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The environmental impact and risks associated with changes in fluvial morphodynamic processes

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Abstract The dynamics of the inter-relationship between the various elements that constitute a hydrographic basin involve cause–effect relationships that can lead to constant alterations in fluvial dynamics. The combination of elements such as morphology, altimetry and structural controls in a fluvial network enable a specific longitudinal profile to develop, which is dynamic and constantly in search of an equilibrium between the rates of water discharge, erosion and transport. Human activities carried out on a stretch of a river may alter this balance in different ways and with differing levels of intensity. Whenever the characteristics and natural evolution of a river are altered as a result of human intervention, this has 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. This paper provides a description of the nature and distribution of the direct and indirect types of impact arising out of the building and operating of 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.

Key words dams; environmental impact; extraction of inert material; morphodynamic processes; risks

INTRODUCTION

The River Minho, which flows for 300 km from the Meira Mountains in Spain (altitude of 750 m) to the Atlantic Ocean by Caminha and La Guardia, creates a natural border between Spain and Portugal along its final 70 km. Although the area of the River Minho hydrographic basin covers 17 080 km^2, only approximately 800 km^2 of this lies in Portuguese territory.

Despite the fact that the river has not yet become very badly damaged, like other Portuguese rivers, it can be seen that recent changes in water systems are the result of use and practices that have been carried out without due care being taken to provide suitable management of the natural resources.

The deterioration of the soils, alteration of the structure and functionality of the landscape, extraction of inert materials, building of hydraulic infrastructures, discharge of untreated urban and industrial effluents and unregulated hunting and fishing activities are all associated with a reduction in the quality of life of local populations that forces us to think about the future in a different way. Arguments are put forward for development based on the relationship between people and nature, linking activities orientated towards economic dynamism with improvements in the quality of life of local populations, participation in political decision-making, a concern for the future and preservation of the natural environment.

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 negatively 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 recognize 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 change on the scale required for a new approach to water resources management requires a *continual supply of financial resources* appropriately mobilized, including private sector investments and community resources.

All this demands a concentrated effort to create public awareness of the issue of water, and a strengthening of the collective bodies for managing hydrographic basins and user organizations, together with investment in development and the transfer of knowledge and technology dedicated towards better use and conservation of environmental resources.

THE BACKGROUND

Over thousands of years a quasi-natural balance has been established in Portugal (which is not a region that is particularly badly affected by adverse natural conditions) for rivers, estuary environments and along the coastline. This balance, which in the past was only disturbed by its own dynamics resulting out of the balance of different forces, sedimentary processes and the form of the alluvial bed, 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.

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.

The River Minho is the primary source that feeds the Portuguese coast and its natural features, which are still far from becoming artificial and unregulated, and are worth preserving. The author, however, feels that it is hardly realistic to imagine it will be possible to contain or even compensate for the imbalances resulting from the construction of large hydraulic enterprises in river environments, of which the large dams and resulting reservoirs are an example. Naturally, studies on the environmental impact should be carried out in all circumstances, including analysis of the risks associated with the existence of both dams and reservoirs during the construction phase and throughout the various phases of the commercial exploitation and eventual abandoning of the venture. Other equally disturbing effects on the natural system with irreversible negative medium and long-term consequences result from the unregulated extraction of inert material from water courses that is not properly supervised and/or authorized (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 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 (Antunes do Carmo, 2001). In fact, once man has begun his “battle” with nature in an attempt to “domesticate” natural systems, a vicious circle is set in motion which is difficult to halt. 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.

Consequently, it is important to recognize that any major change in behaviour that is imposed must involve admitting that the extraction of inert material may represent a necessary evil (understood from an economic point of view and in view of the fact that these resources cannot be returned to the river environment) and not a benefit granted to certain private entities, which serves as currency to balance the books of the public institutions. Nor will the example of certain Portuguese river and port authorities serve as a basis for building the little-opposed and much-needed “moral authority” to safeguard the legitimate interests of everyone.

