgen 1996

2.3 Conceptualisation of stream rehabilitation and design

The assessment of deviations from an ideal state is the base for the conceptualisation of the rehabilitation of the present day urban rivers. Known the actual urban rivers and defined the goals for the interventions it shall be defined a general procedure for the interventions in the stream channels, considering other types of interventions may be present at same time.

Measures for a drainage basin and a river site need to be combined in turn, forming "treatment trains" of measures that supplement each other to meet planning targets. After the conceptualisation follows a pre-design and a final design for construction by which measures are sized to meet the conditions of a site.

2.4 Selection of measures

All the previous steps are required to be taken before a first selection of potential measures is being made. Here we differentiate between: (1) measures for a river basin or sub-drainage area and (2) measures for a channel bank or riparian area of a river section (reach). Both types of measures are required for a comprehensive

project. The specifications described here are only dedicated to the instream and flood prone areas interventions.

In mobilisation of people in planning and implementation of measures, the satisfaction of different interests with multi-purpose arrangements is of importance. Giving information to the public is not enough; the public should be included in the decision-making process and also in implementation procedures. In affecting the largest number of people, amenity is of high importance and a prior condition of many recreational activities.

The process aims at including the public as well as the users. However, it does not provide only information to the public, but it assumes an active participation of users in the decision-making process, including the collection of own means for co-financing in implementation (voluntary service). The implementation takes place in phases depending on the means available.

In each step the characteristics, advantages, disadvantages, multi-purpose use, costs of implementation and maintenance and the predicted influence on the state and conditions are determined.

Here non-structural management practices may be carried out, or structural measures may be built. This requires approved plans, construction specifications, a bidding process and construction observation.

The general process of implementation of all types of urban river rehabilitation aims at including the public as well as the users. However, it does not provide only information to the public, but it assumes an active participation of users in the decision-making process, including the collection of own means for co-financing in implementation (voluntary service). The implementation takes place in phases depending on the means available.

In each step the characteristics, advantages, disadvantages, multi-purpose use, costs of implementation and maintenance and the predicted influence on the state and conditions are determined.

Here non-structural management practices may be carried out, or structural measures may be built. This requires approved plans, construction specifications, a bidding process and construction observation.

However in the instream interventions it is needed a specialised skill to guaranty a sound choice of measures and its design using scientifically based knowledge. Consequently there are limits to a completely open discussion of some types of technical interventions.

2.5 Monitoring and maintenance

The effectiveness of a project is determined by surveying pre-development conditions at the beginning, comparing them to post-development conditions, and

applying criteria through indicators of success. The costs of monitoring involved is money well spent when findings are communicated and used in order to convince the public and its representatives that projects financed with the taxpayers money have been a success.

In an optimal case, the lessons learned during the monitoring process are utilized in revising targets, conceptualisation and design of measure and the operation of controllable systems.

If these are valid for all types of measure, they are technical reasons to reinforce the need of monitoring in the stream channels. Indeed, the rivers are subject to large flood events that involve strong forces in all river bed and river bank founded structures and put in motion the alluvial beds. The large mobility of the rivers imposes a careful monitoring plan.

The maintenance of the interventions shall be done based in the results of the monitoring.

2.6 Improvement of instream morphology with river engineering

To achieve the “good ecological potential” of urban streams a new approach is required. A more natural approach needs to be taken to manage and design channel form and function. In the past, many rivers were stabilised and hardened with concrete and steel in order to accommodate navigation and to protect urban uses from flooding and erosion. River shorelines were typically designed for a single purpose. Today there is a growing support for ecology and multiple uses as well as an interest in using “soft engineering” of shorelines at appropriate locations. Such an approach incorporates flood conveyance concerns, aquatic habitat, riparian habitat, water quality, recreation and aesthetics.

Stream bank protection designs that include vegetation satisfy these multiple objectives. Natural channel design can well be accomplished with soil-bioengineering measures that use a combination of living plant material and mechanical means to achieve specific engineering functions. This type of instream interventions are presented in the Specifications 8.2.

However the “soft engineering” has limitations, and the classical river engineering have always to be present in most cases, because some types of measures do not have alternative.

The specifications of the river engineering interventions are divided in five groups considering different aspects of the rivers.

The first group is dedicated to an important characteristic of the urban rivers, they were in the past confined by revetment of the natural river bed and river banks, being in extreme case covered by panels hidden completely its presence.

The three following groups are based in the three main views of the rivers: cross sections (bed and banks), longitudinal profile and plan form.

Finally in the last group they are considered some singularities, most of them related with infrastructures, like bridges and hydraulic works.

3. Interventions in the river bed

3.1 Introduction

The most sensitive interventions are in the river bed. The natural mobility of the alluvial beds and banks were considered disturbing for the human activity in urban areas, leading in the past to its fixation. The creation of fixed beds prevented the life of planktonic species and the presence of vegetation, consequently implied a decreasing or elimination of life in the rivers.

If the fixation of river beds is relatively easily designed, the inverse intervention is much more difficult. Indeed, the design of a stable slope in a river bed is extremely difficult for the river with a natural regime of discharges, i.e. variations along time of river discharges and also a natural sediment supply. When there is a control on discharges, with a relatively short variation of discharges, and the sediment supply is almost absent, the design is much simpler.

The urbanisation of rivers along time included construction of structures in or over the river bed and buildings on banks. Consequently, the measures to rehabilitate the rivers shall include the removal and the reconstruction of old and abandoned buildings, removal of watercourse culverts, removal of walls and buildings on the banks and in close vicinity of the stream, closing the indirect discharges into the stream etc.

3.2 Rehabilitation of artificial fixed beds

3.2.1 Removal of existing fixed beds

Structures in the stream that were built for multi-purposes and that are disused have to be removed and adapted to today's needs and improvement of the ecological state of the watercourse. There is a need to remove the rigid, non-permeable concrete constructions and replace them by corresponding objects built from natural materials. The measure enables a restoration of natural conditions in the channel prior to the building. It influences both, the hydromorphological and physical states.

