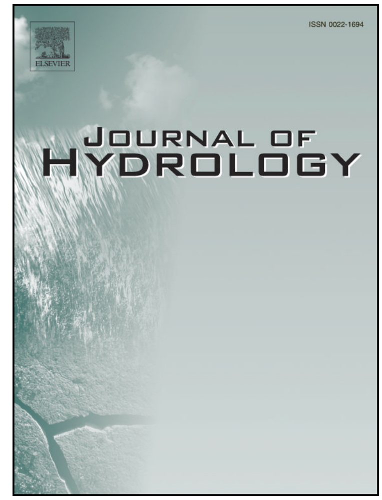


On Resuspension and Control of Reservoir Sediments by Surface Waves and Point Absorbers.

Francisco J. Arias

PII: S0022-1694(18)30568-7
DOI: https://doi.org/10.1016/j.jhydrol.2018.07.054
Reference: HYDROL 22986

To appear in: *Journal of Hydrology*

Received Date: 24 December 2017
Revised Date: 15 June 2018
Accepted Date: 20 July 2018

On Resuspension and Control of Reservoir Sediments by Surface Waves and Point Absorbers.

Francisco J. Arias

Department of Fluid Mechanics, Polytechnic University of Catalonia, ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

Abstract

Consideration is given to a novel approach for resuspension and control of sediment in reservoirs which nowadays and after more than six decades of research remains as the most serious technical problem faced by dam industry. Here, it is proposed the generation of mild surface waves in the reservoir which -because the physical nature of the waves, will spread throughout the reservoir. Then, by using a farm of point absorbers -or technology akin as used in ocean energy conversion, the energy transported by the waves can be transformed into a continuous injection of water flow in the riverbeds balancing the gravitational settling and then in the resuspension and control of sediment settlement. Utilizing a simplified physical model an estimation of the area of riverbed covered in comparison with the area of point absorber needed was derived as function of several parameters. Methods for wave generation were briefly discussed and Computational Fluid Dynamics (CFDs) simulations performed being in good agreement with the theoretical estimations. The proposed concept is presented as a promising alternative technique which can contribute to mitigate the serious global problem of land loss in the river deltas as well as increasing the storable capability and life of large dams.

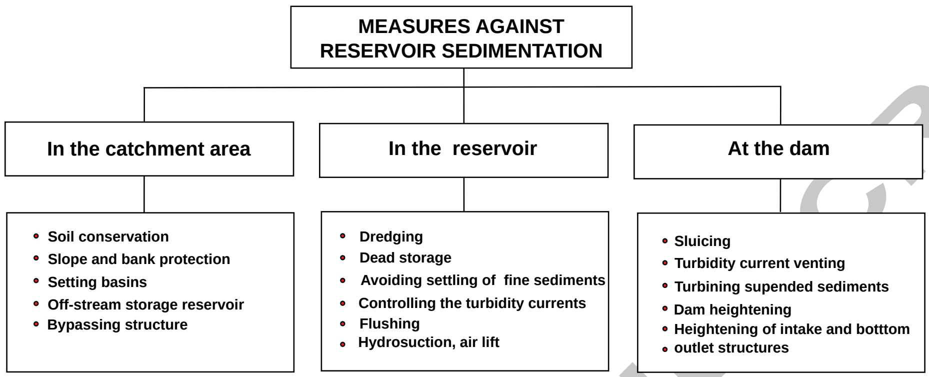
Keywords: Riverbed, Resuspension, Dams, Loss of river deltas

1. Introduction

When a river is stilled behind a dam, the sediments it contains sink to the bottom of the reservoir. The amount of a rivers total sediment load captured by a dam -generally known as its "trap efficiency" -approaches 100 per cent for many projects, especially those with large reservoirs. As the sediments accumulate in the reservoir, there are two serious problems, namely: On one hand, the dam gradually loses its ability to store water and then imposing a serious threat to the sustainability of hydropower by affecting the safety of the dam, reducing its energy production, storage, discharge capacity and flood attenuation capabilities and thus being the life of a reservoir usually limited by sediment accumulation, and on the other hand dams completely change the relationship of water and land with the obstruction of the transport of sediments downward putting in danger the survival of the river deltas. After more than six decades of extensive research in several aspects, [1]-[7], including modern forecasting techniques, [8]-[13], there is limited guidance on how best to address the problem. Today management options available for dealing with sediment problems could be classified into 3 groups of measures for countering reservoir sedimentation as is illustrated in Table. I, [14]- [15]. Nevertheless all these measures, can be observed much more as strategies for managing reservoir sedimentation,[16] rather than technological approaches, and as such, they are of limited application with age specific dependency the specific geometry of the reservoir, climate, as well as its capacity, [17]. Nowadays, sedimentation is still probably the most serious technical threat faced by the dam industry, for example, a recent estimate indicates that the global reservoir storage capacity would be half-loss by 2100, [18]. For those readers interested in the history and politics aspects of the dam problem, the book by McCully (2001), [21] is recommended, and an up to date review in sediment management can be found in Kondolf et.al, (2014), [17].

