

Environmental impacts of human action in watercourses: Responses to changes in morphodynamic processes

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Abstract

The economic, social and environmental conditions of various European river basins and estuarine systems have changed dramatically in the last decades as a consequence of anthropogenic effects, and they will go on changing in the years to come due to increasing human pressure. Particularly in Portugal, various river-estuary systems have undergone several human interventions, notably engineering works to restore considerable stretches of channels and river banks.

Whenever the characteristics and natural evolution of a river are altered as a result of human intervention there is an environmental impact. In other words, it is understood that differences can be observed between any present situation that is the result of the evolution of an environment after human intervention, and the natural situation that would have existed if this type of intervention had not taken place, taking into account our previous knowledge of the situation.

A thorough understanding of the morphodynamic processes and new strategies are needed to develop a multifunctional use structure, which must take into account the many-faceted aims of sustainable development.

This paper provides a brief description of the nature and distribution of the direct and indirect types of impacts on the river morphology arising out of building and operating large dams, as well as some specific points that should be taken into consideration. It also reflects on the way in which the problem of extracting inert material from water environments has been dealt with in Portugal, leading to serious accidents. A brief technical contribution is offered, which although qualitative provides a basic record and explanation of the consequences of significant interventions in water environments that have not been properly assessed or have not taken other mitigating circumstances into consideration.

Keywords: fluvial system; morphodynamic processes; environmental impacts; computational model; numerical simulations

1. Introduction

Erosion in rivers is not a serious problem so far as no human action is present. But this natural hazard becomes a disaster when riparian buffers are not maintained, and human actions are felt in the bed and on river banks. Anthropogenic activities along the river stretch disturb the equilibrium of the river dynamics and accelerate the rate of bank erosion. Anthropogenic activities like gravel mining, sand extraction, construction of dams and bridges, artificial cut offs, bank revetment, deforestation and land use alterations change the morphology and natural dynamics of rivers (Kondolf, 1997). Human activities are stronger with respect to changing river dynamics than natural events as floods, droughts and landslides (Yamani *et al.*, 2011).

Few rivers in Portugal retain their natural state, and some of the more altered are becoming badly damaged. Due to an inappropriate management and insufficient supervisory, practices and interventions have been permitted in natural systems that contributed to their weakening.

The need for multiple and rational use of water is based on the recognition that it is a limited natural resource. However, its productivity is affected by human actions, whether in a positive way through well-planned and managed use or in a negative way when unrestricted use of the soil and other environmental resources leads to a reduction in the supply and quality of the water. Consequently, it is important to recognise and treat water resources as natural assets that must be preserved. Equally, when decisions are made about the use of these resources, they must be based on consistent and reliable information.

With reference to the World Water Vision Commission Report (World Water Vision, 2000), four key points can be identified that must be taken into consideration in relation to integrated water resources management. The first relates to a *holistic approach*, on the basis of which participatory decisions will be taken that will be technically and scientifically well-informed. The second refers to *changes in attitudes towards development and the application of technology*, paying attention to demands to reduce waste and to be more aware of the environment and the social aspects of the decision-making processes. The third states that *economic, social, environmental and political aspects* must be taken into account in any institutional and technological innovations or changes relating to water management. The fourth point establishes that promoting changes on the scale required for a new approach to water resources management requires a *continual supply of financial resources* appropriately mobilised, including private sector investments and community resources.

1 It is essential to cultivate a pro-nature attitude, which means avoiding activities that threaten
2 nature's tendency to establish dynamically stable configurations. Sustainability can only be
3 achieved as a result of a development process based on a relationship between people and nature,
4 combining actions designed to encourage economic dynamism with an improvement in people's
5 quality of life. This should concern future generations and natural environment conservation.
6

7 Among the many construction works and interventions carried out in the water domain, for various
8 purposes, the construction of dams is most likely the one that most affects the fluvial processes.
9 Dams are built for many purposes: water storage for potable water supply, livestock water supply,
10 irrigation, fire-fighting, flood control, recreation, navigation, hydroelectric power, or simply to
11 contain mine tailings. Dams may be multifunctional, serving two or more of these purposes.
12

13 In Portugal, like in other countries, the construction of dams and the consequent creation of
14 reservoirs not only affect the water domain but also represent a potential risk that cannot be
15 overlooked. When the hydrological system of a river is altered by the construction of a dam,
16 changes are generally caused downstream depending on how the dam is operated. The way
17 discharges are controlled and regulated and the seasonal variability of the heavy discharges, are
18 important aspects to consider. Also of great importance are the changes in the characteristics of
19 water and solid effluents generated in the dam and that feed the downstream segment of the river.
20 The environmental impact may also extend to the alluvial plain, affecting the ground water system,
21 since there will be modifications to the piezometric level because of the reduction in the water
22 discharge, which in turn implies that there will be alterations to the rate at which the water
23 infiltrates the soil.
24

25 The operation of these structures requires proper coordination between the various entities with
26 responsibilities in its management, in particular in the case of construction works regarding river
27 regulation, the strong implications of incorrect management measures that could result for the entire
28 valley downstream. Consequently, great care is due to the river management processes.
29

30 Statistical studies show that the critical life period of a dam occurs either during construction or on
31 the first complete filling of the reservoir, extending up to 5-7 years after its completion. However, it
32 should be noted that this conclusion is limited because it refers mainly to the first occurrences
33 (constructive disabilities); several hazardous events may occur with equal probability during the
34 lifetime of a dam.
35

36 In this regard, it should be noted an occurrence that took place in the winter 2001, near Coimbra,
37 Portugal. In the period 26 - 30 January 2001 a clearly inadequate management and operation of the

1 Aguieira dam occurred, which could have led to overtopping or failure of a dam 30 years after its
2 construction.

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4 Figure 1, taken on January 30, 2001, clearly shows the violence of the flood on 29 January, which
5 resulted in high losses and in serious consequences. In the period from 26 to 30 January of that
6 year, 14 breaks occurred in the Lower Mondego dikes - in the Main Canal, especially in the left
7 margin, and in the peripheral channel (Montemor-o-Velho) - and a fast and violent flooding of the
8 fields, as documented in Figure 2.