Specifications for removal of fixed beds

The fixed beds are usually in concrete or in large boulders (free or fixed with concrete). The removal shall be prepared in order to prevent the movement of underneath layers before they are prepared for the rehabilitated situation.

The most important aspect to be taken into consideration is the extreme parts of the removal. In Figure 3-1 they are presented the different cases may occur when the removal of fixed bed is done.

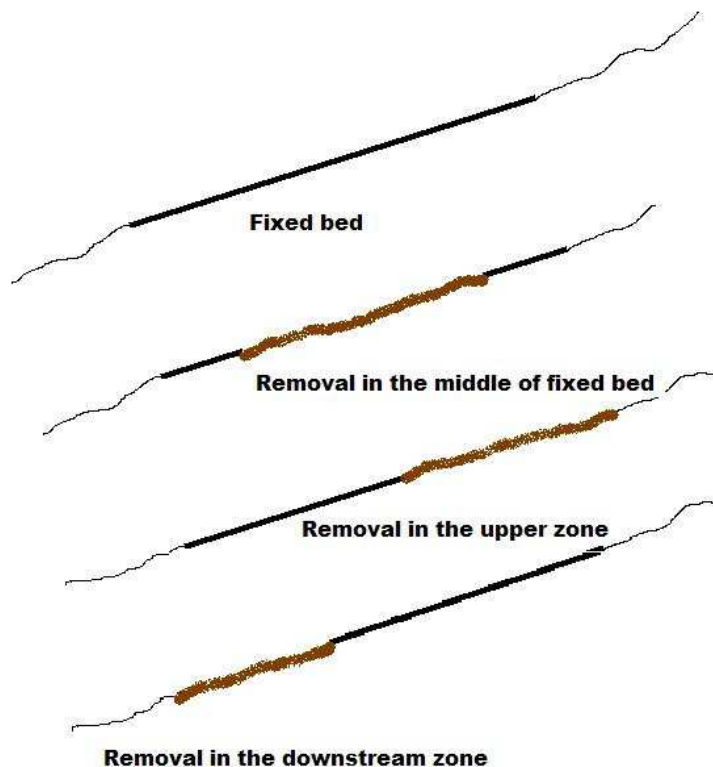


Figure 3-1 – Removal of fixed river beds

In general, a fixed river bed is sided by upstream and downstream natural reach, as indicated in the upper part of the Figure 3-1.

The removal is to be done in all length of fixed bed or alternatively on a part of that length. When it is removed a part of the length it is important to identify its position, on the middle, on the upper zone or in the downstream zone. The position is important to decide the sequence of the works and to design the rehabilitated bed.

Before the removal, to guaranty the success of the intervention it is needed to characterize the hydraulics of the urban river with the fixed bed and to know the sediment transport entering in the reach. The geometric characteristics of the cross sections, the longitudinal slope and the discharges running in the reach are the basic parameters to collect and analyse. The analysis shall determine the flow behaviour including:

- 1) flow depth
- 2) flow velocity
- 3) sheer stress
- 4) sediment transport capacity

for the significant discharges.

The minimum discharges values to be considered shall be the following:

- 1) minimum discharge, eventually zero
- 2) a set of three discharges between minimum and bankfull discharge
- 3) bankfull discharge
- 4) flood discharges (T = 5, 10, 20, 50 and 100 years).

The flow depth may be computed by simple hydraulic equations, such as Manning equation, or other empirically derived for computing the average flow velocity. Assuming uniform and turbulent flow conditions, the mean flow velocity in an open channel can be computed as:

$$V = (1/n) R^{2/3} S^{1/2} \quad (\text{m/s})$$

where V is the mean velocity (m/s)

n is the Manning coefficient of roughness ($\text{m}^{-1/3}\text{s}$)

R is the hydraulic radius (m)

S is the channel slope (m/m).

$$R = A/P$$

where A is the cross sectional flow area (m^2)

P is the wetted perimeter (m).

There is an equivalent equation for the flow velocity, the Strickler equation:

$$V = K_s R^{2/3} S^{1/2} \quad (\text{m/s})$$

where K_s is the Strickler coefficient of roughness ($\text{m}^{1/3}\text{s}^{-1}$).

In the Table 3.1 they are presented representative values of n and K_s for fixed channels. The Table covers a large percentage of the cases found in fixed bed and banks urban rivers.

For estimating the shear stress, simplified equations are used for the mean shear stress τ_m

$$\tau_m = \rho g R S \quad (\text{N/m}^2)$$

where ρ is the water density (kg/m^3)

g is the gravity acceleration (m/s^2).

In previous equations it is used the channel slope S. This is an approximation of the actual energy grade J, to be used when available.

It is possible to use h (flow depth) instead of R in wide flows, say when the channel width exceeds the 30 fold of the perimeter.

Table 3-1 Average values for Manning's and Stickler's roughness coefficients

Type and description of channel	Ks (m ^{1/3} s ⁻¹)			n (m ^{-1/3} s)		
	Maximum	Normal	Minimum	Maximum	Normal	Minimum
A. Concrete						
1. plastered with blow or slap	91	77	67	0,011	0,013	0,015
2. plastered with brush	77	67	63	0,013	0,015	0,016
3. not plastered	71	59	50	0,014	0,017	0,020
4. gunited, regular	63	53	43	0,016	0,019	0,023
5. gunited, rippled	56	45	40	0,018	0,022	0,025
6. over regular rock	59	50		0,017	0,020	
7. over irregular rock	45	37		0,022	0,027	
B. Bed concrete and banks with						
1. plastered stone	67	59	50	0,015	0,017	0,020
2. plastered irregular stone	59	50	42	0,017	0,020	0,024
3. plastered gravel masonry	63	50	42	0,016	0,020	0,024
4. no plastered gravel masonry	50	40	33	0,020	0,025	0,030
C. Brick						
1. glazed	91	77	67	0,011	0,013	0,015
2. plastered	83	67	56	0,012	0,015	0,018
D. Masonry						
1. cemented gravel	59	40	33	0,017	0,025	0,030
2. craving gravel	43	31	29	0,023	0,032	0,034
E. Reveted stonework	77	67	59	0,013	0,015	0,017
F. Asphalt						
1. smooth	77	77		0,013	0,013	
2. rough	63	63		0,016	0,016	

Adapted by Lencastre (1996) from Chow (19xx).