However, without doubt, the larger concern on trapping of sediment by large dams is on the drastic environmental impact caused which have become so con-

Table 1: Measures for countering reservoir sedimentation, [15]



troversial. For the sake of illustration of the severity of the problem, let us consider two cases for two different continents. The Ebro Delta -in Catalonia, Spain, is a wetland of international importance, and is considered one of the coastal systems most vulnerable to climate change in the European Union. The Delta is currently undergoing a loss of wetlands and rice paddies because of coastal regression, caused by diminishing fluvial sediments which are retained in the reservoirs of the basin. The coast is retreating by more than 10 meters per year in the mouth of the delta, where 150 hectares of wetland were lost between 1957 and 2000. The problem is accentuated by the decline in the elevation of the delta. About half of the delta (15000 ha) could be affected by this phenomenon during 21 st century.
In China, in the Mekong River basin, largely undeveloped before 1990, 140 dams are built, under construction, or planned, [19],[17], and a systematic analysis of sediment trapping by the planned dams indicates that full completion of these 140 dams would result in a 96% reduction in sediment load to the Mekong Delta, i.e., the Delta would receive only 4% of its natural sediment load.

The search for innovative engineering methods has led the department of

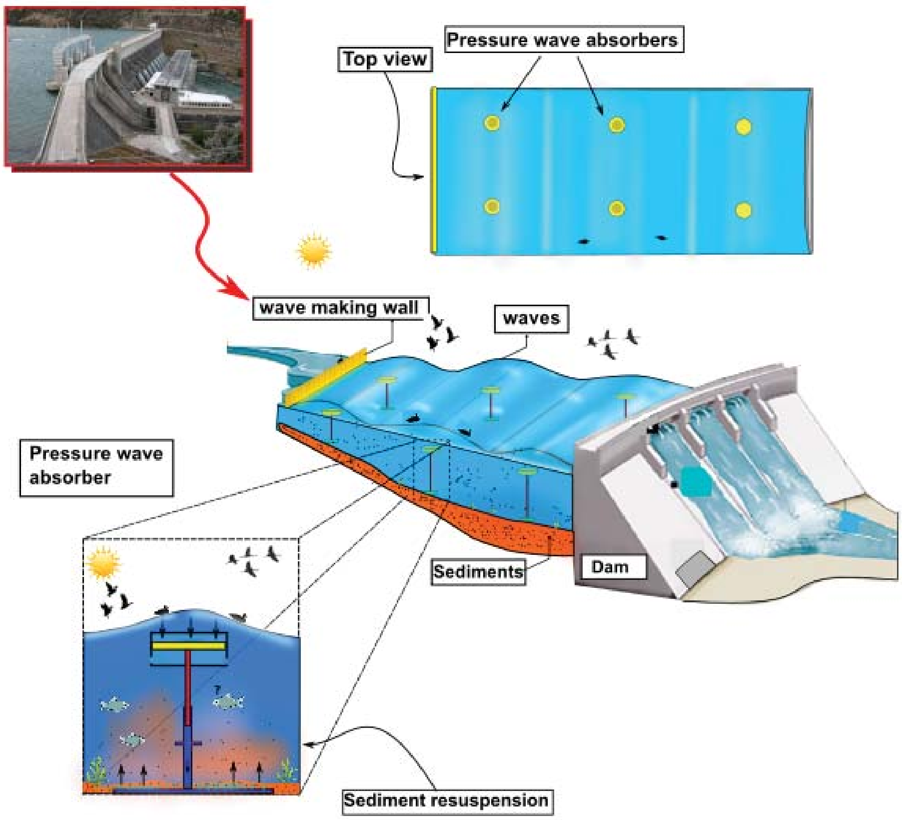


Figure 1: Wave generation and farm of point absorbers (PAs) in the reservoir for resuspension of sediments. The oscillatory energy of the wave at the surface of the reservoir is converted by the PAs into a continuous supply of water flow which is able to resuspend the riverbed sediments.

fluid mechanics at the University Polytechnic of Catalonia (UPC) within the framework of the European project LIFE-EBRO-ADMICLIM (*Adaptation and Mitigation Measures to Climate Change in the Ebro Delta*),[22] to develop a novel solution for the resuspension and control of reservoir sediments in dams.

The core idea is the generation of mild surface waves in the reservoir which -because the physical nature of the waves, will spread throughout the reservoir and then, by using a farm of point absorbers -or technology akin as used today in ocean energy conversion, the energy transported by the waves can be transformed into a continuous injection of water flow in the riverbeds balancing the gravitational settling and then in the resuspension and control of sediments.

2. Methods

Having defined our conceptual framework, we will proceed with a first theoretical treatment of the proposed technique.
To begin with, let us consider Fig. 1 where it is shown the schematics of the core idea here discussed. In this Figure, a conventional reservoir where sediments are accumulated in the riverbed, mild waves are deliberately created on the surface of the reservoir by a proper wave-generator. At this point, let us do not worry about the wave-generator, we will address this issue in the last part of the manuscript. For the moment, let us say that waves are continuously generated and spreading throughout the surface of the reservoir.

Now, as is depicted in the same figure, a farm of Point Absorbers (PAs) is placed. In brief, a PA is just a device which can be a floating structure that heave up and down on the surface of the water or submerged below the surface relying on pressure differential as is sketched in Fig. 2 where some part of the PA structure acts like a piston to pressure changes caused by the passage of the wave.