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12 Figure 1 – Aerial view showing the floodplain completely flooded and, in the foreground, the
13 village of Ereira already converted into an island (Courtesy of Cunha, 2002).

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Figure 2 - Panorama of the dike break on the right of the Main Channel (Lower Mondego), near Santo Varão (Courtesy of Cunha, 2002).

The reasons for the floods that occurred in the Lower Mondego River, in the period 26 - 30 January 2001 are clearly expressed in the Final Report prepared by the Working Group set up by the Portuguese Association of Engineers (Central Region).

This Report clearly shows that the floods occurred due to an unexpected hydrological behavior of the river Ceira *"probably resulting from an excessive deforestation of the slopes produced by dramatic succession of fires and/or a nonexistent or inadequate policy of forest planning and agricultural land management"*, and even as a result of *"a less correct management of the Aguieira dam"*. Another reason is *"the lack of regular and effective maintenance of the Lower Mondego control system"*.

Regardless of the events recorded in those days, the operating data relating to the design phase of the dam and at the time of the accident were:

- *Design conditions*
 - Maximum filling level: 125.0 m => Stored volume: 425.0 hm³.
 - Minimum level of exploitation: 112.5 m => Stored volume: 277.0 hm³.
 - Available volume for floods: ≈150.0 hm³.

1 ● *When the accident occurred*

- 2 - Minimum level of exploitation: 116.0 m => Total stored volume: 327.0 hm³.
3 - Available volume for floods: ≈100.0 hm³ (that is, an ability to fit more 50 hm³ was lost).
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5 The Final Report cited above suggests the following immediate actions to be implemented:

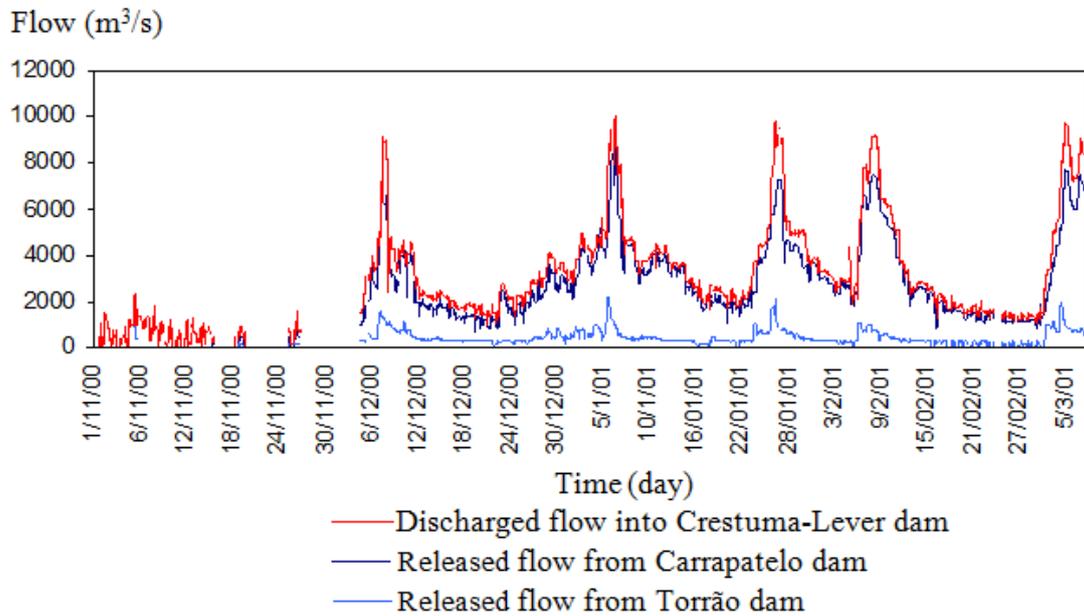
- 6 - review the operation protocol in force at that time for the Aguieira and Fronhas dams, this
7 last one upstream;
8 - reassess the operating conditions of the Aguieira-Fronhas system; and
9 - installing a management system in real time.
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11 These recommendations were implemented, among others, particularly in the Lower Mondego.
12 Consequently, despite of the storms that occurred in the last 12 years with equal or even greater
13 severity, no such flooding occurred downstream of Aguieira.
14

15 In March 2001 an even bigger accident occurred in Portugal. The collapse of the Hintze Ribeiro
16 Bridge killed 59 people traveling in a bus and three cars that were crossing the Douro River (Sousa
17 and Bastos, 2013).

18 The collapse of this bridge occurred on the night of March 4, 2001, during a flood wave
19 propagation on the Douro River. This was the 5th flood wave in a series of floods that began on
20 December 6, 2000, all with peaks exceeding 8000 m³/s, as is shown in the record of Figure 3
21 (Rocha *et al.*, 2008).
22

23 This Figure shows instantaneous flows released from the Carrapatelo (dark blue) and Torrão (navy
24 blue) dams and instantaneous flow discharged into the Crestuma-Lever (red) dam, all resulting from
25 observations made in one hour intervals.
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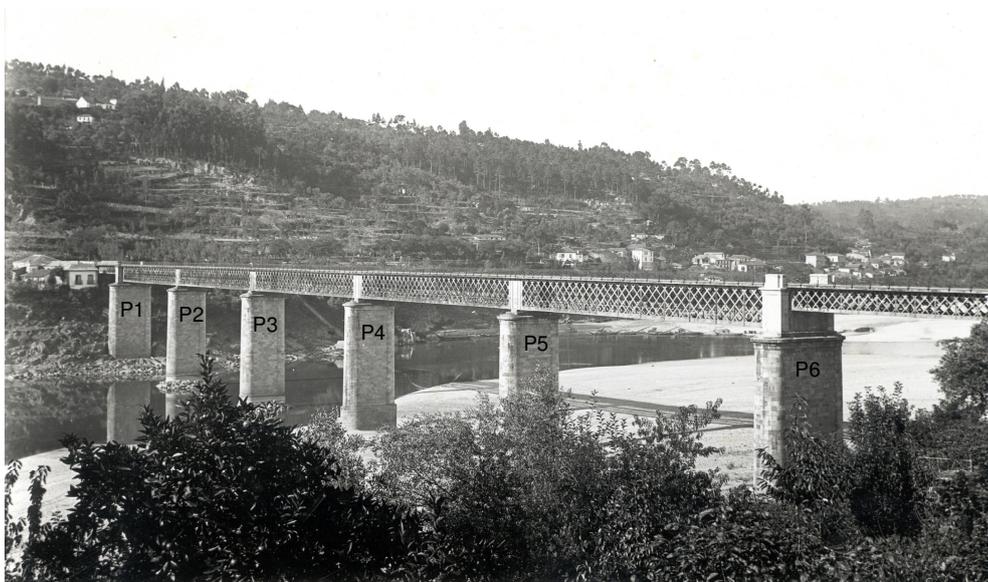