From all data presented before it is possible to compute the sediment transport capacity of the fixed river. It is very important to note the differences between capacity and actual sediment transport. The actual sediment transport is the minor of two situations: the capacity if the incoming sediment load is larger or the incoming sediment load if the capacity is larger.

Another important point is to consider in the analysis mainly the bed load, discarding the suspended load (or better, the wash load). The reason is last one do not have, in general, importance for the stability of the mobile bed. The exception may occur in very flat zones, such as in tidal dominated flows or very flat plains.

The sediment transport capacity may be computed by a large number of equations. It is not presented the available equations. Indeed, this is a very specific technical work to be done by experts.

Only a simple general equation is presented for sediment transport capacity in the river bed:

$$Q_{sv} = K B \tau_m (\tau_m - \tau_c) \quad (m^3/s)$$

where K is a constant depending of transported material in the bed

B is the width of river bed

τ_c is the critical shear stress, when the material begins to be transported.

The analysis of the existing conditions of the fixed river bed is important to determine the more probable situation regarding the differences between sediment transport capacity and incoming sediment in the river. When the last one is larger than capacity may occur a mobile bed over a fixed one. The presence of the fixed bed without any deposition shows the capacity is larger the incoming sediment.

Finally, the characterisation of present situation shall include the upstream and downstream reaches where the alluvial material is not covered by a fixed revetment. This characterisation is not necessary when the removal is done between two fixed beds. The characterisation of downstream natural reach or upstream natural reach is also not necessary if we are on the situations presented in the Figure 3-1, respectively, removal of the upstream zone or removal of the downstream zone.

Alternatively, if the fixed bed have a larger length compared with the removed zone it is possible to sample the underneath bed characteristics instead of the far from natural reaches.

The removal of the fixed river beds shall be done in low discharge season, when the capacity to transport sediment is low. The removal shall also be done from downstream to upstream in order the flow is cleaning the working zone.

The removal of the cover of rivers (culvert reaches) is much simpler because do not need any hydraulic analysis and do not interfere with river bed and banks. They were made as a result of urbanisation that included the stream channel as well or as a protection against the effects of streams in a bad ecological condition.

The simple removal of the cover helps to improve the ecological state, enlightening the river bed. The measure brings about a better state of the watercourse in all its elements.

3.2.2 Definition of rehabilitated bed

In hard paved river beds, a layer of natural substrate can be located upon the existing lining or completely replace the artificial material. Sand, gravel and cobble are placed into the wetted perimeter of streams that are deficient of this bed load. The goal is to protect the channel bed from further degradation, to increase habitats for aquatic life forms and to provide spawning areas for some fish species. Sediments, corresponding to the natural size and shape composition are the preferred bed material.

Specifications for rehabilitate fixed beds

The rehabilitation of fixed beds will transform them in a new natural river bed, or alternatively in a new much less fixed bed. In first case a solution of continuity will be implemented in the river bed, linking the natural river bed, downstream or upstream, with the rehabilitated reach. This will be the most deeply rehabilitation intervention guarantying the continuity of the alluvial river bed.

Alternatively, it is possible to create a new mobile river bed, but not necessarily with the same characteristics of previous natural alluvial bed, or with the same characteristics of the confining natural alluvial river bed. This alternatively is much more appropriate for a reach rehabilitated between fixed river beds, as shown in the Figure 3-1.

Theoretically, if the first option is done, rehabilitation with the same river bed sediments existing in confining reaches, no accurate studies of bed stability will necessary, except on the characterisations of the behaviour of flow before and after the rehabilitation, namely, changes in water levels.

When the rehabilitation creates a new mobile river bed the same kind of computations presented in previous section shall be done. The main differences are found in the coefficients of roughness and in the adoption of the material to fill in the river bed.

In Table 3-2 additional roughness coefficients are presented for the case of rehabilitation.

Table 3-2 Average values for Manning's and Stickler's roughness coefficients

Type and description of channel	Ks (m ^{1/3} s ⁻¹)			n (m ^{-1/3} s)		
	Maximum	Normal	Minimum	Maximum	Normal	Minimum
Natural or renaturalised channel						
A. Width smaller 30 m						
1. clean, straight, without falls	40	33	30	0,025	0,030	0,033
2. same, stone and vegetation	33	29	25	0,030	0,034	0,040
3. clean, winding, pools, riffles	30	25	22	0,033	0,040	0,045
4. same, vegetation, stone	29	22	20	0,034	0,045	0,050
5. same 3, pools, riffles, contract	25	21	18	0,040	0,048	0,056
6. same 4, more stone	22	20	17	0,045	0,050	0,059
7. slow, vegetation, deep zones	20	14	13	0,050	0,071	0,077
8. intense vegetation, deep, tree	13	10	7	0,077	0,100	0,143
B. Width larger 30 m						
1. regular section without gravel	40	-	17	0,025		0,059
2. irregular and rough	29	-	10	0,034		0,100

Adapted by Lencastre (1996) from Chow (19xx).

From the comparison of two tables it is evident the renaturalisation lead to higher water depths for the same cross section, comparing the fixed river bed and the renaturalised. Consequently, for the same level of safety it is simultaneously necessary to increase the cross section. The decision to do this correction shall be

based in the analysis of the flood consequences. Indeed, the decrease of flow capacity in the main channel may minor compared with the flood plain capacity.

Either in complete natural sediment river bed, refilling the present fixed bed, a artificial sediment river bed, in contrast with natural confining sediment there will be a complex flow dynamic and erosion / deposition sequences, both a vital part of the flow regime. On urban rehabilitated rivers, these natural processes are to be maintained to a certain degree, even in the cases of a completely artificial mobile river bed.

