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Environmental impacts of human action in watercourses

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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 fluvial 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 impact 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 and offers a brief technical contribution 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.

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Environmental impacts of human action in watercourses

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1 Introduction

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.

It is essential to cultivate a pro-nature attitude, which means avoiding activities that threaten nature's tendency to establish dynamically stable configurations. Sustainability

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can only be achieved as a result of a development process based on a relationship between people and nature, combining actions designed to encourage economic dynamism with an improvement in people's quality of life. This should concern future generations and natural environment conservation.

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

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

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

Statistical studies show that the critical life period of a dam occurs either during construction or on the first complete filling of the reservoir, extending up to 5–7 years

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after its completion. However, it should be noted that this conclusion is limited because it refers mainly to the first occurrences (constructive disabilities); several hazardous events may occur with equal probability during the lifetime of a dam.

In this regard, it should be noted an occurrence that took place in the winter 2001, near Coimbra, Portugal. In the period 26–30 January 2001 a clearly inadequate management and operation of the Aguieira dam occurred, which could have led to overtopping or failure of a dam 30 years after its construction.

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

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 hm^3.
  - Minimum level of exploitation: 112.5 m ⇒ Stored volume: 277.0 hm^3.
  - Available volume for floods: ≈ 150.0 hm^3.
- When the accident occurred

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– Minimum level of exploitation: 116.0 m ⇒ Total stored volume: 327.0 hm^3.
– Available volume for floods: ≈ 100.0 hm^3 (that is, an ability to fit more 50 hm^3 was lost).

The final report cited above suggests the following immediate actions to be implemented:

- review the operation protocol in force at that time for the Aguieira and Fronhas dams, this last one upstream;
- reassess the operating conditions of the Aguieira–Fronhas system; and
- installing a management system in real time.

These recommendations were implemented, among others, particularly in the Lower Mondego. Consequently, despite of the storms that occurred in the last 12 years with equal or even greater severity, no such flooding occurred downstream of Aguieira.

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

The collapse of this bridge occurred on the night of 4 March 2001, during a flood wave propagation on the Douro River. This was the 5th flood wave in a series of floods that began on 6 December 2000, all with peaks exceeding 8000 $m^3 s^{-1}$, as is shown in the record of Fig. 3 (Rocha et al., 2008).

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

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

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 (Fig. 4, with designations P1–P6 for the pillars of the bridge starting from the right bank).

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 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

Over thousands of years an almost natural balance was established in Portugal which is not a region particularly affected by adverse natural conditions. This balance, which in the past was only disturbed by its own dynamics resulting in out of balance of different forces, sedimentary processes and the alluvial bed form, has only very recently (in geological terms) been disturbed by actions that are human in origin and are understood as the real cause, either directly or indirectly, affecting or damaging the natural balance. It is, in fact, important to note that the so-called coastal protection work on Portuguese shores has not always been in response to natural needs; on the contrary, much of the present-day need for coastal protection has arisen precisely as a consequence of some of this work, which has had consequences and effects that have not infrequently been extremely damaging.

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Naturally many other river projects will be added to these, with very disturbing and equally damaging effects, from an environmental point of view. The permanent lack of sediment flowing into the Portuguese coastline is clear proof of this.

With rare exceptions, today, the Portuguese rivers are far from their natural state. And for the few rivers still unregulated and far from becoming artificial, it is hardly realistic to imagine that it will be possible to contain or even redress imbalances resulting from the construction of large hydraulic projects in these rivers, examples of which are the large dams and their reservoirs. Naturally, studies on the environmental impact should be carried out in all circumstances, including analysis of the risks associated with the existence of the dams and reservoirs during the construction phase and throughout the various phases of the commercial exploitation and eventual abandoning of the works.

Other equally disturbing effects on the natural system, are the irreversible negative medium and long term consequences resulting from the unregulated extraction of inert material from water courses that are not properly supervised and/or authorised (both in terms of the extraction site and the amounts extracted). These activities can and should be drastically reduced and heavily controlled by regular and systematic analysis of the evolutionary developments in the alluvial depths and over significant extended areas, both downstream and upstream of the affected areas.