2.1. Theoretical calculations

Bearing in mind the above idea, we will proceed with some preliminary calculations to asses the feasibility for resuspension and control of sediments by

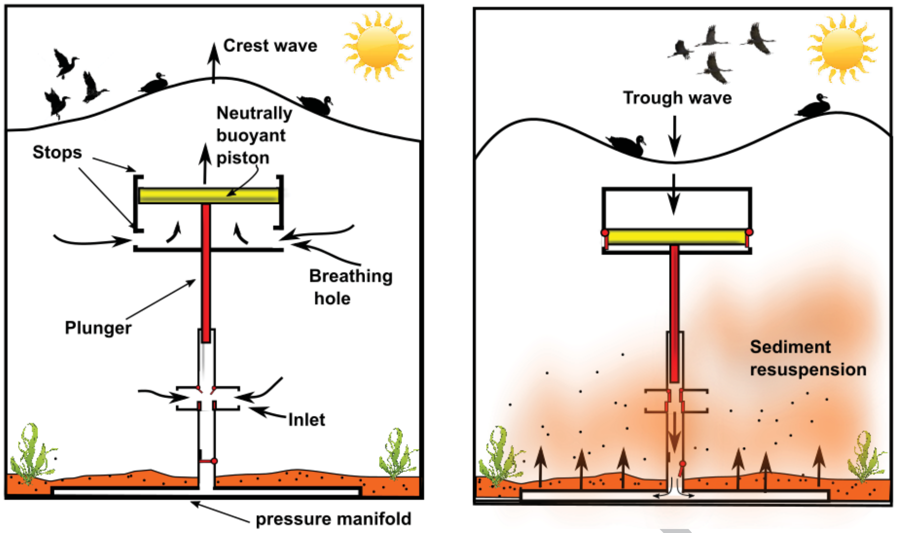


Figure 2: A kind of point absorber (PA).

hydrodynamic pumping of water by the PAs.

First of all, we need to asses the minimum upwards velocity of the water flow pumped by the PAs, u_u, required to propel vertically the sediment from the riverbed. The precise calculation of this velocity encompass a certain complexity owing to the number of parameters involved. Nevertheless, some lower limit for this velocity can be inferred theoretically as follows.

First, the riverbed sediment may be assimilated as a packed bed, [25], and then before being lifted by the water flow pumped by the PAs it is must be *fluidized* or in other words converted from a granular material from a static solid-like state to a dynamic fluid-like state. This process occurs when a fluid (liquid or gas) is passed up through the granular material which is the case that concern us, where the water flow is introduced through the bottom of the riverbed via the empty spaces between the particles. At low water velocities, aerodynamic drag on each particle is also low, and thus the sediment bed remains in a fixed state. Increasing the velocity, the aerodynamic drag forces will begin to counteract the gravitational forces, causing the bed to expand in volume as the particles of sediment move away from each other. Further increasing the velocity, it will reach a critical value at which the upward drag forces will exactly equal the downward gravitational forces, causing the particles of sediment to become suspended within the fluid. This process is which we call as *fluidization*.

Then, a lower limit for the required velocity to resuspend the sediment is the minimum *fluidizing velocity* u_{mf}. This velocity is given by, [26]

$$u_{mf} = \left[\frac{d_p(\rho_s - \rho) g \varepsilon_{mf}^3 \phi_s}{1.75\rho} \right]^{\frac{1}{2}} \tag{1}$$

where d_p and ϕ_s are the diameter and sphericity of particle ($\phi = 1$ for spheres and $0 < \phi < 1$ for all other particle shapes), respectively., ρ_s and ε_{mf} the density and fractional voidage (void fraction) of the packed bed, respectively., g is gravity., and ρ the density of water.

However, even if the velocity of the water flow is enough to propel vertically and resuspend the sediment, doesn't implies that there will be not an accumulation of sediment because the gravitational continuous settling down of the sediment acting in the opposite direction. In order to prevent accumulation of sediment in the river bed, it is necessary that the upward mass flow of sediment (driven by the flow of water pumped by the PAs) be at least equal or higher than the downward mass flow of sediment falling by gravity, which according with Fig. 3 may be expressed as

$$n_u \bar{u}_u A_d = n_d u_d A_d \tag{2}$$

where n_u and n_d are the number of particles per unit of volume crossing the packed bed up and down, respectively., A_d the cross section area of the riverbed parcel, u_d the downward velocity of the sediment, which is the gravitational terminal velocity u_t of the particles; and $\bar{u}_u$ is the upward *time-averaged velocity* induced by the surface wave motion. Because it is desired a homogeneous distribution of the sediments and then avoiding *uncovered riverbed spots*, then $n_u \approx n_d$, otherwise, if $n_u \neq n_d$ and even accomplishing the mass balance from

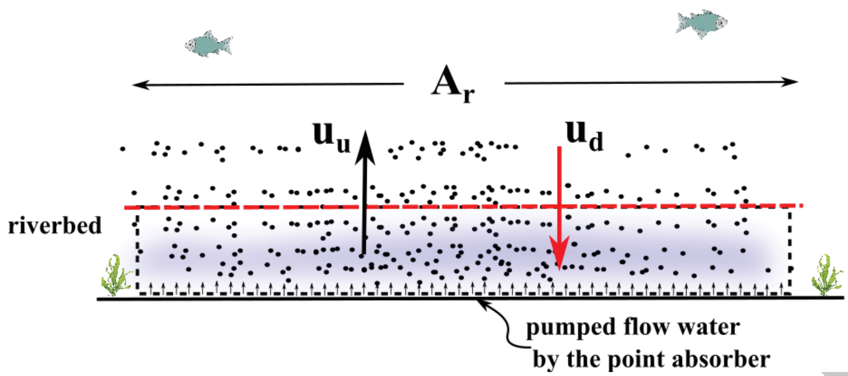


Figure 3: Sediment riverbed model.

Eq.(2) there will be a pilling up of sediments (spots empty of sediments and mounds of sediments). Therefore Eq.(2) simplifies as

$$\bar{u}_u \approx u_t \tag{3}$$

The terminal velocity of the particle of sediment can be estimated by the well-known expression,

$$u_t = \left[\frac{4d_p(\rho_s - \rho)g\phi_s}{3\rho C_D}\right]^{\frac{1}{2}} \tag{4}$$

where C_D is the drag coefficient.