The computation of water levels is much more difficult on natural river beds because there are strong variations of roughness coefficients during a passage of flood wave. This shall be also a job for experts on river hydraulics to guaranty successful interventions.

For lower velocities, when there is not sediment transport in the river bed, the roughness is only controlled by the grain size of the bed material and for roughness quantification may be used an equation like

$$n = (D_{75})^{1/6} / 21.1 \quad (\text{m}^{-1/3}\text{s})$$

where D_{75} (m) is the sieving grain size fraction 75% finer in weight, Lane (1955).

For larger discharges there are sediment transport in river bed originating bed configurations, like dunes and ripples, and the adoption of a representative of roughness is much more difficult. One example of the methods to compute the water levels considering the roughness river bed roughness when configurations are present is presented in White *et al.* (1979).

Specifications for materials to rehabilitate fixed beds

The rehabilitation of fixed beds using the confining natural river bed materials is straightforward as concerning the specifications for materials. They are simply used, by transportation from downstream or upstream parts. Also, it may be used the natural material underneath the removed lining. The only care to be done is to compute the differences in the water levels, and flow velocities after the rehabilitation.

The rehabilitation of river bed with non coherent material may be different from the natural confining river bed material. In this case the scope is the improvement of river bed from a fixed and rigid one to a potentially mobile material. In the limit this non coherent river bed material may behave like a rigid one, never being moved by the river flow, or hardly moved, but at same time having a porous characteristic compatible with the presence of flora and fauna.

The critical velocities, putting in movement the new material filling up the rehabilitated river bed, are presented in the Table 3-3. Inversely, it may be chosen the grain sizes of the material taking into account the velocities in the river.

Table 3-3 Critical velocities for non coherent materials

Material	Diameter (mm)	Velocity (m/s)
Fine silt	0.005	0.15
Coarse silt	0.05	0.20
Fine sand	0.25	0.30
Coarse sand	1.00	0.55
Grit	2.50	0.65
Fine pebble	5.00	0.80
Medium pebble	10.00	1.00
Medium pebble	15.00	1.20
Coarse pebble	25.0	1.40
Very coarse pebble	40.0	1.80
Small cobble	75.0	2.40
Small cobble	100.0	2.70
Large cobble	150.0	3.50
Large cobble	200.0	3.90

Referred by Dupont (1974) from S.S.U.R. rules.

In the Wentworth's classification of grain size the material larger than 2 mm is gravel. The gravel is divided in pebble, cobble (larger than 64 mm) and boulder (larger than 256 mm) until about 3 m.

The Table 3-3 is valid for water depths with 1 m. The correction factors of the values to determine the critical velocities for all cases are presented in

Table 3-4 Correction factors for water depths \neq 1 m

Average depth (m)	0.3	0.5	0.75	1.0	1.5	2.0	2.5	3.0
Correction factor	0.8	0.9	0.95	1.0	1.1	1.15	1.2	1.25

Referred by Dupont (1974) from S.S.U.R. rules.

Another criterion to choose the river bed material, when no movement of bed is admitted, is to use the critical shear stress.

For finer material the critical shear stresses are presented in Table 3-5.

Table 3-5 Critical shear stresses for non coherent materials (N/m^2)

Diameter D_{50} (mm)	0.1	0.2	0.5	1.0	2.0	5.0
Clear water	1.2	1.3	1.5	2.0	2.9	6.0
Water with low concentration fine sediments	2.4	2.5	2.7	2.9	3.9	8.1
Water with high concentration fine sediments	3.8	3.8	4.1	4.4	5.4	9.0

Referred by Dupont (1974) from Lane.

For coarse non coherent material following equation may be used

$$\tau_c = 8 D_{75} \text{ (cm)} \quad (\text{N/m}^2).$$

Specifications for improvement of natural beds

Rocks and boulders placed in the streambed may create a stream feature that provides habitat for macro invertebrates (a vital component of the food chain). They raise turbulence that aerates streams, and raise dissolved oxygen levels that may be critical for fish survival.

Boulders clusters are strategically placed groups of large rock established along a channel bed in order to break up flows and to form scour pools used by juvenile fish as resting areas. They establish shelter for aquatic life and breeding areas.

Being these larger natural elements more resistant to the transport it is not necessary to compute the river bed stability. However, its presence will increase flow resistance and consequently higher depths will occur. A simple computation may provide the percentage of increase of water depths. If the density of these new elements is not large no significant consequents are forecast.

4. Interventions in the river banks

4.1 Introduction

Urbanisation has been narrowing the watercourses to the minimum space possible. Due to urbanisation pressure and narrowing of watercourses within a very limited space, safety fencing and supporting walls have been built, as well as other buildings that strongly reduce the hydromorphological state and influence the physical state and biological state of the river. The river rehabilitation shall include measures to create basic conditions for widening of the stream and management of river banks. The basic problems are issues in terms of ownership rights and water-related rights linked with the buildings.

Besides providing additional space for the improvement of the hydromorphological state, by widening the channel and the banks the channel flow is enhanced and the water level locally reduced. The extended channel enables meandering, formation of pools and rapids, dunes and wetland riparian areas. Also, the channel provides for a better flow of flood waters. The influence is favourable for the ecological state of the water body in its entirety.

The extensions can be done in several variants, i.e. widening of the river bed only, or widening of banks with different approaches and modern consolidations made of natural materials. The rehabilitation may also include the reconstruction of bridges and enhancement of their scale.

4.2 Rehabilitation of fixed river banks

It should be recognized that rivers in alluvial reaches have inherent dynamic properties by which changes may continuously occur in river position and shape. In natural alluvial rivers whose bed and banks are composed of materials deposited in water, the banks may erode, sediments may deposit, and islands and side channels form and disappear with time. The natural mobility creates an urban discomfort, being the reason to fix the banks. Consequently, in river rehabilitation, the banks shall be built in a way to continue the guarantee of a fixation but simultaneously giving a natural aspect, combining well with the rehabilitated river bed.