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3 Figure 3 – Released flows from the Carrapatelo and Torrão dams, and discharged flow into the
4 Crestuma-Lever reservoir, between 11/01/2000 and 03/07/2001 (Rocha *et al.*, 2008).

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6 This bridge was located, since the late nineteenth century, at a curve in the river Douro, near the
7 mouth of the Tâmega River. The bridge section is located in the reservoir of the Crestuma-Lever
8 dam, downstream of the Douro River. Upstream of the bridge section are located the Torrão dam on
9 Tâmega River, and the Carrapatelo dam on Douro River (Figure 4).



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12 Figure 4 - Photo of Hintze Ribeiro Bridge, dated 1931.

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It has been found that the combined effects of unplanned, uncontrolled, continuous and increasing dredging of sand in the last 25 years before the accident (period of 1975-2000), and the scour produced by five floods between December 2000 and March 2001 were the primary causes of this accident, involving the pillar P4 (Figure 4, with designations P1 to P6 for the pillars of the bridge starting from the right bank).

In the Hintze Ribeiro Bridge photo, shown in Figure 4, both the geometry and the shape of the cross section of the river bed are clearly visible. The P2 and P3 pillars were the most affected by the river flow. The protections of these pillars existed in 1931 as well as the sandbar at the intrados of the Douro river curve. Figure 4 also shows that the P4 pillar was founded in the sandbar, and with a sand level similar to that of the P5 pillar. With the increase of sand extractions, since the 70's, the sandbar has been decreasing, due to direct extraction, having nearly disappeared in 1982, as stated in a survey carried out that year.

The lowering of the bottom topography in the order of four meters, on average, recorded between 2000 and 2001 in the Hintze Ribeiro Bridge section, was primarily the result of the five major floods observed in the period from December 2000 to March 2001 (Figure 3). As the sand was not sufficient in order to supply the needs created by the five flood waves, the large holes created upstream by sand extraction, over more than two decades, were not able to be silted up, thus restoring the conditions prior to sand extractions.

A picture taken just a few days after the bridge collapse show that the P4 pillar fell upriver, against the natural effect of the flow, whose strength and resulting impulse would point in the opposite direction. Such behavior can only be explained due to infra-excavation, which was the dominant process at the base of the pillar P4, putting it out of service.

More recently, another bridge situated at approximately 10 km downstream of the Raiva dam, in the Mondego River, and about 20 km upstream of Coimbra, Portugal, collapsed. The scour around one pillar of the bridge, in this case due to lack of sand that is retained in the Aguieira and Raiva dams, led to the lowering of the river bottom about 6 m in relation to the initial level.

Aiming to help prevent occurrences such as that recorded in Portugal with the Hintze Ribeiro Bridge collapse, we present a brief framework of the bridge, the causes which led to its collapse, some reflections on the processes involved and, above all, the lessons learned.

2. Background

1 In general, all anthropogenic actions that change the river morphology will have regional-scale
2 impacts. Even interventions limited to small areas, as levee construction, linearization of a river
3 stretch, sand extractions and gravel mining, the effects can be felt until long distances downstream
4 and upstream of the affected areas. Other interventions, to an even broader regional-scale, should be
5 considered, such as flow and sediment regulation by large dams and changes caused by
6 groundwater extraction.
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8 Over thousands of years an almost natural balance was established in Portugal which is not a region
9 particularly affected by adverse natural conditions. This balance, which in the past was only
10 disturbed by its own dynamics resulting in out of balance of different forces, sedimentary processes
11 and the alluvial bed form, has only very recently (in geological terms) been disturbed by actions
12 that are human in origin and are understood as the real cause, either directly or indirectly, affecting
13 or damaging the natural balance. It is, in fact, important to note that the so-called coastal protection
14 work on Portuguese shores has not always been in response to natural needs; on the contrary, much
15 of the present-day need for coastal protection has arisen precisely as a consequence of some of this
16 work, which has had consequences and effects that have not infrequently been extremely damaging.
17 Naturally many other river projects will be added to these, with very disturbing and equally
18 damaging effects, from an environmental point of view. The permanent lack of sediment flowing
19 into the Portuguese coastline is clear proof of this.
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21 With rare exceptions, today, the Portuguese rivers are far from their natural state. And for the few
22 rivers still unregulated and far from becoming artificial, it is hardly realistic to imagine that it will
23 be possible to contain or even redress imbalances resulting from the construction of large hydraulic
24 projects in these rivers, examples of which are the large dams and their reservoirs. Naturally,
25 studies on the environmental impact should be carried out in all circumstances, including analysis
26 of the risks associated with the existence of the dams and reservoirs during the construction phase
27 and throughout the various phases of the commercial exploitation and eventual abandoning of the
28 works.
29

30 Other equally disturbing effects on the natural system, are the irreversible negative medium and
31 long term consequences resulting from the unregulated extraction of inert material from water
32 courses that are not properly supervised and/or authorised (both in terms of the extraction site and
33 the amounts extracted). These activities can and should be drastically reduced and heavily
34 controlled by regular and systematic analysis of the evolutionary developments in the alluvial
35 depths and over significant extended areas, both downstream and upstream of the affected areas.
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1 Above all it is important to prevent the constant and rapid general debasement of environmental
2 features and conditions and to restore the balance of the fluvial system with the missing sediment in
3 the appropriate places, that is, in the areas where a tendency towards erosion has been observed. In
4 fact, once the "battle" between man and nature started, in an attempt to "dominate" the natural
5 systems, a vicious circle that is difficult to stop was set in motion. We may study the relevant cases
6 but these no longer represent simple imbalances that nature itself can correct and overcome with
7 certain obvious local negative repercussions.