THE INSTITUTIONAL FRAMEWORK

Efficient management of water resources necessarily includes measures to strengthen institutions, support for citizen participation and the development and transfer of technology for this purpose. As a basis for this management model, we present some concepts whose working definition may help unify the language of the various actors and agents involved. We therefore take as our reference point the concepts of integrated management, management tools and citizen participation used as a basis and argument for the management of water resources.

According to Barth (1996), integrated management of water resources involves a "set of actions that aim to provide multiple and rational use of water resources, serving all purposes and all users satisfactorily in terms of quantity and quality standards, as well as in terms of the control, conservation, protection and recuperation of these resources, with an equal distribution of costs amongst users and beneficiaries". In other words, the need for the multiple and rational use of water should be based on the recognition that this is a limited and, in some areas, scarce natural resource.

We must avoid seeing water simply in terms of its uses, to supply people, for example, or for irrigation, industry and the environment, all of which are almost always in competition with each other. It is necessary to promote the kind of management that takes into account the close links between use, quality and quantity of water, the well-being of people and care for nature.

The instruments of water resources management may be considered legal-administrative, economic-financial and political-institutional in nature. This study basically covers aspects which relate to legal-administrative instruments, including water resource planning and water resource information systems, in addition to the right to use water and the classification of different types of water, according to their main use.

Water resource information systems bring together information on quality, quantity, availability and demand for water, as well as the factors—natural or resulting from human actions—that affect its use. They should be founded on, and remain accessible through, a reliable database that is scientifically and technically solid. They should also be dynamic systems which, on the one hand, incorporate information generated by the integrated management system and, in addition, supply the information needed to define projects, activities and intervention in hydrographic basin areas.

We should also recognize that social participation is the most effective means of selecting the best path to follow in terms of conserving natural resources and guaranteeing their rational and democratic use. In order for this to happen, it is necessary for the social actors and agents in public office to actually be aware of the role that each one has to play. Guaranteeing and exercising social participation are difficult tasks that demand space and adequate mechanisms to ensure that: (i) water management is orientated towards collectively established guidelines and goals, and that (ii) projects based on user and community needs and priorities are economically efficient, socially effective and do not damage the environment.

To sum up, participatory and decentralized management of water resources happens when decisions are taken in collective forums, are appropriate for the specific situation, and the local associations and forms of political organisation, and the mechanisms for planning, negotiating and controlling these are duly applied. Decree-Law no. 45/94 of 22 February (also Law no. 58/2005 of 29 December) regulates planning processes for water resources and the subsequent elaboration and approval of plans which include projects for hydrographic basins, particularly with relation to international rivers.

The plan for the River Minho hydrographic basin was drawn up in compliance with the principles and objectives defined in this document, published as a Regulatory

Decree on 5 December 2001. Independent of any other factors, it is important to stress that the River Minho hydrographic basin possesses very specific features that affect the objectives of water resources planning in the basin and which are as follows:

– it is an international basin and 90% of its total area lies in Spanish territory;
– the River Minho never flows only in Portuguese territory but serves as a border between the two countries. Any *a priori* programme of water resources involving measures and actions based on the hydrographic basin of this river must therefore be carried out in conjunction with the situation on Spanish territory.

ENVIRONMENTAL IMPACT AND ASSOCIATED RISK FACTORS

The types of environmental impact which occur during the constructional phase of a large hydraulic venture are above all local and take place within a clearly defined period of time. Basically they are as follows:

(a) The provisional diverting of the river, to enable work to be carried out on the river bed.
(b) Access and transport of materials and equipment to the area where the work is being carried out.
(c) Areas affected by temporary buildings and deposits of essential or excess materials.
(d) Local quarries for the use and/or extraction of inert materials;
(e) The cutting down and clearing of vegetation in the area to be flooded.

During the operational phase of a large dam and its reservoir, the impact depends on the type of dam being constructed but:

(a) They alter the characteristics (the quality and quantity) of the water and sediment discharges;
(b) They affect the surface and ground hydrological systems.
(c) They produce alterations in geomorphological processes as a result of changes in fluvial dynamics.