Rectangular cross sections, with vertical banks, are often the only solution to convey large flows in areas with limited right of way. The vertical banks are expensive to construct, since the wall must be designed as earth retaining structures.

The most natural like cross section approaches a trapezoidal shape, where the banks have slopes compatible with the stability of natural incoherent materials.

The artificial surfacing of banks to resist erosion or scour is called armour. The armour solutions may be flexible, with self adjustment or, when necessary, rigid, as in the case of vertical banks.

There are a lot of solutions to build a flexible type of bank protection.

4.2.1 Rock slope protection (riprap)

The more common is the rock slope protection. This kind of protection, called riprap, consists of rock pieces placed upon the embankment. Rock, as a slope protection material, has a number of desirable features which have led to its widespread application.

It is usually the most economical type of revetment where stones of sufficient size and quality are available.

The main advantages are the following:

- 1) It is flexible not being impaired nor weakened by slight movement of the bank resulting from settlement or other adjustments;
- 2) Appearance is natural, and acceptable for urban areas, depending also from the type of rock used;
- 3) Being exposed to water, vegetation may be induced to grow through the rocks adding structural value to the bank material and restoring natural roughness;
- 4) Construction is not complicated and no special equipment or construction practices are necessary;
- 5) Local damage or loss is easily repaired by the addition of rock where required;
- 6) It is reused if necessary.

Specifications for rock slope protection (riprap)

In designing the rock slope protection for given river bank the following specifications are to be made for the typical section:

- 1) Size of stone;
- 2) Depth of which the stones are founded (bottom of toe trench);
- 3) Elevation at the top of protection;
- 4) Thickness of protection;
- 5) Need for geotextile and backing material.

The size of the stone is defined by its stability on the slope. The stability of the slopes in the banks is conceptually the same of the stability on the river bed. The equation following the Table 3-5 shall be corrected by a coefficient K

$$\tau_{cs} = K \cdot 8 D_{75} \text{ (cm)} \quad (\text{N/m}^2)$$

being
$$K = \cos \Phi [(1 - (\text{tg}^2 \Phi / \text{tg}^2 \Psi)]^{0.5} \approx [(1 - (\sin^2 \Phi / \sin^2 \Psi)]^{0.5}$$

where Φ is the bank angle with horizontal,

Ψ is the angle of repose of riprap material.

The values of K are presented in Table 4-1. It is evident one of the equilibrium condition is $\Phi < \Psi$, or the slope of river bank is less than angle of repose.

In Table 4-2 is presented the appropriate angle of repose (Ψ) for the riprap material. For larger sizes the angle of repose does not change significantly.

Assuming a uniform gradually varying flow, mean diameter riprap particle size (D_{50}) may be directly computed by the following equation

$$D_{50} = 0.00594 V^3 / (h^{0.5} K^{1.5}) \quad (\text{m})$$

where V is the average velocity in the main channel (m/s)
 h is the average flow depth in the main channel (m).

Table 4-1 Coefficient K for stability of river bank riprap

Bank angle Φ (°)	Angle of repose, Ψ (°)					
	45	40	35	30	25	20
45	0	-	-	-	-	-
40	0.40	0	-	-	-	-
35	0.60	0.45	0	-	-	-
30	0.70	0.63	0.50	0	-	-
25	0.80	0.76	0.68	0.55	0	-
20	0.88	0.84	0.80	0.73	0.60	0
15	0.93	0.91	0.89	0.85	0.80	0.67

Adapted from Lencastre (1996)

Table 4-2 Angle of repose, Ψ (°)

Type of material	Diameter (cm)						
	0.5	1.0	1.5	2.5	5	7.5	10
Very angular	33	35	37	38.7	40.3	40.8	40.9
Moderate angular	29	33	35	37.3	39.6	40.2	40.5
Little angular	27.5	31	33	36	38.9	39.7	40
Little round	24	28.5	31	34.2	38	39	39.5
Moderate round	21	26.5	29.5	33	37	38.4	39
Very round	16	24	27.5	31.6	36	37.7	38.5

Adapted from Lencastre (1996)

The following criteria apply to the riprap layer thickness (HEC, 1989):

- 1) It should not be less than the spherical diameter of the D_{100} stone, or less 2 times the spherical diameter of the D_{50} stone, whichever results in the greater thickness;
- 2) It should not be less than 0.3 m for practical placement;

- 3) The thickness determined by either 1 or 2 should be increased by 50 % when the riprap is placed underwater to provide for uncertainties associated with this type of placement.

The stone of riprap shall be reasonable well graded throughout the riprap layer thickness. Table 4-3 presents suggested guidelines for establishing gradation limits.

If the use of four point gradation is too difficult to use, the 85 % specification can be dropped, and a uniform gradation between D_{50} and D_{100} will result appropriate.

Table 4-3 Rock riprap gradation limits

Stone size range (m)	Stone weight range (kg)	Percent of gradation smaller than
1.5 D_{50} to 1.7 D_{50}	3.0 W_{50} to 5.0 W_{50}	100
1.2 D_{50} to 1.4 D_{50}	2.0 W_{50} to 2.75 W_{50}	85
1.0 D_{50} to 1.4 D_{50}	1.0 W_{50} to 1.5 W_{50}	50
0.4 D_{50} to 0.6 D_{50}	0.1 W_{50} to 0.2 W_{50}	15

HEC (1989)

A filter is needed as a transitional layer of gravel, small stone, or fabric placed between the underlying soil and the riprap. The filter prevents the migration of the fine soil particles through voids in the riprap, distributes the weight of the armour units to provide more uniform settlement, and permits the relief of hydrostatic pressures with the soils.

A straightforward method to design a riprap knowing the river velocity is presented in Table 4-4.