Above all it is important to prevent the constant and rapid general debasement of environmental features and conditions and to restore the balance of the fluvial system with the missing sediment in the appropriate places, that is, in the areas where a tendency towards erosion has been observed. In fact, once the "battle" between man and nature started, in an attempt to "dominate" the natural systems, a vicious circle that is difficult to stop was set in motion. We may study the relevant cases but these no longer represent simple imbalances that nature itself can correct and overcome with certain obvious local negative repercussions.

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3 Responses of the fluvial system to changes in morphodynamic processes

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

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

$$Q_\mathrm{s} \cdot D_\mathrm{n} \propto Q \cdot i \quad (1)$$

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

Expression Eq. (1) represents the tendency of four variables to establish a natural equilibrium. Thus, for a system in equilibrium, any change in any of the variables involves an imbalance in the system. Over time, a new equilibrium will tend to settle down with contributions of one (or more) of the remaining variables. Therefore, based on the expression Eq. (1), we can predict qualitatively the responses of a fluvial system to natural alterations or changes imposed in the morphodynamic processes.

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

1. Response of the alluvial bed to the construction of a dam.
2. Response of the alluvial bed to sediment discharge reduction.
3. Response of the alluvial bed to rectification of a river stretch.
4. Response of the alluvial bed to extractions of inert material, creating holes.
5. Fluvial system response to a decrease in the free surface level of the main watercourse.
6. Fluvial system response to an increase in the free surface level of the main watercourse.

3.1 Response of the alluvial bed to the construction of a dam

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

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.

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 Eq. (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 Fig. 6, in which A represents a fixed point.

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.

The analysis of this occurrence should also be taken in light of the expression Eq. (1). There is, in this case, an increase in the mean slope of the bed; i.e., the original slope i increases to i^+. Keeping the water flow rate and the bed material diameter, an increase of the sediment transport downstream of the linearized stretch will occur, from Q_s to

Q_s^+. Large part of the transported sediment is retained in the stretch that follows, since its slope remains unchanged and, therefore, there is no sufficient transport capacity to drain all excess sediment arriving there.

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

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

3.4.1 Mathematical formulation

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

$$\begin{aligned} &\frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \\ &\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = E_x \\ &\frac{\partial V}{\partial t} + \frac{\partial G}{\partial x} + \frac{\partial S}{\partial y} = E_y \end{aligned} \tag{2}$$

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

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depth, and g the acceleration due to gravity. The terms E_x and E_y are written:

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

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

where ξ represents bed levels, ε is the turbulent diffusion coefficient and f is the Coriolis coefficient associated with the Coriolis force, on Earth equal to $2\Omega\sin(\varphi)$, where Ω is the angular rotation rate of the Earth ($\pi/12\,\mathrm{rad\,h^{-1}}$) and φ is the latitude. Bottom shear stresses, τ_f/ρ, are computed by the Gauckler–Manning–Strickler formula, which are written:

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

where n represents Manning's roughness coefficient. In terms of the equivalent sand-grain diameter k_s, n is given by $n = k_\mathrm{s}^{1/6}/21.1$.

The two-dimensional continuity equation of the solid phase Eq. (6), to be solved together with Eq. (2), is written (neglecting the contribution of local variations of the sediment concentration) (Antunes do Carmo and Seabra-Santos, 2002; Chiang et al., 2011):

$$(1-\lambda)\frac{\partial \xi}{\partial t} + \frac{\partial\langle q_\mathrm{b}+q_\mathrm{s}\rangle_x}{\partial x} + \frac{\partial\langle q_\mathrm{b}+q_\mathrm{s}\rangle_y}{\partial y} - \langle\varepsilon_b|q_\mathrm{b}|+\varepsilon_\mathrm{s}|q_\mathrm{s}|\rangle_x\frac{\partial^2\xi}{\partial x^2} - \langle\varepsilon_\mathrm{b}|q_\mathrm{b}|+\varepsilon_\mathrm{s}|q_\mathrm{s}|\rangle_y\frac{\partial^2\xi}{\partial y^2} = \langle q_\mathrm{sl}\rangle \tag{6}$$

where $\langle\cdots\rangle$ represents average quantities, λ is the sediment porosity, q_b and q_s [$\mathrm{m^2\,s^{-1}}$] represent bed load and suspended load, respectively, per unit width of the watercourse,

q_{sl} [$m^2 s^{-1}$] represents input or output sediment transport, per unit width of the main watercourse and per unit width of a tributary.