It is important, however, to distinguish between the environmental repercussions caused by the construction and operation of a dam and those resulting from the appearance of a large reservoir. On the one hand, the presence of a large dam:

(a) alters the morphology of the alluvial beds;
(b) reduces the capacity for transporting flow;
(c) contributes towards increasing the already high levels of sedimentary deficit;
(d) contributes towards destabilising ecosystems or making them disappear;
(e) creates profound changes in local fauna and flora.

On the other hand, the presence of a reservoir:

(a) increases erosion and instability on the slopes of the banks by the action of winds, waves and currents;
(b) reduces the daily and annual thermal amplitudes;
(c) causes fog and mist, as well as alterations in local rainfall patterns;
(d) reduces the frequency of frosts.

Nature and the extent of the impact

The direct area of influence of a dam corresponds to the area that is to be flooded, which must be studied prior to the project being implemented, since it is one of the first environmental areas to be altered. The immediate impact of dam construction is registered there, as the result of a simple cause–effect relationship. The nature and distribution of the impact created in the indirect areas of influence of a dam has important and specific features that should also be considered:

- firstly, *spatial amplitude*, since this may extend far beyond the immediate area of a reservoir, both along the main bed and the tributaries, and possibly covering the whole of the hydrographic basin, so that it may therefore have an impact on a regional level;
- in relation to the *longitudinal profile* of the river and its tributaries, the impact extends from its source to the fluvial plain downstream of the dam and may reach the estuary and even the nearby coastal area;
- the *nature and sequence of the different types of impacts* are completely distinct according to geographical location, whether in the sector upstream of the reservoir, on the periphery of the reservoir, in the sector downstream of the reservoir or at the river mouth;
- the *type of dam and the way in which it will operate*, according to its purpose and the planned uses for the water stored there. The diversity and intensity of the impact may often be the result of the model and/or the way in which the dam is operated;
- the *time factor*, since these alterations may be observed immediately during construction, or in the medium or long term. In spatially distinct areas, both upstream and downstream, the impact will only occur in the medium and long term, since the effects are only felt much (i.e. years) later after the work has been completed;
- the impact occurs as a *chain reaction*, so that the initial physical impact unleashes a secondary impact, which in turn can create a third impact and so on, giving rise to new processes in the main river bed, the hydrographic basin and/or even altering already existing processes;
- the impact does not only affect the physical environment but also the *human and biotic environment*. As the indirect product of different types of physical impacts, new sequences of anthropic (social and economic) and biotic impacts are generated.

Regarding the effects on the human environment, it is important to distinguish between the population directly affected by negative impact, in particular those inhabiting the area surrounding the reservoir and the flood plain, compared to those who live further away from the hydrographic basin and are more likely to benefit. We may quote, as an example, the use of water to supply cities and to generate electricity. In terms of the specific objectives of this study, we will now focus only on the hydrological, sedimentological and geomorphological impacts in the segment of the river that lies downstream of the dam/reservoir (system).

Potential hydrological impacts downstream of dams

The hydrological characteristics of a river control channel dynamics. These include rate of flow, variability of discharge (on a time scale that may range from minutes to weeks) and frequency of discharge lifted, and they exert important controls over the physical and also the chemical and biological conditions of the river.

However, when the hydrological system of a river is altered by the construction of a dam, alterations downstream are generally caused by the way in which the dam operates, both as a consequence of the way it controls and regulates discharge and also due to the reduction/alteration in seasonal variability and heavy discharges, as well as modifications to the characteristics of the water and solid effluents generated in the dam which feed the segment of the river downstream.

The environmental impact may also extend to the alluvial plain, affecting the ground hydrological system, since with a reduction in the water discharge there will be modifications to the piezometric level, which in turn implies alterations to the rate at which the water infiltrates the soil.

Risks associated with the construction and operation of large dams

According to the *Regulamento Português de Segurança de Barragens* (Portuguese Safety Regulations for Dams—Decree-Law no. 11/90, of 6 January), which "has as its objective the security of dams during the phases of planning, construction, initial filling, operation and abandonment", a large dam is considered to be one which is higher than 15 m, or lower but with a reservoir that has a capacity of over 0.10×10^6 m^3.