Table 4-4 Riprap design guide

Mean river velocity (m/s)	Parallel flow along tangent bank		
	Bank velocity (m/s)	Minimum stone (kg)	Layer thickness (m)
1.4	0.9	0.02	0.3
1.8	1.2	0.05	0.3
2.3	1.5	0.5	0.5
2.7	1.8	1.4	0.5
3.2	2.1	3.2	0.8
3.7	2.4	6.8	1.0
4.1	2.7	14	1.0
4.6	3.1	26	1.0
5.5	3.7	77	1.3
6.4	4.3	195	1.3

Caltrans (2001)

The undermining of revetment toe protection has been identified as one of the primary mechanisms of riprap revetment failure. In the design of bank protection, estimates of the depth of scour are needed so that the protective layer is placed sufficiently low in the river bed to prevent undermining.

The estimated probable maximum depth scour, d_s (m), based on data presented by Blodgett (1986), can be calculated by

$$\begin{aligned} d_s &= 3.66 \text{ m} && \text{for } D_{50} < 0.0015 \text{ m} \\ d_s &= 1.74 D_{50}^{-0.11} && \text{for } D_{50} > 0.0015 \text{ m} \end{aligned}$$

where D_{50} is the median diameter of bed material (m).

In application, the depth of scour, d_s , should be measured from the lowest elevation in the cross section. It is assumed that the low point in the cross section may eventually move adjacent to the riprap, even if this not the case in all cases.

The depth of scour predicted by equation must be added to the magnitude of predicted degradation and local scour (if any) to arrive at the total required toe depth.

The heavy material used in the riprap, beside the natural rock, may be done with other materials like broken concrete (for instance, as an urban residue).

4.2.2 Rock slope protection (gabion)

Other common flexible type of armour protection is the gabion. Gabion revetments consist of rectangular wire mesh baskets filled with stone. There are two types of gabions:

- wall type;
- mattress type.

In the wall type the empty cells are positioned and filled in place to for walls in a stepped fashion. Wall type revetment is not fully self adjusting but has some flexibility.

When the gabion has a small height (thickness) it is designated by Reno mattress. This confers a relatively high flexibility, very important to suit to bank movements.

Mattress type baskets are positioned on the slope and filled. The mattress type is very flexible. For some locations, gabions may be more aesthetically acceptable than rock riprap.

Where larger stone sizes are not readily available and the flow does not abrade the wire baskets, they may also be more cost effective.

Specifications for rock slope protection (gabion and mattress)

Rock and wire mattress revetments can be constructed from commercially available wire units, Table 4-5, or from available wire fencing material.

The use of commercially available basket units is the most common practice, and is also usually the least expensive practice.

Table 4-5 Standard gabion sizes

Thickness (m)	Width (m)	Length (m)	Wire-mesh opening size (mm x mm)
0.229	1.289	2.743	63.5 x 82.55
0.229	1.289	3.658	63.5 x 82.55
0.305	0.914	1.829	82.55 x 114.3
0.305	0.914	2.743	82.55 x 114.3
0.305	0.914	3.658	82.55 x 114.3
0.457	0.914	1.829	82.55 x 114.3
0.457	0.914	2.743	82.55 x 114.3
0.457	0.914	3.658	82.55 x 114.3
0.914	0.914	1.829	82.55 x 114.3
0.914	0.914	2.743	82.55 x 114.3
0.914	0.914	3.658	82.55 x 114.3

HEC (1989)

The thickness of the mattress is determined by three factors:

1. The erodibility of the bank soil;
2. The maximum velocity of the water;
3. The bank slope.

The minimum thickness required for various conditions is presented in the Table 4-6.

Table 4-6 Criteria for gabion thickness

Bank soil type	Maximum velocity (m/s)	Bank slope	Minimum required mattress thickness (mm)
Clays, heavy cohesive soils	3	< 3V:1H	230
	5	< 2V:1H	305
	Any	< 2V:1H	>460
Silts, fine sands	3	< 2V:1H	305
Clays, heavy cohesive soils	5	< 3V:1H	230
	6	< 2V:1H	305
	Any	< 2V:1H	>460

HEC (1989)

The baskets are linked with naked wire, or to prolong the useful life, wire with a revetment of polymer materials. The main drawback of gabions is the useful life of the wires, suffering the water corrosion. Consequently is very important to use good quality wire, like zinc coated (galvanized), when naked. This material may be used in fresh water and where the pH of the water in contact is not greater than 10. For highly corrosive conditions such as in salt water, a polyvinyl chloride (PVC) costing must be used over the galvanizing.

When used for bank protection, rock and wire mattress revetments consist of two distinct sections: a toe section and upper bank paving. The toe section takes into

consideration the anticipated bed scour. Two main types of toe are to be used: an apron, with enough length to play with scour, or a toe wall with enough height to fit with the scour.

4.3 Training structures (jetty or groin)

Point protection is practised at pockets along stream banks that pose problems. Point protection is an efficient method that can harvest fluvial processes, leading to the deposition of gravel that modifies flow to improve the hydromorphology of streams.

Their influence often extends to untreated portions downstream. Vegetated nodes have a habitat improvement function that can be combined with architectural features in urban areas. One alternative technique is a training structure (jetty) or equivalent structure.

Training structures, inserted in the river channel, control the direction, velocity, or depth of water flow. They control scour on banks by deflecting the currents.

Some of the training structures are linked to the banks and act to protect the bank.

A jetty is an elongated artificial obstruction projecting into the stream from bank to control scour by deflection of currents.

There are two main types of jetties: permeable and impermeable.

The permeable jetties are used not only to deflect the stream but to permit some flow through the structure to minimize the formation of eddies immediately downstream.

Specifications for jetties

There is a long list of materials to be used in the construction of jetties. When piles and netting are used they may form jetties called palisades. An alternative is the use of single and double rows of timber braced piling. Also timber or steel jacks may be used. Probably the most used material is the rock, like in riprap. But artificial materials like precast concrete, with interlocking shapes or hollow blocks can be used. In all cases the presence of voids facilitates the development of life in the middle of the jetties.

The jetties encourage deposition of bed material and growth of vegetation. They may be placed at an angle with the bank, different the right angle. The angle with downstream bank is between 30° and 120° . When the angle is less than 90° is a convergent jetty, being divergent for angles larger than 90° .