Therefore, the minimum velocity of the water flow pumped by the PAs should be the higher velocity between that given by Eq.(1) and that given by Eq.(4). By dividing both equations one obtains

$$\frac{u_t}{u_{mf}} = \left[\frac{7}{3C_D\varepsilon_{mf}^3}\right]^{\frac{1}{2}} \tag{5}$$

The draw coefficient, has been determined experimentally and gives,

$$C_D = \frac{24}{Re_p}\left[1 + (8.171e^{-4.0655\phi_s})Re_p^{0.0964+0.5565\phi_s}\right]$$

$$+\frac{73.69(e^{-5.0748\phi_s}Re_p}{Re_p + 5.37e^{6.21222\phi_s}} \tag{6}$$

where Re_p is the particle Reynolds number, $Re_p = \frac{d_p u_t \rho}{\mu}$, and μ the dynamic viscosity.

For low Reynolds numbers $1.0 < Re_p < 100$ as is expected in the settling down of particles in a stilled reservoir at the riverbed, thus Eq.(6) simplifies to

$$C_D \approx \frac{24}{Re_p} \tag{7}$$

with $1 < C_D < 100$. Therefore, considering Eq.(5), it is easy to see, that even considering a very improbable hypothetical compact regular packing bed with a theoretical packing factor of $\varepsilon_{mf} = 0.7405$ we have $u_t > u_{mf}$ and then, for sediment resuspension and control is the terminal velocity which must be considered as the minimum limit of velocity in which water flow must be pumped by the PAs.

Finally, it is interesting to note that for the case when gravitational settling want to be avoided and then preventing the growth of an already existent bed of sediments, then the drag force from the jet flow of water must exactly balance the downwards buoyancy force acting on the particle i.e.,

$$\frac{\pi d_p^2 \phi_s^2 C_D \rho u_u^2}{8} = \frac{\pi d_p^3 \phi_s^3 g(\rho_p - \rho)}{6} \tag{8}$$

and then

$$u_u = \left[\frac{4 d_p(\rho_s - \rho) g \phi_s}{3 \rho C_D}\right]^{\frac{1}{2}} \tag{9}$$

which is the same terminal velocity as calculated in Eq.(4). Therefore, it seems that either for resuspension and control of a bed of sediments or for preventing the growth of an already existent bed of sediments, the terminal velocity of the particle is the determinant velocity.

2.2. The resuspension efficiency of the PAs

Once we have a first estimate of the required velocity to avoid sedimentation in the riverbed, we need to estimate the efficiency or the *profitability* of the PAs. Although there are a number of ways in which profitability may be defined,

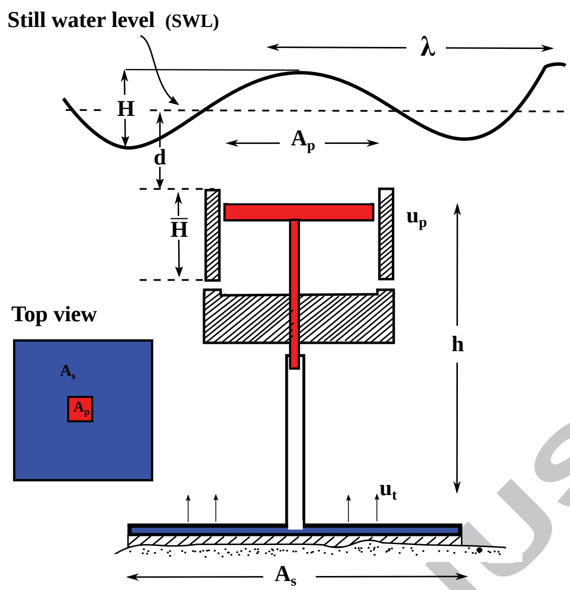


Figure 4: Schematics for the calculation of the profitability of the point absorber.

however a simple way is perhaps, by defining a profitability factor Γ of the PAs as the ratio between the effective area of the riverbed A_s -which is lifted by the flow water pumped by a PA, and the area of PAs A_p. With this definition we will have some idea of the number of PAs required per area of reservoir. Consequently we have

$$\Gamma = \frac{A_s}{A_p} \tag{10}$$

where A_s and A_p are the area of the riverbed and the PA, respectively., as depicted in Fig. 4.

This ratio can be found by considering a mass balance as

$$A_p \bar{u}_w = A_s u_t \tag{11}$$

where $\bar{u}_w$ is the vertical *time-averaged velocity* induced by the surface wave motion of the water column of the PAs. On the other hand, the motion of the PAs is directly related with the wave motion as, [28]