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

$$\left\langle q_{b_x} \right\rangle = \frac{c_f}{g(s-1)} \frac{\varepsilon_b}{\tan\phi} |u|^2 u \qquad \left\langle q_{b_y} \right\rangle = \frac{c_f}{g(s-1)} \frac{\varepsilon_b}{\tan\phi} |v|^2 v \tag{7}$$

$$\left\langle q_{s_x} \right\rangle = \frac{c_f}{g(s-1)} \frac{\varepsilon_s}{w_s} |u|^3 u \qquad \left\langle q_{s_y} \right\rangle = \frac{c_f}{g(s-1)} \frac{\varepsilon_s}{w_s} |v|^3 v \tag{8}$$

where s is the sediment density ($s \approx 2.65$), ϕ is the internal angle of friction of the sediment, w_s represents the sediment fall velocity, ε_b and ε_s are efficiencies, with values in the intervals $0.05 \le \varepsilon_b \le 0.25$ and $0.01 \le \varepsilon_s \le 0.03$, and c_f is a current friction coefficient given by $c_f = \sqrt{0.5 f_c}$, with the bed-roughness coefficient $f_c = 0.06 \left(\log_{10} \frac{12h}{k_r} \right)^{-2}$, $k_r \approx 3D_{90}$.

3.4.2 Numerical solution

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

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Operator L_x

$$
\begin{aligned}
&\frac{\partial H}{\partial t}+\frac{\partial U}{\partial x}=0\\
&\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}=-gH\frac{\partial \xi}{\partial x}-\frac{\tau_{fx}}{\rho}+fV+\frac{\partial}{\partial x}\left(\varepsilon\frac{\partial U}{\partial x}\right)\\
&\frac{\partial V}{\partial t}+\frac{\partial G}{\partial x}=\frac{\partial}{\partial x}\left(\varepsilon\frac{\partial V}{\partial x}\right)
\end{aligned}
\tag{9}
$$

Operator L_y

$$
\begin{aligned}
&\frac{\partial H}{\partial t}+\frac{\partial V}{\partial y}=0\\
&\frac{\partial U}{\partial t}+\frac{\partial G}{\partial y}=\frac{\partial}{\partial y}\left(\varepsilon\frac{\partial U}{\partial y}\right)\\
&\frac{\partial V}{\partial t}+\frac{\partial S}{\partial y}=-gH\frac{\partial \xi}{\partial y}-\frac{\tau_{fy}}{\rho}-fU+\frac{\partial}{\partial y}\left(\varepsilon\frac{\partial V}{\partial y}\right)
\end{aligned}
\tag{10}
$$

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:

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

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

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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 Fig. 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 (950–1050 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 h (orange) and after 20 days (green) of simulation are shown in Fig. 8a and b, the latter displaying a *zoom* of a stretch 650 m long, between 750 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.

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

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

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

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

This case corresponds to a management measure that has a widespread sediment deposition effect, transport capacity reduction of the tributaries, with eventual formation of small dams, creating conditions for floods, breakings and formation of other secondary channels. Figure 10 illustrates this situation (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 construction works performed in the fluvial system, including river regularization, stretches rectification and riverbeds correction, must always be preceded by environmental impact studies covering large stretches of the river, both upstream and downstream of the area directly affected.

In relation to the 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 sufficiently detailed topo-hydrographic survey including the upstream and downstream areas of the project and not just the affected area; (ii) check the present riverbed levels and if the extracted sand corresponds to the

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authorized amount, and (iii) provide an estimation of the maximum amount of sand to be extracted during the new license.

References

Antunes do Carmo, J. S.: Consequences of unplanned interventions in fluvial systems, V SILUSBA, Aracaju, Brazil, 25–29 November, 10 pp., 2001 (in Portuguese) .

Antunes do Carmo, J. S.: The Environmental Impact and Risks Associated with Changes in Fluvial Morphodynamic Processes, Inter-Celtic colloquium on Hydrology and Management of Water Resources, Guimarães, Portugal, 11–15 July, 23 pp., available at: http://www.aprh.pt/celtico/PAPERS/ts5p8_presentation.pdf, last access: 25 July 2014, 2005.

Antunes do Carmo, J. S. and Seabra-Santos, F. J.: Near-shore sediment dynamics computation under the combined effects of waves and currents, Adv. Eng. Softw., 33, 37–48, 2002.