When installed in a series the first groin should be kept short, while consecutive groins increase in length uniformly. The length of jetty is always a part of total width of river. The relation between length and spacing of jetties should approximate unity

as a general rule to assure complete entrapment and retention material. The spacing can be increased if the resulting effect is not detrimental to the desired result.

5. Interventions in the river profile

5.1 Introduction

The interventions in the river profile are very sensitive. The natural river profile depends on the conjunction of water flow forces and the resistance and movements of river bed. The stability of the river profile in an alluvial river is dependent of the natural variation of river discharges and sediment supply. The relations between river discharges and sediment transport are highly variables, being current to find natural oscillations on river bed from one year to another, beside the variations occurring during floods.

The main interventions in river profiles are done to decrease the bed slope or to decrease only the water surface slope, maintaining the bed slope. The alternative of increase the bed slope is much rarer, unless in very short lengths, associated to the general decrease of river bed.

5.2 Rough bed ground ramps and rock ground ramps

The ramps are used for stabilising a streambed where differences in level have to be overcome at short distances. The body of the ramp is built of rocks that are narrowly set to create cascades. Poles at the top and bottom of the structure stabilise the ramp that is meant to be flexible enough to permit a slight shifting during flood events.

Differences of level within the streambed can be overcome through steps of large sized coarse rocks, placed loosely into the streambed. They function as an energy dissipater and as a non-erosive surface. These rocks are secured in place by their own weight.

Specifications for ramps

The same specifications presented in 3.2.2, rehabilitate fixed beds.

5.3 Transverse structures (sills)

Timber logs and/or rocks creating a transversal barrier. Like other transverse structures it collects and retain gravel for spawning habitat, deepens existing resting/jumping pools, creates new pools above and/or below the structure and promote deposition of organic debris. Sills also hinder scouring of the channel bed and stabilises it. They are appropriate for degrading rivers, preventing its evolution. The result is a decrease in the river bed slope.

Specifications for sills

There is not a specific value for the height of the sill. In order to not increase the flood depths the height shall be relatively low, say less than 30 cm high. It is more important to guaranty it do not moves, preventing the degradation of river bed, and not increasing the depths of river flow.

The same specifications presented in 3.2.2, rehabilitate fixed beds, are applied.

Note pools and riffles are a characteristic of an alluvial stream with large grain bed. The variability of depths is found in the cross-sections as well as in the longitudinal profile. Transverse structures that cross the streambed can re-establish the functions of riffles that have unfortunately been removed through ill-guided maintenance in most urban streams.

Pools and riffles stabilise the streambed against erosion by reducing the riverbed gradient.

5.4 Transverse structures (weirs)

There is other type of transversal barriers acting mainly in the water depth, not trying influence the river bed slope. However, they may also have some influence in river bed deposition, for the cases where are conditions to occur. A set of this transverse structures create a cascade of pools, creating, for instance, a permanent water table for all river discharges, even for the minima, in dry period. They are appropriate for mild rivers, where the river bed evolution is not a problem. The result is a decrease in the water slope for low discharges. For flood discharges they may have a minor influence, because they are submerged without inconvenient.

Specifications for weirs

There is not a specific value for the height of the weir. In order to be felt its influence for low river discharges, the height shall be the necessary to compensate the natural slope of river bed. This means the height is a function of river bed slope and the distance between weirs, or between weir and the upstream limit for the effect.

In Table 5-1 are presented examples of the height of the weir to create water tables in dry season.

Table 5-1 – Height of weirs to create a water table in dry season

Bed slope (%)	Height of weir (m)				
	Length of the effect or weir spacing (m)				
	100	200	500	1000	2000
0.01				0.1	0.2
0.1			0.5	1	2
1	1	2	5	10	20

For very low slopes small weirs with 0.5 m can cover distances until 5 km. When the slope increases until 0.1% a weir with 0.5 m height can cover a distance of 500 m. When the slope increases up to 1% the 1 m height covers only 100 m.

By practical reasons heights less than 0.5 m are not current. When the height increases, more carefully shall be designed the weir, for the structural point of view. Until a height of a few meters, say 5 m, the problems are low. For higher heights the design must be done by experimented designer. For higher values (for instance, 15 m in Portuguese regulations), strict rules must be complied, because the ruin of a dam have associated a large danger.

The weir, like small dams, may be built with loose material (rocks) or as a fixed barrier, with concrete or equivalent material.

Finally, it is necessary to consider the impact of the presence of the weirs in the fish movements. When the barrier prevents the fish passage, it will be necessary to provide the presence of fish ladders.

5.5 Dredging

Another type of intervention is dredging of river bed. This action may recover the flow capacity of cross section.

The dredging is associated in general with an increase of river bed slope, because the dredging removes the excess of deposition, associated with a trend in decreasing slope.

The useful life of dredging depends on the sediment transport dynamics. The isolated dredging do not modify the sediment yield, and some time forward the river will return to the same bed level. However, for certain local conditions this may be an economic and justified intervention.

Some care shall be put on the maintenance of planktonic habitats, and on the stability of river banks.

6. Interventions in the river plan form

6.1 Introduction

The intervention on river plan form is most complex, compared to other types.

As a result of increasing urbanisation of alluvial lowlands, old arms of braided rivers were cut off and turned into stagnant water bodies. Among others, rehabilitation works aim on feeding old arms and residual meanders with fresh water from the main river or tributaries. These measures address quantitative aspects of channel flow and ground water as well as qualitative issues due to water exchange.

The basic guideline of giving the river more space can also be accomplished within some urban schemes. Free space is required for constructing islands, meanders, increasing widths-variability, for re-establishing a braided or winded character, for extending the shoreline and for allowing sediment dynamics. Larger undeveloped areas, adjacent to the rivers and existing schemes for sedimentation or flood detention can be employed.

Pools and riffles are a characteristic of a naturally meandering stream. On average they tend to occur at intervals of 5 to 7 times the bank full channel width of streams (Leopold and Wolmann, 1964). In sound rivers, the variability of depths is found in the cross-sections as well as in the longitudinal profile.