These regulations contain certain definitions and it is important, as part of this study, to highlight the notion of "*accident*—an exceptional occurrence relating to the behaviour of a dam whose uncontrolled evolution is liable to lead to a rupture in one or more of the structural components and may create a flood wave" and "*scenarios*—situations which must be investigated in order to assess the security of the work and which can be classified into two categories, according to whether the structures are being used normally (current scenarios) or are associated with exceptional events (dam break scenarios). Turning to an analysis of ruptures in dams identified in the bibliography, it has been possible to create the graphs presented in Figs 1 and 2 (Amado Mendes, 1996) which show the number of breaks by type and by age of dam, respectively.

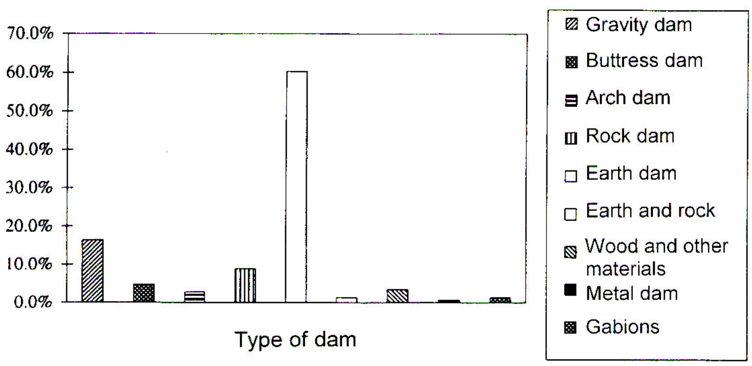


Fig. 1 Distribution of dam breaks by type (Amado Mendes, 1996).

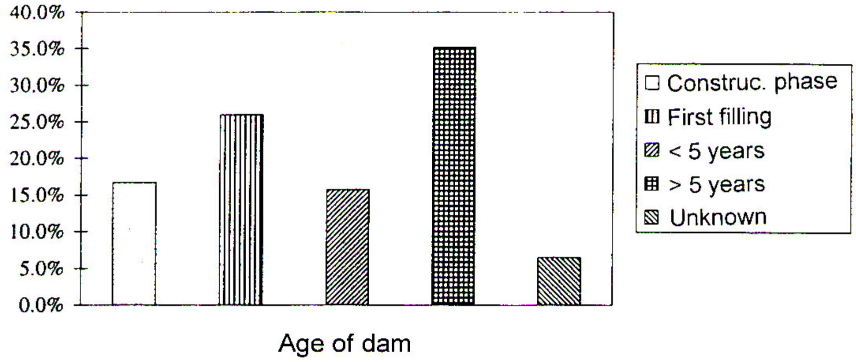


Fig. 2 Distribution of dam breaks by age (Amado Mendes, 1996).

It can therefore be seen that the greatest number of dam breaks occur in embankment dams (earth and rock) [>60%], gravity dams [≈18%] and rock dams [≈10%]. Moreover, it can be seen that the safest period for a dam is between 10 and around 60 years. From the construction phase to a little after the initial filling is the most critical time; during this time and up to 5–8 years after construction, around 90% of dam breaks occur, particularly in embankment (earth and rock) dams, at a rate of around 70%.

THE REACTION OF THE FLUVIAL SYSTEM TO ALTERATIONS IN MORPHODYNAMIC PROCESSES

Throughout the world, the morphology of fluvial systems has been dramatically altered by man's actions. 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 course of a river, the morphology of the alluvial bed is adjusted according to the amount of sediment in transit and the flow system, and is only modified by local conditions. 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):

$$Q_s * D_n \propto Q * i \qquad (1)$$

in which Q_s represents the total sediment transport; D_n represents the characteristic diameter of the solid material transported (normally $D_n \cong D_{50}$, this being the median diameter, since 50% of the material is finer); Q is the water flow and i represents the average slope of the thalweg.

Equation (1) represents the tendency of four variables to establish a natural balance. Any alteration to any one of them implies an imbalance in the system and a new balance will tend to establish itself in time, with necessary contributions from one (or more) of the remaining variables.