Antunes do Carmo, J. S., Seabra-Santos, F. J., and Almeida, A. B.: Numerical solution of the generalized Serre equations with the MacCormack finite-difference scheme, Int. J. Numer. Meth. Fl., 16, 725–738, 1993.

Antunes do Carmo, J. S., Seabra-Santos, F. J., and Amado-Mendes, P. A.: Sudden bed changes and wave-current interactions in coastal regions, Adv. Eng. Softw., 33, 97–107, 2002.

Barth, F. T.: Institutional Aspects for the Water Resources Development, National Conference on Water Resources and Sustainable Development, Final Report, Associação Brasileira de Educação Agrícola Superior, Brasília, 124 pp., 1996.

Brandt, S. A.: Classification of geomorphological effects downstream of dams, Catena, 40, 375–401, 2000.

Cunha, P. P.: Vulnerability and risk resulting from the floodplain occupation – the example of the River Mondego floods (central Portugal), in Winter 2000/2001, Territorium , 9, 13–35, 2002 (in Portuguese).

Garcia, R. and Kahawita, R. A.: Numerical solution of the Saint-Venant equations with the MacCormack finite-difference scheme, Int. J. Numer. Meth. Fl., 6, 259–274, 1986.

Chiang, Y.-C., Hsiao, S.-S., and Lin, M.-C.: Improved technique for controlling oscillation of coastal morphological modeling system, J. Mar. Sci. Technol., 19, 625–633, 2011.

MacCormack, R. W.: Numerical solution of the interaction of a shock wave with a laminar boundary layer, Lect. Notes Phys., 8, 151–163, 1971.

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Simons, D. B. and Sentürk, F.: Sediment Transport Technology, Water Resources Publications, Fort Collins, Colorado, USA, 1976.
Sousa, J. J. and Bastos, L.: Multi-temporal SAR interferometry reveals acceleration of bridge sinking before collapse, Nat. Hazards Earth Syst. Sci., 13, 659–667, doi:10.5194/nhess-13-659-2013, 2013.
World Water Vision/Commission Report: A Water Secure World: Vision for Water, Life and The Environment, UNESCO, Paris, 2000.

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Figure 1. Aerial view showing the floodplain completely flooded and, in the foreground, the 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).

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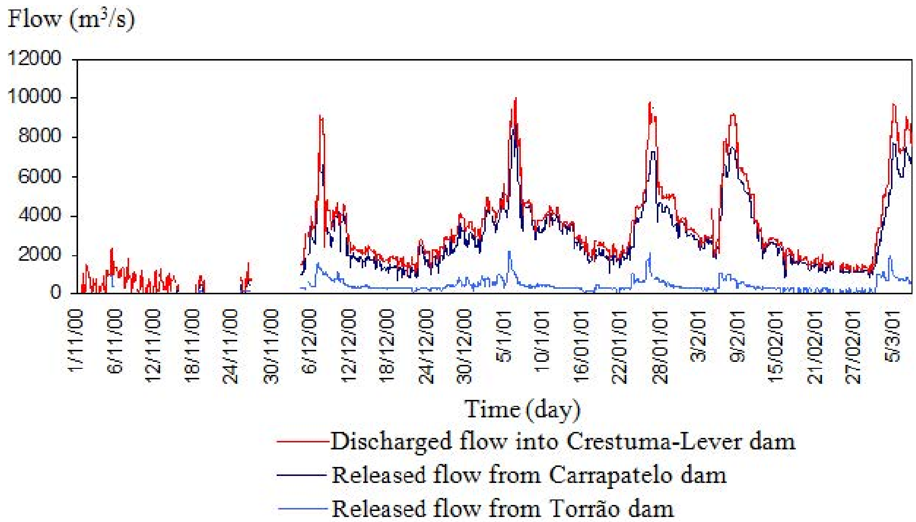

Figure 3. Released flows from the Carrapatelo and Torrão dams, and discharged flow into the Crestuma–Lever reservoir, between 1 November 2000 and 7 March 2001 (Rocha et al., 2008).