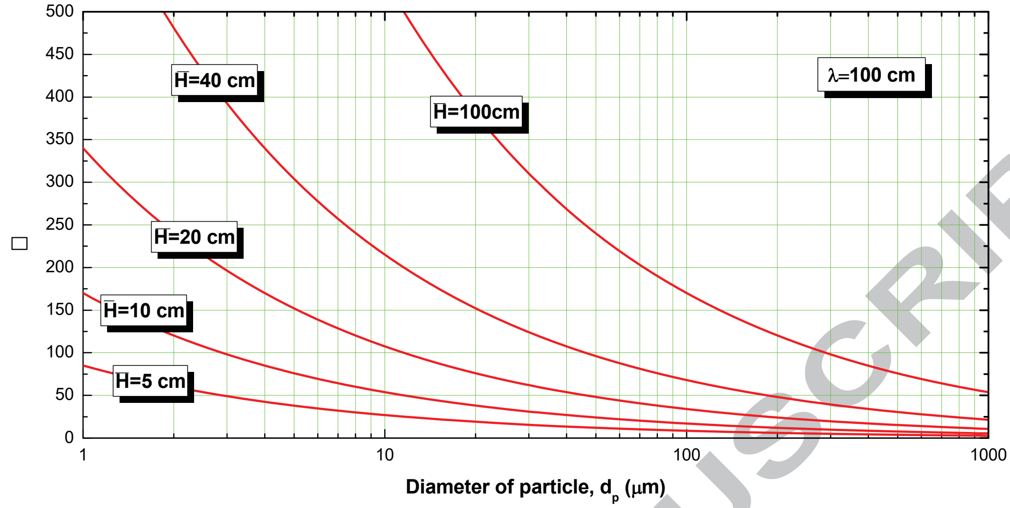


Figure 5: The profitable ratio Γ as function of the diameter of particle sediment and several possible values of the wave amplitude for a wavelength $\lambda = 100$ cm.

$$u_w = \frac{\omega \bar{H}}{2} \sin \omega t \tag{12}$$

where ω is the water wave frequency and $\bar{H}$ is the average vertical displacement. This displacement is normally greater that the double amplitude of the wave, [28], so for preliminary calculations, let us consider that is exactly the same. From Eq.(12), the average velocity $\bar{u}_w$ yields

$$\bar{u}_w = \frac{\omega \bar{H}}{2\pi} \tag{13}$$

Thus, taking into account Eq.(4) and Eq.(12) into Eq.(11), and considering that $\omega = \frac{2\pi}{T}$ being T the wave period, the profitability becomes

$$\Gamma = \frac{\bar{H}}{T} \left[\frac{3\rho C_D}{4 d_p (\rho_s - \rho) g \phi_s} \right]^{\frac{1}{2}} \tag{14}$$

for large dams the water depth of the reservoir, h, is much larger than the expected wavelength of the wave λ and then the approximation of *deep water* when $\frac{h}{\lambda} \geq \frac{1}{2}$ can be used, [28]. In this approximation, the wave period may be expressed as function of the wavelength as

$$\lambda = \frac{gT^2}{2\pi} \tag{15}$$

and then, Eq.(14) may be rewritten as

$$\Gamma = \bar{H}\left[\frac{3\rho C_D}{8\pi d_p(\rho_s - \rho)\phi_s \lambda}\right]^{\frac{1}{2}} \tag{16}$$

- **Discussion**

To obtain some idea of the shape of the curves predicted by Eq.(16), we assume some typical values of the parameters: $\rho = 10^3$ kg/(m^3); $C_D = 50$; $\rho_s = 3 \times 10^3$ kg/(m^3); $g = 9.8$ m/(s^2) and assuming a sphericity of the particles of $\phi = 1$. The resulting curves are shown in Fig. 5 and Fig. 6 for $\lambda = 100$ cm and $\lambda = 200$ cm, respectively. From these figures, it is seen that technique has merit to be considered. For example, for a stilled river, with sediment particles around 10 μm, and considering a modest wave with an amplitude around $H = 10$ cm, the area of riverbed covered by the PA could be around 50 times its own area, or conversely, a reservoir could be controlled by the use of PAs covering a 1/50th area of the reservoir. For larger amplitudes as $\bar{H} = 20$ cm, the profitability is around 75 times, or thereabouts.

2.3. Shallow waters

If the water depth is not large enough, for example under very shallow waters -e.g., at reservoir upstream areas, the use of PAs is difficult. Nevertheless for these cases PAs actually are not necessary and the situation is much more simple. In fact, the use of PAs in the preceding sections for *deep waters* was necessary because the profile velocity at the bottom of the reservoir induced by the surface wave motion is negligible and then it was necessary a PAs or akin technology to *transmit* the motion from the surface to the bottom of the reservoir. However, for *shallow waters* the velocity at the bottom of the reservoir induced by the wave at the surface can be large enough and then PAs are not

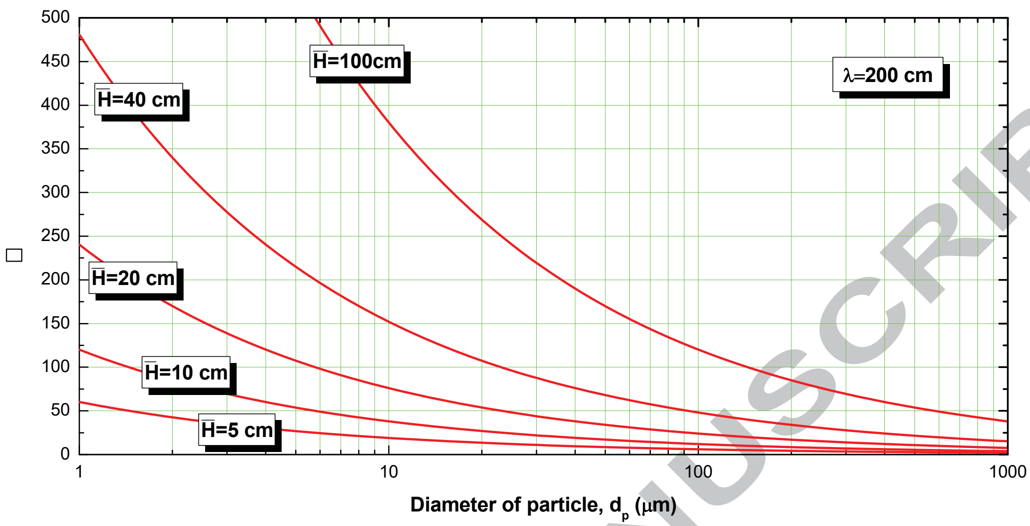


Figure 6: The profitable ratio Γ as function of the diameter of particle sediment and several possible values of the wave amplitude for a wavelength $\lambda = 200$ cm.