On the basis of this expression we may therefore forecast the qualitative responses of a fluvial system to natural modifications or alterations imposed on the morphodynamic processes. To understand this type of analysis better, let us turn to some examples of concrete situations, namely:

- the reaction of the alluvial bed to the building of a dam;
- the reaction of the alluvial bed to a reduction in sediment transport;
- the reaction of the alluvial bed to a localised lowering of its base level;
- the reaction of the fluvial system to a lowering of the base level of the free surface of the main water course;
- the reaction of the fluvial system to the raising of the base level of the free surface of the main water course.

The reaction of the alluvial bed to the building 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 in the average slope of the river bed, *i*, downstream of the dam, in the proportions: $Q_s^- * D_n \propto Q * i^-$. As shown in Fig. 3, the initial profile downstream of the dam CA will tend to erode until hypothetically it achieves the profile C'A, which, in turn, will revert to profile CA if more solid material is available, which may occur after the filling of the reservoir with sediments has been completed.

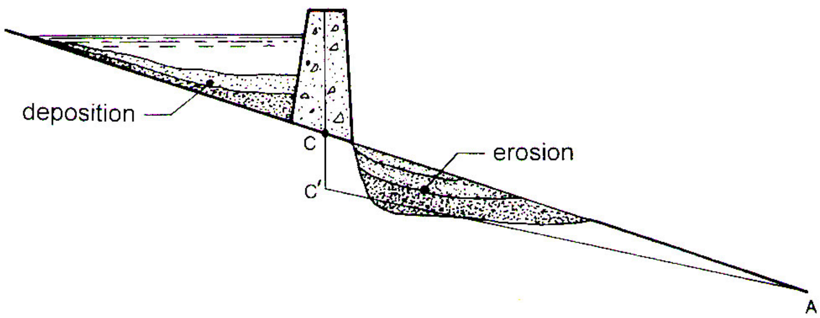


Fig. 3 Reaction of the alluvial bed to the construction of a dam (Cardoso, 1998).

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 sector downstream of the dam, significant effects will be felt on the channel processes. In fact, erosion of the river bed and banks of the channel 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 consequence of the lowering of the alluvial bed downstream of the dam:

(i) there may be regressive erosion in the tributaries in the area;
(ii) there may be damage to bridges and support walls along the banks due to excavation beneath their foundations;
(iii) water collection works in the river may be put out of action.

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, the water discharge and the quality of the water, and are all directly linked to the effluent flow of the dam;
– changes of the 2nd order, which are alterations to the form of the channel, the composition of the substratum, the macrophyte population, etc.;
– changes of the 3rd order, which are alterations to the fish and invertebrate populations.

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

The reaction of the alluvial bed to a reduction in sediment transport

Let the affluent which under natural conditions discharges into the bed of the main water course be a solid discharge, Q_S. Due to human intervention, this solid discharge is significantly reduced and becomes Q_S^-. As the values of the water discharge in the main water course and the diameter of the base material remain unaltered, the average slope of the bed of the main water course 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 Fig. 4, in which A represents a fixed point.