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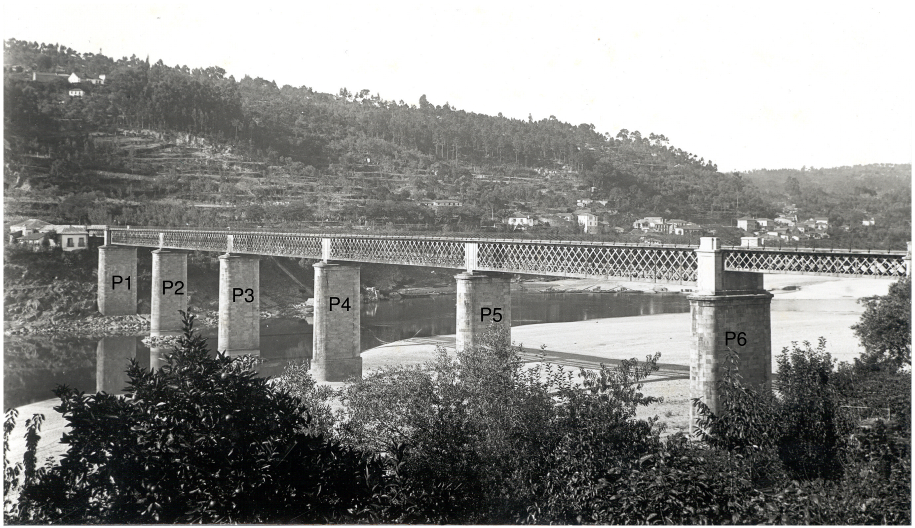

Figure 4. Photo of Hintze Ribeiro Bridge, dated 1931.

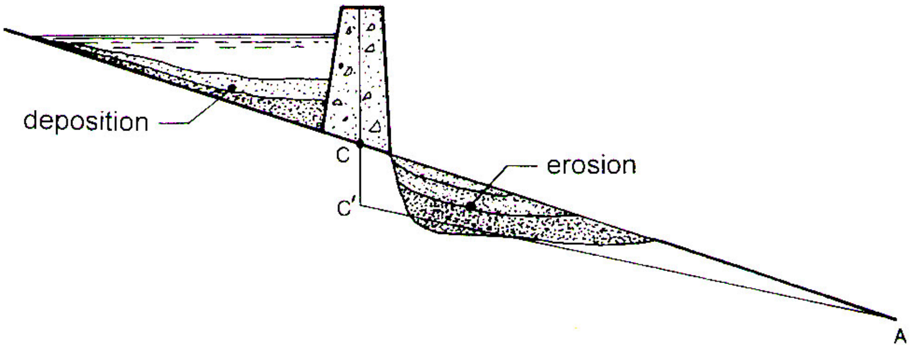

Figure 5. Response of the riverbed to the construction of a dam (Antunes do Carmo, 2005).

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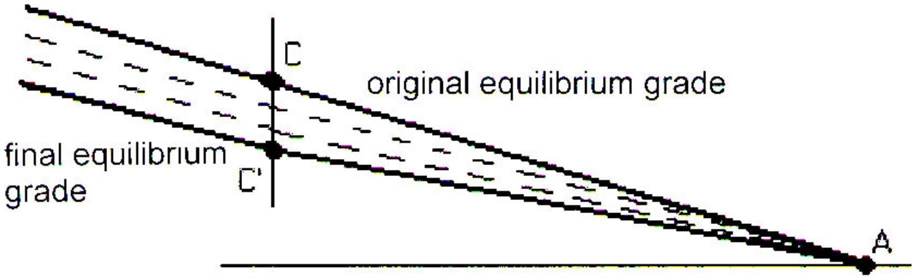

Figure 6. Behaviour of the alluvial bed in the event of solid discharge reduction (Antunes do Carmo, 2005).

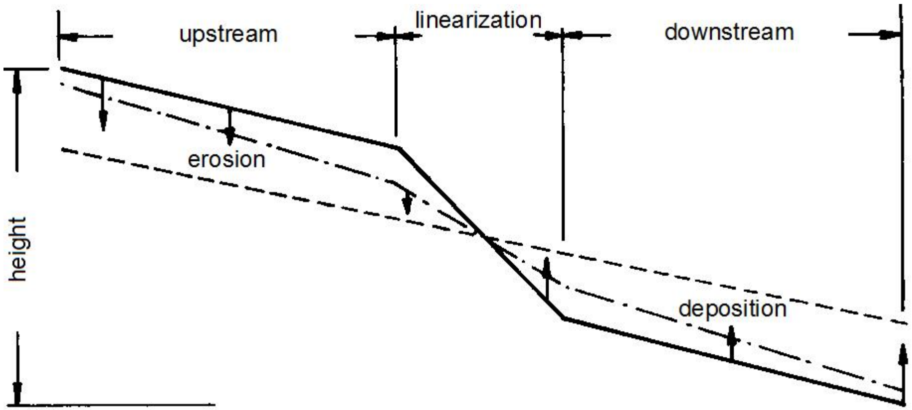

Figure 7. Behavior of the alluvial bed due to rectification (linearization) of a river stretch.