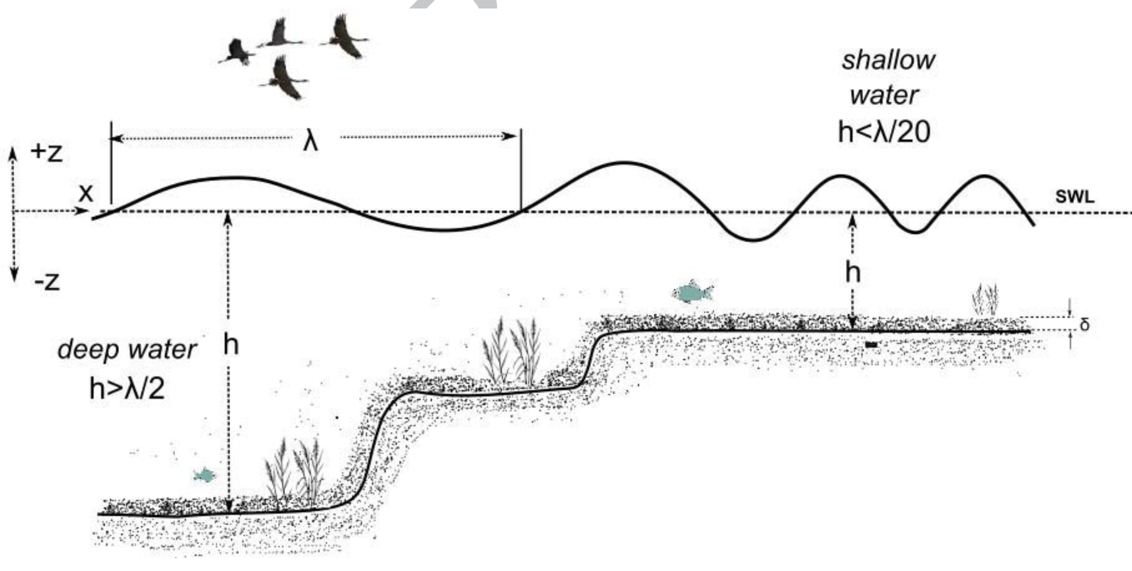


Figure 7: Wave profile for the condition of deep water, $h \geq \frac{\lambda}{2}$, and shallow water $h \leq \frac{\lambda}{20}$.

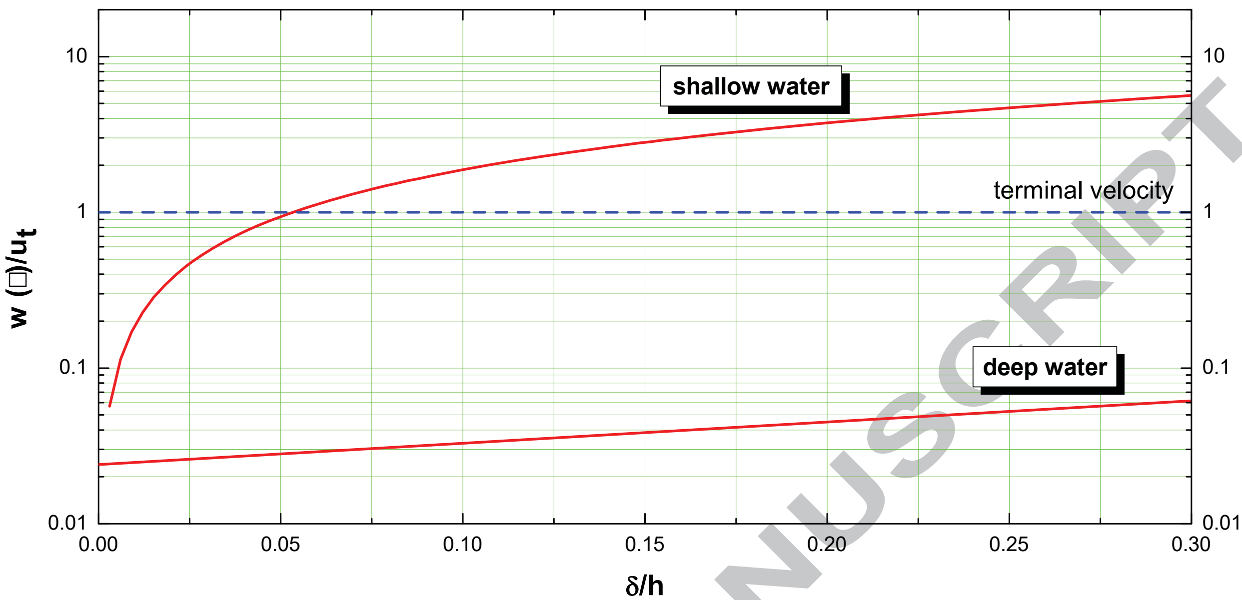


Figure 8: The ratio of the velocity at the bed and the terminal velocity $\frac{w(\delta)}{u_t}$ for *deep water* and *shallow water* as function of the thickness of the bed $\frac{\delta}{h}$ for a passing wave at the surface with $\lambda = 2$ m and $H = 0.2$ m.

longer necessary.