9 **3. Responses of the fluvial system to changes in morphodynamic processes**

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11 Worldwide in recent decades, the natural waterways have been drastically altered by human
12 intervention. In general, changes in riverbeds, rectifications of stretches, dredging and sand mining,
13 bridge pillars, breakwaters, groins and dams, among others, proved inadequate or improperly
14 installed. These actions have led to profound alterations in local features over considerable stretches
15 of rivers. Depending on their level of stability or the pre-existing balance between the predominant
16 variables, at any point in the watercourse, the bottom morphology is adjusted according to the river
17 flow and the amount of available sediments. The general trend of equilibrium is only modified by
18 local conditions or human interventions. Consequently, any form of human intervention in the
19 fluvial system should respect the natural tendency of a river to seek out overall conditions of
20 stability.

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22 Starting from the basic principles of fluvial morphodynamics and taking into account the most
23 relevant variables in this process, we can establish in a simplified but essentially correct form, the
24 following proportional relationship (Lane, 1955; Antunes do Carmo, 2001; Antunes do Carmo,
25 2005):

$$26 \quad Q_s \times D_n \propto Q \times i \quad (1)$$

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29 in which Q_s represents the total solid discharge; D_n represents the characteristic diameter of the
30 solid material in transit (in general $D_n \cong D_{50}$, this being the mean diameter, since 50% of the
31 material is finer); Q is the water discharge and i represents the average slope of the thalweg.

32
33 Expression (1) represents the tendency of four variables to establish a natural equilibrium. Thus, for
34 a system in equilibrium, any change in any of the variables involves an imbalance in the system.
35 Over time, a new equilibrium will tend to settle down with contributions of one (or more) of the
36 remaining variables. Therefore, based on the expression (1), we can predict qualitatively the

1 responses of a fluvial system to natural alterations or changes imposed in the morphodynamic
2 processes.

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4 Expansions of Lane's relation (1) to account for changes in cross-sectional, planform and bedform
5 geometry have been suggested recently (Dust and Wohl, 2012; Huang *et al.*, 1014). We recognize
6 that these changes are typically associated with complex channel adjustments, but for the analyzes
7 considered in this work is sufficient to use the classical relation (1).

8
9 To better understand this type of analysis, let us turn to some examples of concrete situations,
10 namely:

- 11 *i) Response of the alluvial bed to the construction of a dam*
- 12 *ii) Response of the alluvial bed to sediment discharge reduction*
- 13 *iii) Response of the alluvial bed to rectification of a river stretch*
- 14 *iv) Response of the alluvial bed to extractions of inert material, creating holes*
- 15 *v) Fluvial system response to a decrease in the free surface level of the main watercourse*
- 16 *vi) Fluvial system response to an increase in the free surface level of the main watercourse*

17 18 **3.1 Response of the alluvial bed to the construction of a dam**

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20 As a result of a reduction in the rate of flow, solid material will be deposited in the reservoir.
21 Consequently, the water discharged downstream of the dam will contain far less sediment than a
22 similar amount entering the reservoir or, in other words, the solid discharge will be reduced from
23 Q_s to Q_s^- . Given that the water discharge and the diameter of the material on the bottom remain
24 constant, a new balance will only be established through a reduction of the average slope of the
25 river bed, i , downstream of the dam, in the proportions $Q_s^- \times D_n \propto Q \times i^-$. As shown in Figure 5, the
26 initial profile downstream of the CA dam will tend to erode until hypothetically it achieves the C'A
27 profile, which, in turn, will revert to the CA profile if more solid material is available, which may
28 occur after the completion of the filling of the reservoir with sediments.

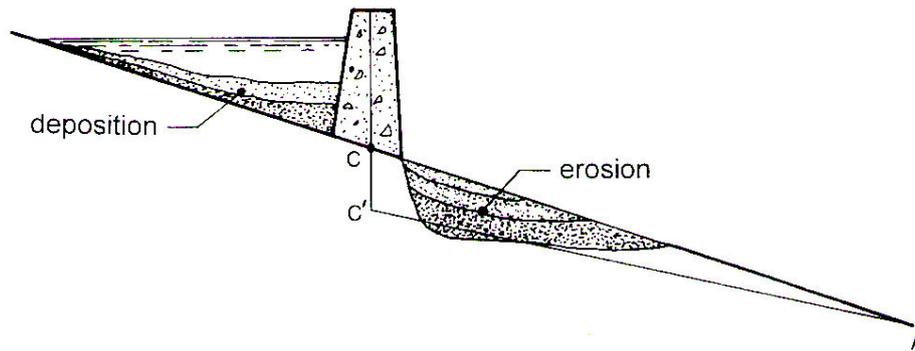


Figure 5 - Response of the riverbed to the construction of a dam (Antunes do Carmo, 2005).

Upstream of the dam, the average profile of the bed will tend to parallel the original profile. Inside the reservoir, sediments will be deposited and the role played by wind, waves, currents and gravitational processes will have a significant effect on the contours of the sides of the reservoir.

In the downstream sector of the dam, significant effects will be felt on the channel processes. In fact, erosion of the river bed and channel banks will increase, as a result of the increased energy of the current, caused by a reduction in the solid load it had previously transported, most of which is retained in the reservoir. The eroded material is subsequently deposited downstream in another stretch of the river, much further away. The longitudinal profile of the main river and its tributaries is thus gradually reshaped and deepened, producing new alluvial beds. Changes in the fluvial system may eventually reach the river mouth and affect the nearby coastline.

As a result of the riverbed lowering downstream of the dam may occur: (1) regressive erosions in the tributaries; (2) damage in bridges, as well as in support walls along the banks, due to excavation beneath their foundations, and (3) water captations in the river out of service.