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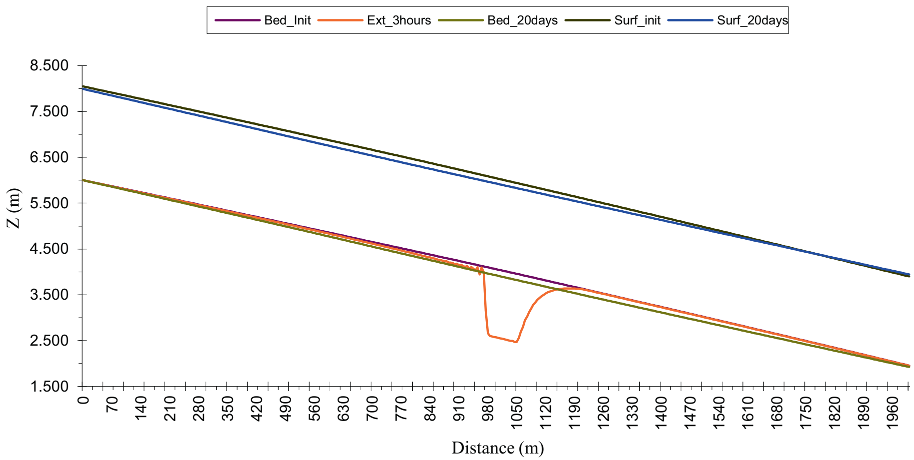

Figure 8a. Behaviour of the alluvial bed in an event of inert material extraction, creating a hole. Initial riverbed (purple), bottom profile three hours after the event (orange), and riverbed twenty days after (green).

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Figure 8b. Behaviour of the alluvial bed in an event of inert material extraction, creating a hole. *Zoom* of the stretch between 750 and 1400 m.

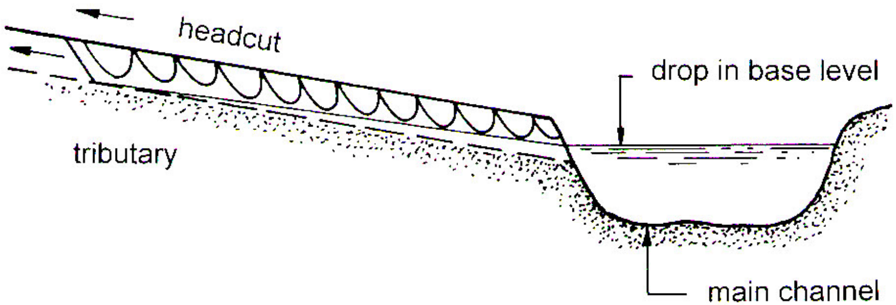

Figure 9. Erosions on a tributary caused by lowering the free surface level of the main watercourse (adapted from Simons and Sentürk, 1976; Antunes do Carmo, 2005).

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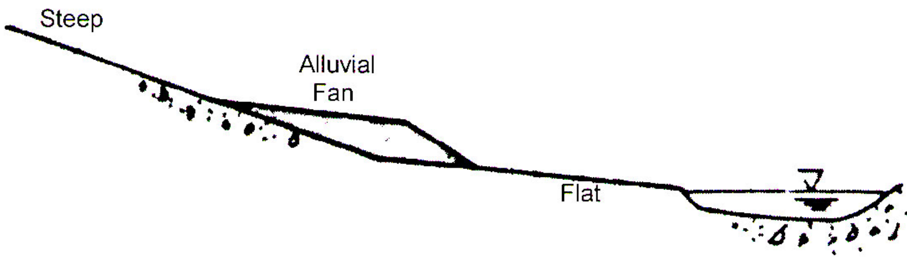

Figure 10. Deposition of sediments in a tributary caused by increasing the free surface level of the main watercourse (adapted from Simons and Sentürk, 1976; Antunes do Carmo, 2005).

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