To see this, let us compare the vertical velocity component of a wave at a given position using the *deep water* ($\frac{h}{\lambda} \geq \frac{1}{2}$) and the *shallow water*($\frac{h}{\lambda} < \frac{1}{20}$)) approximation,[28], which are given by

$$w = \pi H \left[\frac{g}{2\pi\lambda}\right]^{\frac{1}{2}} e^{\frac{2\pi z}{\lambda}} \sin(\omega t) \qquad deep \quad water$$

$$w = \pi H \left[\frac{g}{\lambda}\right]^{\frac{1}{2}} \left[\frac{h}{\lambda}\right]^{\frac{1}{2}} \frac{(z+h)}{h} \sin(\omega t) \qquad shallow \quad water \qquad (17)$$

where h is, as before, the water depth; z is the upwards vertical coordinate (negative in the downward direction as shown in Fig. 7). Thus the velocity at the bed with a thickness δ transmitted by the passing of waves at the surface of the reservoir is given by taking $z = -h + \sigma$ (see Fig. 7) yielding

$$w(\delta) = \pi H \left[\frac{g}{2\pi\lambda}\right]^{\frac{1}{2}} e^{-\frac{2\pi h}{\lambda}} e^{\frac{2\pi\delta}{\lambda}} \sin(\omega t) \qquad deep \quad water$$

$$w(\delta) = \pi H \left[\frac{g}{\lambda}\right]^{\frac{1}{2}} \left[\frac{h}{\lambda}\right]^{\frac{1}{2}} \left[\frac{\delta}{h}\right] \sin(\omega t) \qquad shallow \quad water \qquad (18)$$

Fig. 8 shows the ratio of velocity at the bed and the terminal velocity $\frac{w(\delta)}{u_t}$ for *deep water* and *shallow water* calculated from Eq.(18) for a wave with $\lambda = 2$ m and $H = 0.2$ m as function of the thickness of the bed. It is seen that whereas the use of PAs for *deep water* is required, nevertheless for *shallow waters* are not necessary.

With regard the wave generation in *shallow waters*, it could be used the same *wave generators* than for *deep waters* taking advantage of the gain in amplitude H and wavelength when a wave is passing from a *deep water* to a *shallow water* as is depicted in Fig. 7. The dimensionless wave properties as functions of the depth to deep water wavelength ratio as predicted by linear theory is given in Fig. 9, [28], and in Fig. 10 is plotted the same as Fig. 8 but taking into account the variation of wavelength and amplitude from a *deep water* to a *shallow water*.

Therefore, waves could be generated in deliberated ditches where once generated will propagate though the shallow waters much more as depicted in Fig. 7

2.4. Wave generation

In previous section it was assumed that at the surface of the reservoir waves were constantly generated and neglecting how these were actually generated. It was shown, however, that with small wave amplitudes it is possible resuspension and control of the sedimentation in the riverbed using a reasonable discreet number of PAs (see Fig. 5 and Fig. 6). In this section we will discuss how these waves can be generated.

The problem of generation of waves actually had been resolved long ago. Effectively, the methods for wave generation are identical than those used in ocean wave energy conversion industry with the only difference in the application. In fact, in ocean wave conversion it is desired to convert a given ocean wave into an electrical output by the use of the converter,[28], and here, we

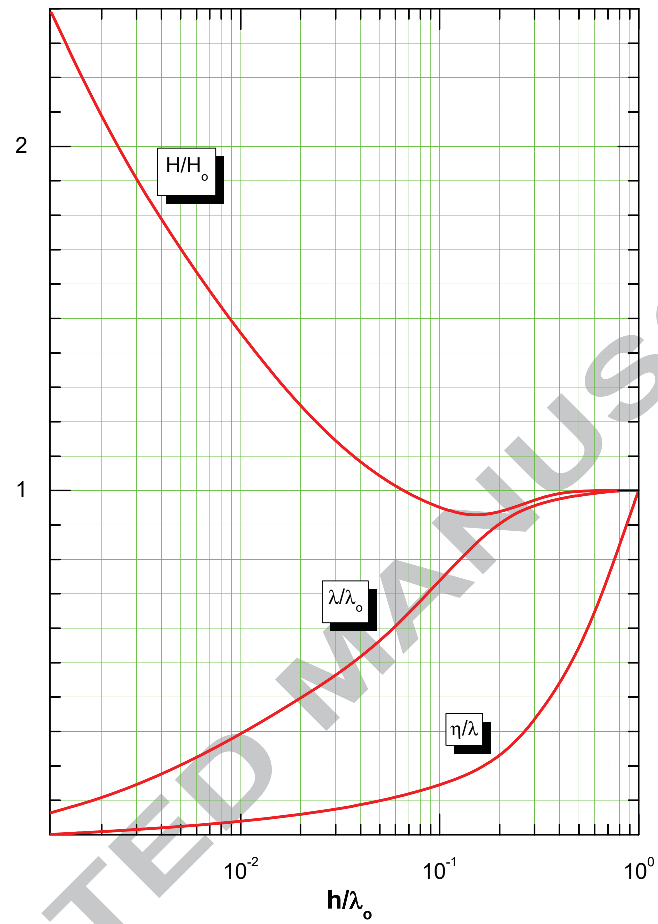


Figure 9: Properties as functions of the depth to deep water wavelength ratio as predicted by linear theory, [28]