Of course, other effects occur. According to Brandt (2000), the effects downstream of the dam may be classified into three types:

- changes of the 1st order, which occur in the sedimentary load, where the water discharge and the water quality are directly linked to the released flow of the dam;
- changes of the 2nd order, which are alterations of the channel form, substratum composition, macrophytes population, etc.;
- changes of the 3rd order, which are alterations to the fish and invertebrate populations.

Associated with changes in the gradients, water discharges and sediment transport, there are also changes in the alluvial bed material (both the particles size and the resulting bed form), in the outline configurations of the channel and in the distribution of depressions and elevations along the channel, as well as responses of tributaries due to changes in the main channel.

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3.2 Response of the alluvial bed to sediment discharge reduction

Consider a tributary that, under natural conditions, discharges into the bed of the main watercourse a solid flow Q_s . Due to human intervention, this solid discharge is significantly reduced and becomes Q_s^- . As values of the water discharge in the main watercourse and the mean diameter of the solid material remain unaltered, the average slope of the bed of the main watercourse downstream of the confluence must therefore be significantly reduced, changing from i to i^- , in accordance with expression (1). Upstream of this confluence, the bed will develop a parallel configuration to the original bed, although the final slope will be less steep. This situation is clearly illustrated in Figure 6, in which A represents a fixed point.

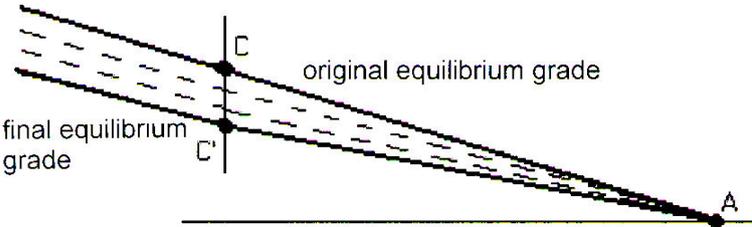


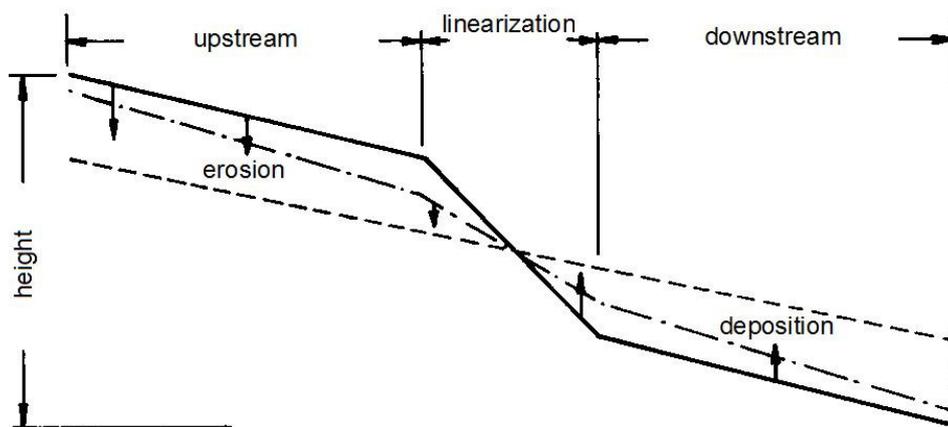
Figure 6 - Behaviour of the alluvial bed in the event of solid discharge reduction (Antunes do Carmo, 2005).

Therefore, the observed behaviour is similar to what occurs downstream of a dam (previous case).

3.3 Response of the alluvial bed to rectification of a river stretch

The elimination of meanders is often accomplished through deviations, or by rectification (linearization) of the natural river bed. Since the final length of the linearized stretch is lower than the original, this procedure usually translates to an increase of the average slope of the bottom and hence an increased ability to sediment transport, which may lead to significant changes in the natural equilibrium conditions.

Indeed, the mismatch of the final riverbed slope to the pre-existing conditions of sediment transport leads to depositions downstream of the linearized stretch, with a consequent increase of the bottom levels, as well as flood levels, and to erosions upstream of this stretch, which may be highly undesirable. Figure 7 clearly illustrates this situation.



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3 Figure 7 - Behavior of the alluvial bed due to rectification (linearization) of a river stretch.
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5 The analysis of this occurrence should also be taken in light of the expression (1). There is, in this
6 case, an increase in the mean slope of the bed; ie, the original slope i increases to i^+ . Keeping the
7 water flow rate and the bed material diameter, an increase of the sediment transport downstream of
8 the linearized stretch will occur, from Q_s to Q_s^+ . Large part of the transported sediment is retained
9 in the stretch that follows, since its slope remains unchanged and, therefore, there is no sufficient
10 transport capacity to drain all excess sediment arriving there.

11 12 **3.4 Response of the alluvial bed to extractions of inert material, creating holes**

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14 This situation creates a reduction in the solid discharge downstream of the affected area, which will
15 be reduced from Q_s to Q_s^- . Consequently, keeping the same flow conditions, Q , and sediment
16 transport characteristics, D_n , prior to the opening of the hole, a new balance will only be established
17 through a reduction in the average slope of the river bed, which will change from i to i^-
18 downstream of the hole. Thus, it will behave identically to the situation described in the previous
19 point. To show this behaviour, we have used a numerical model, based on the Saint-Venant
20 equations, or “shallow water equations”, which is briefly described below.