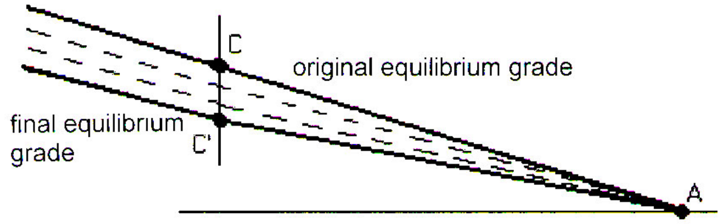
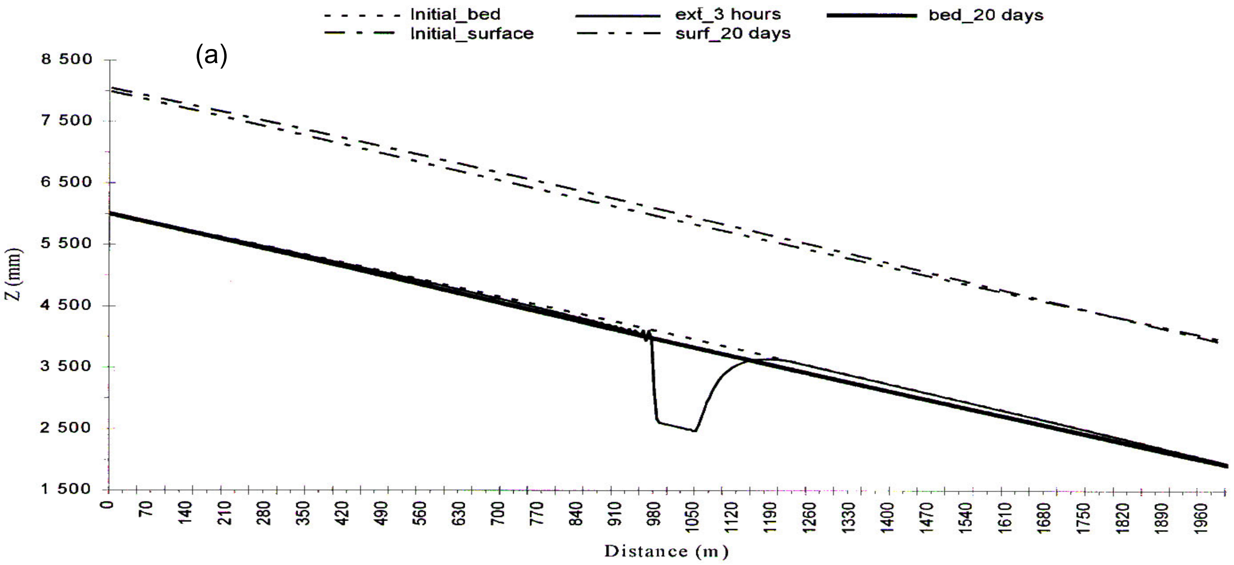


Fig. 4 Behaviour of the alluvial bed in the event of a reduction in sediment transport.

Consequently, occurrences of this type may have similar implications to those previously quoted.

The reaction of the alluvial bed to a localized lowering of its base level

This situation creates a reduction in the average slope of the bed downstream of the affected area, which changes from *i* to $\bar{i}$. Consequently, it will behave identically to the situation described in the previous point or, in other words, in the surrounding area there will eventually be a general reduction in the slope downstream and general rise upstream. Fig. 5 illustrates this.