It is very difficult to define the type of interventions in the river plan form, because there is a large spectrum of possibilities. The natural plan forms are controlled by complex relationships between river discharge regimes, sediment supply and geological formations. The presence of urban settlements strongly changed those interrelationships. The interventions to modify the plan forms from the present situation to a more natural situation are subject to reduced technical options because the rehabilitation based in geomorphologic criteria continues to be restricted by the urban reality.

6.2 Definition of plan form for rehabilitation of urban rivers

The rivers have natural bends, being rare the presence of natural long righteous reaches.

The definition of the plan form is dependent of the form of the river valleys, and are conditioned by geologic, urban (like buildings and bridges) and hydraulic factors.

There is not a robust method to define the sound river plan form, but some specifications can be presented. There is some freedom to deviate from the specifications.

It is noticed there is a trend to create sinuosity only to provide a good landscape. However this approach needs to be based in valid technical criteria, unless strongly fixed banks are built, and the sediment supply is not intense.

Specifications for river bends

The meanders are the most common plan form in rivers. The plan form of meanders can be approximate by cosine functions. According to Przewojnski *et al.* (1995) the definition of the axis of a theoretical meander, knowing the minimum curvature radius, R_{min} , and the meander length along the axis, λ_m , may be done by the equation

$$1/r_i = (1/R_{min}) \cos[(\pi/\lambda_m) s_i]$$

where r_i is the curvature radius at distance s_i from the average point of the meander (for $r_i = R_{min}$).

The same authors present the values of R_{min}/B for natural meanders, being B the width of cross section of river, as indicated in Table 6-1.

Table 6-1 Values of R_{min}/B for natural meanders

Source	R_{min}/B	Observations
Lepold and Wolman (1960)	2 to 3	
Lepold <i>et al.</i> (1964)	1.5 to 4.3	Average 2.7
Nanson and Hickin (1986)	2 to 3	
Hey (1976)		
Grisin (1979)	4 to 4.75	Used in the East countries

(Cardoso, 1998)

According to Hey and Thorne (1983) and Yalin (1977) the meander length may be obtained by the next equations

$$\lambda_m = 6.31 B$$

or the equivalent

$$\lambda_m = 2\pi B.$$

7. Interventions in the river singularities

Each river may present singularities which are not covered by previous sections. The singularities shall be analysed by skilled river experts.

Beside the hydraulic issues presented in the previous sections, being considered, as WFD admits, as a support of biological issues, the concept habitat may be found as a grey zone between hydraulic and biological elements of the river characteristics.

Aquatic habitats are highly dependent on the quantity and dynamics of water flow. Aquatic habitat provides cover, food, nesting and spawning sites; shelter and escape cover for fish, amphibians and other wildlife. Habitat protection and improvement refers to in-stream conditions and to riparian habitat. Both are connected. Vegetation on the waters edge provides shade and an input of leaves that directly affects the quality of the aquatic habitats. The riparian habitat as a transition area between terrestrial and aquatic environment is particularly rich in life forms. In-stream habitats such as gravel riffles, deep pools, driftwood piles, sandbars, and boulder clusters are points of interest to any sport-fisherman's association, which often willingly organizes to support improvements. Among a list of different interventions on habitat improvement may be included the two following interventions:

Fish ladders, fish passage improvement

This is a technique in which changes are made to the stream channel to eliminate natural or manmade barriers, which obstruct the migration of fish to upstream areas to spawn. Fish passages provide access to upstream areas, habitat utilization, and an improved fishery value.

Removal of migration barriers

Barriers to fish migration include any obstacles that may interfere with, or prevent the upstream or downstream movement of fish. These obstructions may include dams, culverts, and heavily engineered channels of concrete. Modification and/or removal of barriers can open up large sections of streams to fish populations (including spawning habitat) that was previously unreachable. Temporary migration barriers may be set up to block rapidly spreading species from reaching not yet fully rehabilitated sites.

These types of in-stream interventions have a large possibility of solutions, being difficult to compile general specifications. These are examples of the need of skilled river experts.

REFERENCES

- Blodgett, J.C. (1986) – Hydraulic Characteristics of Natural Open Channels, Volume 1 of “Rock Riprap Design for Protection of Stream Channels near Highway Structures”, U.S.A. Geological Survey, Water Resources investigations Report 86-4127, prepared in cooperation with the Federal Highway Administration, USA.
- Caltrans (2001) – Highway Design Manual, California State, Caltrans Publication Unit, USA.
- Cardoso, A.H. (1998) – Hidráulica Fluvial (in Portuguese), Fundação Calouste Gulbenkian, Lisboa.
- Dupont, A. (1974) – Hydraulique Urbaine. Tome II, Paris, Eyrolles.
- Hey, R.D. (1976) – Geometry of river meanders, Nature, 262, August, 5.
- Hey, R.D. and Thorne, C.R. (1983) – Hydraulic geometry of mobile gravel-bed rivers, Proceedings of the Second International Symposium on River Sedimentation, Nanjing, China, Vol. 1, paper C11.
- HEC (1989) – Design of riprap revetment, HEC 11, Metric Version. Report N°. FHWA-IP-89-016, Hydraulic Engineering Circular Series, Federal Highway Administration.
- Lane, E.W. (1955) – A study of stable channels, Trans. ASCE 120, paper no.2776, pp.1234-1279.
- Leopold, L.B.; Wolman, M.G. (1960) – River meanders. Bulletin of Geological Society in America, volume 71, pg. 769, June.
- Leopold, L.B.; Wolmann, M.G.; Miller, J.P. (1964) – Fluvial Processes in Geomorphology, W.H. Freeman and Co., San Francisco, California.
- Rosgen 1994 or 1996 (pg. 4)
- White, W.R.; Paris, E. and Bettess, R. (1981) – A new general method for predicting the frictional characteristics of alluvial streams, Report no. IT 187, Hydraulics Research Institute, Wallingford, UK.
- Yalin, M.S. (1977) – Mechanics of sediment transport, 2nd edition, Pergamon Press, Paris.