21 22 **3.4.1 Mathematical formulation**

23
24 The Saint-Venant equations can be deduced from integration of the fundamental equations of Fluid
25 Mechanics applied to a three-dimensional flow, assuming incompressibility of the fluid and
26 hydrostatic pressure. In the conservative form, these equations are written:

$$27$$

$$28 \quad \frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

$$1 \quad \frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = E_x \quad (2)$$

$$2 \quad \frac{\partial V}{\partial t} + \frac{\partial G}{\partial x} + \frac{\partial S}{\partial y} = E_y$$

3

4 where $H = h(x, y, t)$, $U = u(x, y, t)h(x, y, t)$, $V = v(x, y, t)h(x, y, t)$, $F = u^2h + \frac{1}{2}gh^2$, $G = uvh$ and

5 $S = v^2h + \frac{1}{2}gh^2$, being (u, v) the mean flow velocity components, h the water depth, and g the

6 acceleration due to gravity. The terms E_x and E_y are written:

7

$$8 \quad E_x(x, y, t) = -gH \frac{\partial \xi}{\partial x} + fV - \frac{1}{\rho} \tau_{fx} + \frac{\partial}{\partial x} \left(\varepsilon \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon \frac{\partial U}{\partial y} \right) \quad (3)$$

$$9 \quad E_y(x, y, t) = -gH \frac{\partial \xi}{\partial y} - fU - \frac{1}{\rho} \tau_{fy} + \frac{\partial}{\partial x} \left(\varepsilon \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon \frac{\partial V}{\partial y} \right) \quad (4)$$

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11 where ξ represents bed levels, ε is the turbulent diffusion coefficient and f is the Coriolis

12 coefficient associated with the Coriolis force, on Earth equal to $2\Omega \sin(\varphi)$, where Ω is the angular

13 rotation rate of the Earth ($\pi/12$ radians/hour) and φ is the latitude. Bottom shear stresses, τ_f/ρ , are

14 computed by the Gauckler-Manning-Strickler formula, which are written:

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$$16 \quad \frac{\tau_{fx}}{\rho} = \frac{gn^2(u^2 + v^2)^{1/2}u}{h^{7/3}} \quad \frac{\tau_{fy}}{\rho} = \frac{gn^2(u^2 + v^2)^{1/2}v}{h^{7/3}} \quad (5)$$

17

18 where n represents Manning's roughness coefficient. In terms of the equivalent sand-grain

19 diameter k_s , n is given by $n = k_s^{1/6}/21.1$.

20 The two-dimensional continuity equation of the solid phase (6), to be solved together with

21 equations (2), is written (neglecting the contribution of local variations of the sediment

22 concentration) (Antunes do Carmo and Seabra-Santos, 2002; Chiang *et al.*, 2011):

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$$24 \quad (1 - \lambda) \frac{\partial \xi}{\partial t} + \frac{\partial \langle q_b + q_s \rangle_x}{\partial x} + \frac{\partial \langle q_b + q_s \rangle_y}{\partial y} \quad (6)$$

$$- \langle \varepsilon_b |q_b| + \varepsilon_s |q_s| \rangle_x \frac{\partial^2 \xi}{\partial x^2} - \langle \varepsilon_b |q_b| + \varepsilon_s |q_s| \rangle_y \frac{\partial^2 \xi}{\partial y^2} = \langle q_{st} \rangle$$

25

26 where $\langle \dots \rangle$ represents average quantities, λ is the sediment porosity, q_b and q_s [$m^3s^{-1}/m.l.$]

27 represent bed load and suspended load, respectively, per unit width of the watercourse, q_{st}

1 [m³s⁻¹/m.l./m.l.] represents input or output sediment transport, per unit width of the main
2 watercourse and per unit width of a tributary.

3 The solid flows transported by entrainment (7) and in suspension (8) are written (Antunes do Carmo
4 and Seabra-Santos, 2002; Antunes do Carmo *et al.*, 2002):

$$6 \quad \langle q_{b_s} \rangle = \frac{c_f}{g(s-1)} \frac{\epsilon_b}{\tan \phi} |u|^2 u \quad \langle q_{b_v} \rangle = \frac{c_f}{g(s-1)} \frac{\epsilon_b}{\tan \phi} |v|^2 v \quad (7)$$

$$7 \quad \langle q_{s_s} \rangle = \frac{c_f}{g(s-1)} \frac{\epsilon_s}{w_s} |u|^3 u \quad \langle q_{s_v} \rangle = \frac{c_f}{g(s-1)} \frac{\epsilon_s}{w_s} |v|^3 v \quad (8)$$

8
9 where s is the sediment density ($s \approx 2.65$), ϕ is the internal angle of friction of the sediment, w_s
10 represents the sediment fall velocity, ϵ_b and ϵ_s are efficiencies, with values in the intervals
11 $0.05 \leq \epsilon_b \leq 0.25$ and $0.01 \leq \epsilon_s \leq 0.03$, and c_f is a current friction coefficient given by $c_f = \sqrt{0.5f_c}$, with
12 the bed-roughness coefficient $f_c = 0.06 \left(\log_{10} \frac{12h}{k_r} \right)^{-2}$, $k_r \approx 2.5d_{50}$.

13

14 **3.4.2 Numerical solution**

15

16 The system formed by equations (2) is solved numerically using an explicit finite difference method
17 based on the MacCormack time-splitting scheme (MacCormack, 1971; Garcia and Kahawita, 1986;
18 Antunes do Carmo *et al.*, 1993). The application of MacCormack method to the Saint-Venant
19 equations (2) proceeds in two steps: a *predictor step* which is followed by a *corrector step*. For this
20 purpose, equations are split into two systems of equations throughout the Ox and Oy directions,
21 corresponding to the operators L_x and L_y defined as follows:

22

23

Operator L_x

$$24 \quad \frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} = 0$$

$$25 \quad \frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} = -gH \frac{\partial \xi}{\partial x} - \frac{\tau_{fx}}{\rho} + fV + \frac{\partial}{\partial x} \left(\epsilon \frac{\partial U}{\partial x} \right) \quad (9)$$

$$26 \quad \frac{\partial V}{\partial t} + \frac{\partial G}{\partial x} = \frac{\partial}{\partial x} \left(\epsilon \frac{\partial V}{\partial x} \right)$$

27

28

Operator L_y

$$29 \quad \frac{\partial H}{\partial t} + \frac{\partial V}{\partial y} = 0$$

$$\frac{\partial U}{\partial t} + \frac{\partial G}{\partial y} = \frac{\partial}{\partial y} \left(\varepsilon \frac{\partial U}{\partial y} \right) \quad (10)$$

$$\frac{\partial V}{\partial t} + \frac{\partial S}{\partial y} = -gH \frac{\partial \xi}{\partial y} - \frac{\tau_{fy}}{\rho} - fU + \frac{\partial}{\partial y} \left(\varepsilon \frac{\partial V}{\partial y} \right)$$