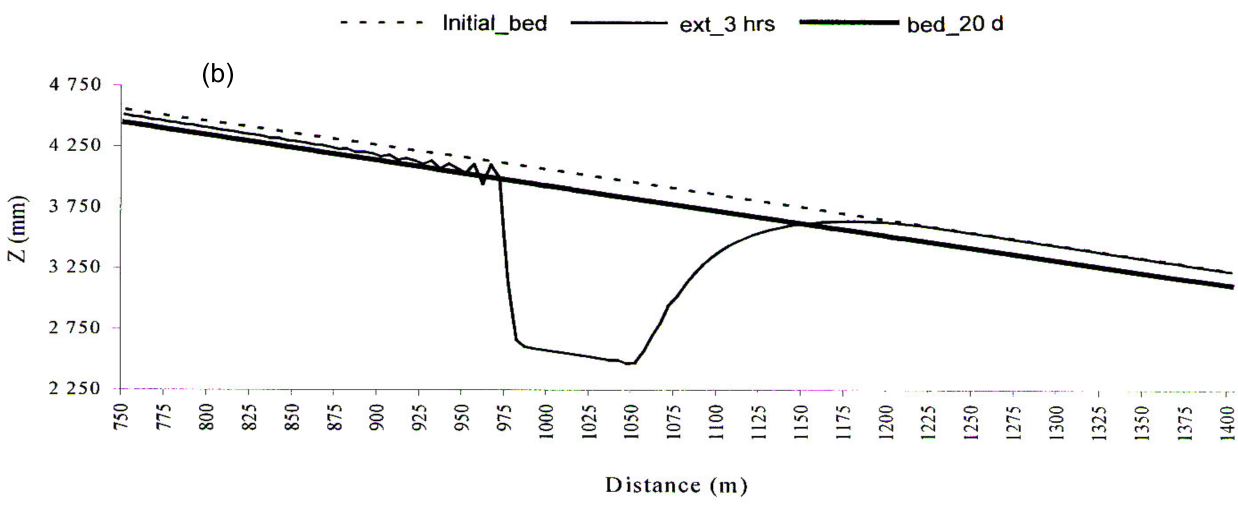


Fig. 5 Behaviour of alluvial bed in the event of localised lowering of its base level (Antunes do Carmo, 2001). (a) Configurations of the initial bed (in a uniform system), 3 hours after extraction of inert material and 20 days after. (b) Increase in section at between 750 m and 1400 m.

The numerical simulation shown in this figure is based on a situation in which there is a uniform system, so it therefore deals with the configurations of a natural balance modified by human intervention. In an initial instance, the extraction of inert material from the river bed was simulated over an area of 100 m (950 m to 1050 m of the section represented) that was 1.50 m deep. The daily evolution of the river was analysed for a period of 20 days, and the two extreme points (borders) were considered fixed.

The initial configurations and those after 3 hours and after 20 days of the simulation are represented in Fig. 5(a),(b), with the latter displaying an extension of the section from between 750 m and 1400 m. As expected, there is general erosion both upstream and downstream of the affected area.

The reaction of the fluvial system to a lowering of the base level of the free surface of the main water course

This situation may occur as a result of any of the previous situations, giving rise to general erosion and creating a lowering of the base levels of the tributaries. The situation is clearly illustrated in Fig. 6.

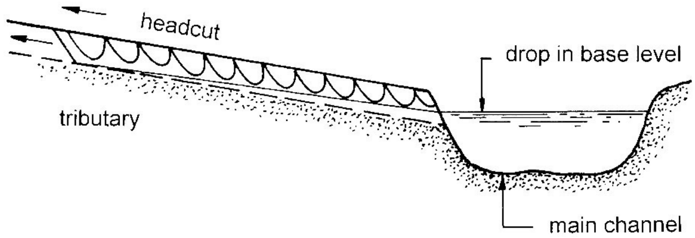


Fig. 6 Effect on a tributary caused by the lowering of the base level of the free surface of the main water course (Simons & Sentürk, 1976).

The reaction of the fluvial system to the raising of the base level of the free surface of the main water course

This may occur as a result of the first two situations, giving rise to generalized deposits that cause elevations in the base levels of tributaries and reduce their ability to transport, thus creating generally undesirable flood conditions. Figure 7 illustrates this situation.

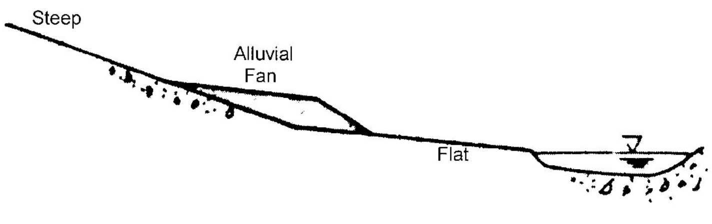


Fig. 7 Effect on tributary caused by the raising of the base level of the free surface of the main water course (Simons & Sentürk, 1976).

CONCLUSIONS

The building and operating of a large dam and its reservoir has an important direct and indirect environmental impact, which demands serious analysis. The balance between the resulting types of environmental impact and the risk factors associated with a possible dam break due to an exceptional event, such as an earthquake or part of the reservoir bank collapsing, may or may not justify the venture.

Although the probability of a dam breaking is very slight, even in global terms (in the order of $4–7 \times 10^{-4}$), 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 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;
- it is recognized 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).

In relation to the extraction of inert material in river environments, it is suggested that both 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 topographic survey that is valid for the area upstream and downstream of the project and not just for the immediate area affected; (ii) verification of the maximum figures for diversions given in estimates for the purpose of requesting/renewing licences.

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