Following Antunes do Carmo *et al.* (1993), the solution at time $(n+1)\Delta t$ for the computational point (i, j) , is obtained through the following symmetric application:

$$Q^{n+1} = L_x \left(\frac{\Delta t}{2} \right) L_y \left(\frac{\Delta t}{2} \right) L_y \left(\frac{\Delta t}{2} \right) L_x \left(\frac{\Delta t}{2} \right) Q^n \quad (11)$$

where Q represents a generic variable, n is a generic time t , and each operator L_x and L_y uses an alternately sequence of backward and forward finite difference approximations for spatial derivative, at each time step, according to the following discretization (Antunes do Carmo *et al.*, 1993):

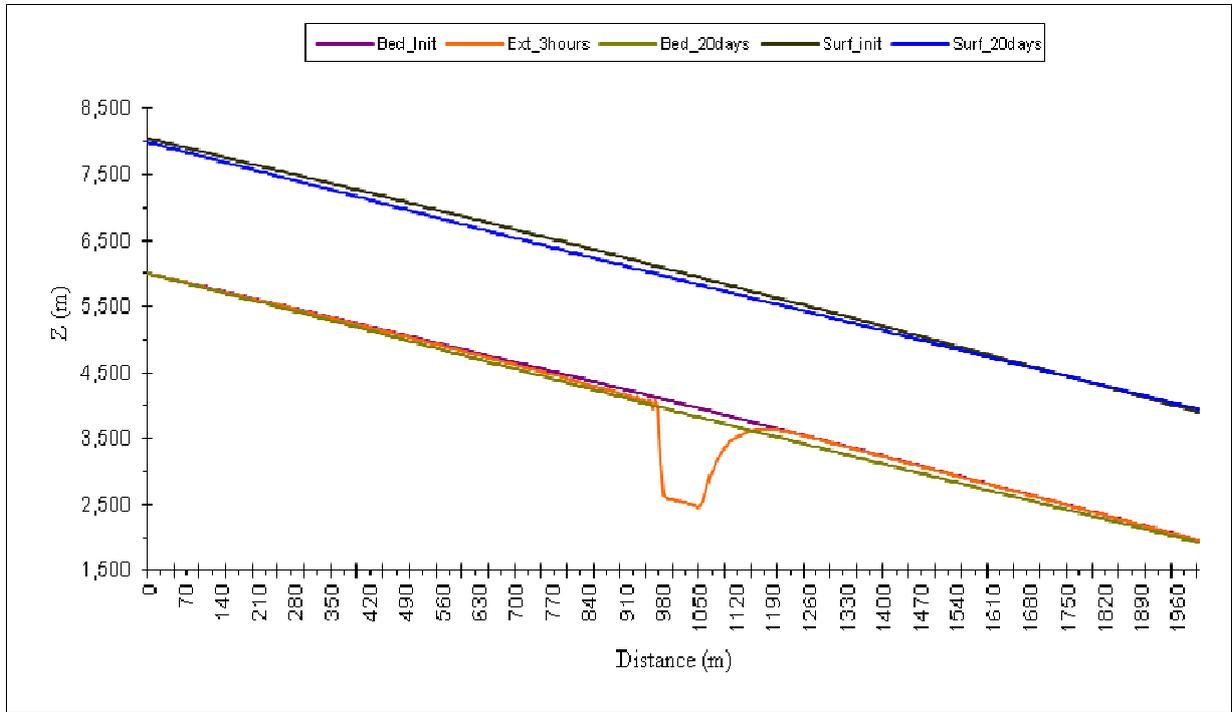
First operator L_x :	Predictor – backward differences
	Corrector – forward differences
First operator L_y :	Predictor – backward differences
	Corrector – forward differences
Second operator L_y :	Predictor – forward differences
	Corrector – backward differences
Second operator L_x :	Predictor – forward differences
	Corrector – backward differences

3.4.3 Numerical results

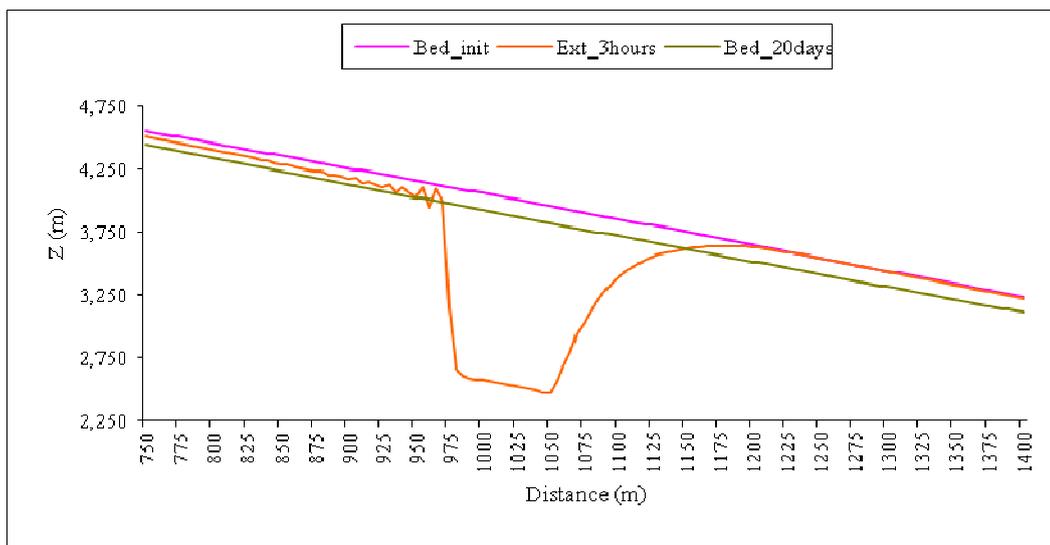
The numerical simulation shown in Figure 8 is based on a situation in which there is a uniform system, so it deals with a typical configuration of a natural balance modified by human intervention. To establish the initial conditions, the extraction of inert material from the river bed was simulated over an area of 100 m length (950 m to 1050 m of the represented stretch) and 1.50 m deep.

The daily evolution of the river was analysed for a period of 20 days, and the two extreme points (borders) of the channel were considered fixed. The initial configuration and the numerical results obtained after 3 hours (orange) and after 20 days (green) of simulation are shown in Figures 8 a) and b), the latter displaying a *zoom* of a stretch 650 m long, between 750 m and 1400 m. The results show that 20 days after the occurrence, the large hole resulting from sand extraction was completely filled and the general evolution of the riverbed, both before and after the extraction zone, corresponds to widespread erosion.

1
2
3



4 a) Initial riverbed (purple), bottom profile three hours after the event (orange), and riverbed
5 twenty days after (green).



6 b) *Zoom* of the stretch between 750 m and 1400 m.

7
8 Figure 8 - Behaviour of the alluvial bed in an event of inert material extraction, creating a hole.

1

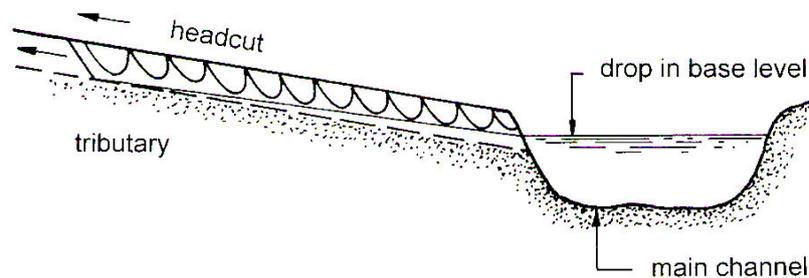
2 3.5 Fluvial system response to a decrease in the free surface level of the main watercourse

3

4 Let's consider a management measure that has the effect of lowering the free surface level of a main
5 watercourse. This can happen as a result of changes in the roughness of the bed and river banks,
6 changes in the riverbed slope, changes on a river stretch, or even a lowering of the initial riverbed.

7 Consequently, general erosion may occur in the river banks, and in the beds of tributaries
8 downstream and upstream of the affected area. The situation is clearly illustrated in Figure 9
9 (Antunes do Carmo, 2005).

10



11
12

13 Figure 9 - Erosions on a tributary caused by lowering the free surface level of the main watercourse
14 (adapted from Simons and Sentürk, 1976; Antunes do Carmo, 2005).

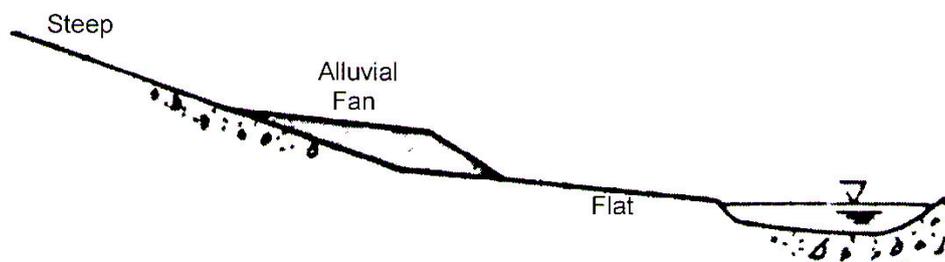
15

16 3.6 Fluvial system response to an increase in the free surface level of the main watercourse

17

18 This case corresponds to a management measure that has a widespread sediment deposition effect,
19 transport capacity reduction of the tributaries, with eventual formation of small dams, creating
20 conditions for floods, breakings and formation of other secondary channels. Figure 10 illustrates
21 this situation (Antunes do Carmo, 2005).

22



23
24

25 Figure 10 - Deposition of sediments in a tributary caused by increasing the free surface level of the
26 main watercourse (adapted from Simons and Sentürk, 1976; Antunes do Carmo 2005).

4. Conclusions

The building and operating of a large dam and its reservoir has important direct and indirect environmental impacts which demand serious analysis. From the morphological point of view, many impacts are produced by a dam on the fluvial system; most notably:

- changes in geomorphological processes as a result of changes in river dynamics;
- contributions to increased sedimentary deficits as a result of sediments retention in the reservoir;
- changes in the hydrological surface and groundwater regimes.

Although the probability of a dam breaking is very slight, even in global terms (in the order of 4×10^{-4} to 7×10^{-4}), the human and material damage associated with such an accident is so serious that increased concern is justified, not only on the part of those responsible, but also in the technical and scientific community worldwide. These concerns are now the order of the day and are fully justified, particularly given the fact that:

- the construction rate for large new dams has remained constant in recent years at about 350 per year;
- problems are now likely to arise with the large dams built in the latter half of the 1940s and with dams from the 1950s in the near future;
- the discharge capacity of a dam (spillway) may be insufficient due to recent effects induced by climate change, deforestation, forest fires, and others;
- it is recognised that the risk of a dam break and the number of associated accidents will increase as dams reach the end of their working life (after around 60 years).

It should be concluded that all interventions performed in the fluvial system, including regularization of rivers, rectification of stretches and correction of riverbeds, must always be preceded by environmental impact studies covering large stretches of the river, both upstream and downstream of the area directly affected.

From the hydrological point of view, we highlight the fact that none of the five floods that occurred in three months exceeded half of the local PMF (the flood that can be expected from the most severe combination of meteorological and hydrological conditions possible for the region in a given period, typically a hundred years). This means that security and stability of hydraulic constructions installed in alluvial riverbeds should be evaluated taking into account possible sequences of floods with short intervals of occurrence, even with intensities well below the PMF.

In relation to extraction of inert material in river environments, if authorized, it is suggested that both the licences and licence renewals should only be granted for short periods of time (never more than a year) and only if certain requirements have been fulfilled, including: *i*) submission of a

1 sufficiently detailed topo-hydrographic survey including the upstream and downstream areas of the
2 project and not just the affected area; *ii*) check the present riverbed levels and if the extracted sand
3 corresponds to the authorized amount, and *iii*) provide an estimation of the maximum amount of
4 sand to be extracted during the new license.

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