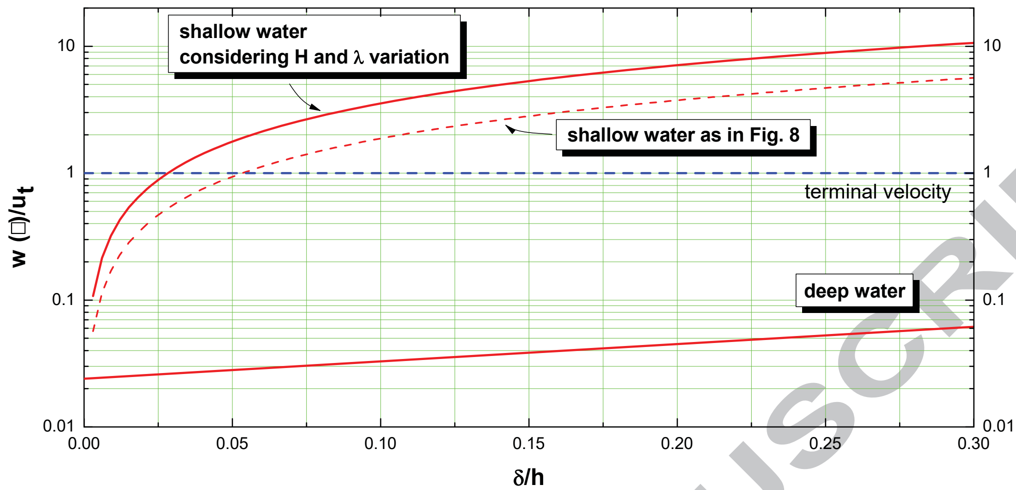


Figure 10: The ratio of the velocity at the bed and the terminal velocity $\frac{w(\delta)}{u_t}$ for *deep water* and *shallow water* as function of the thickness of the bed $\frac{\delta}{h}$ for a passing wave at the surface with $\lambda = 2$ m and $H = 0.2$ m, and considering the change in H and λ between a deep and shallow water.

want the opposite, i.e., converting an electrical input into a wave. Therefore, the technology for large wave generation already exist, ocean wave converters are actually wave generators if operating in the opposite direction.

By aforementioned, it is instructive to know the *wave power* associated with a given wave as function of its parameters. knowing the *wave power* transported by a wave is equivalent to know the power needed to generate the wave. The *wave power* P per crest length b of the wave in the approximation of *deep water*, i.e., when $\frac{h}{\lambda} \geq \frac{1}{2}$ is given by, [28]

$$\frac{P}{b} = \frac{\rho g^2 H^2 T}{32\pi} \tag{19}$$

Therefore if we want to generate a wave with, say, an amplitude around 0.2 meters, and with periodicity of 3 seconds, the power per crest length will be above $\frac{P}{b} = 0.25$ kW/m, and then for a 100 meters reservoir length, and assuming a 100% efficiency in the conversion, this translates into a 25 kW, which for

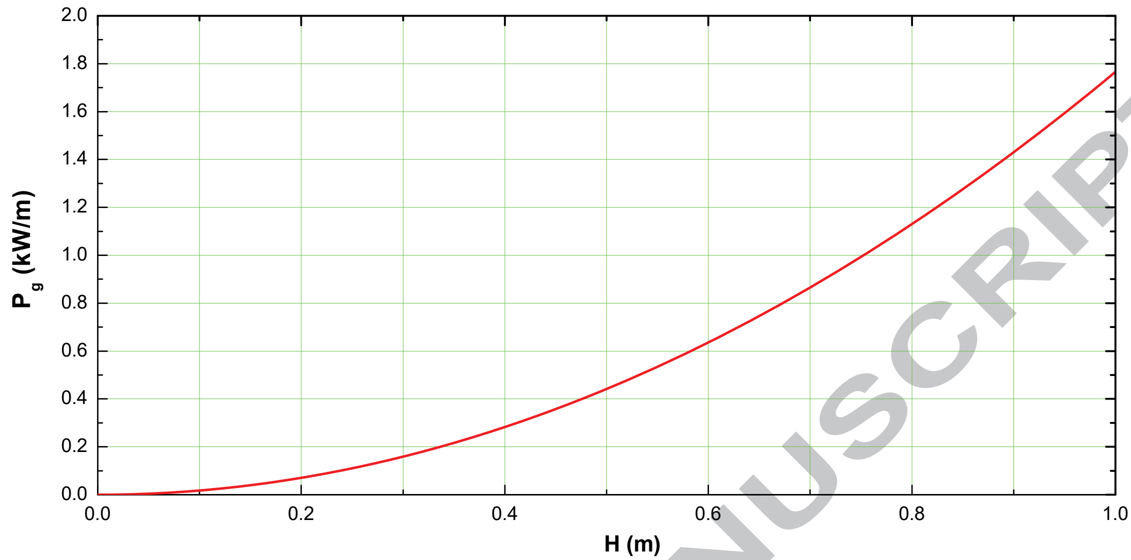


Figure 11: Plot of the wave power as function of its height.

50 generators like this distributed along the reservoir will translate in a total power above ≈ 0.13 MW. This figure, will vary more or less depending of the specific *wave generator* and the specific efficiency in the conversion, but even assuming a rather poor efficiency around 30%, the figure is a very modest one for a rather common dam of say 300 MW. In Fig. 11 is illustrated as example the *wave power* per crest length of the wave as function of the amplitude of the generated wave H and for a period of 3 seconds.

Although the core of the idea discussed in this paper is the deliberate generation of waves spreading throughout the surface of the reservoir and their conversion into a water flow in the riverbed for the resuspension and control of sediments and with such a goal many technological approaches for generation and conversion of waves are suitable to be used, and therefore, in illustrating a specific given technology one runs the risk of being misinterpreted that this specific technology is required (for example a particular kind of PAs for the conversion of waves or a specific *wave-generator*), nonetheless, for a preliminary theoretical treatment the choice of a given illustrative technology -which almost

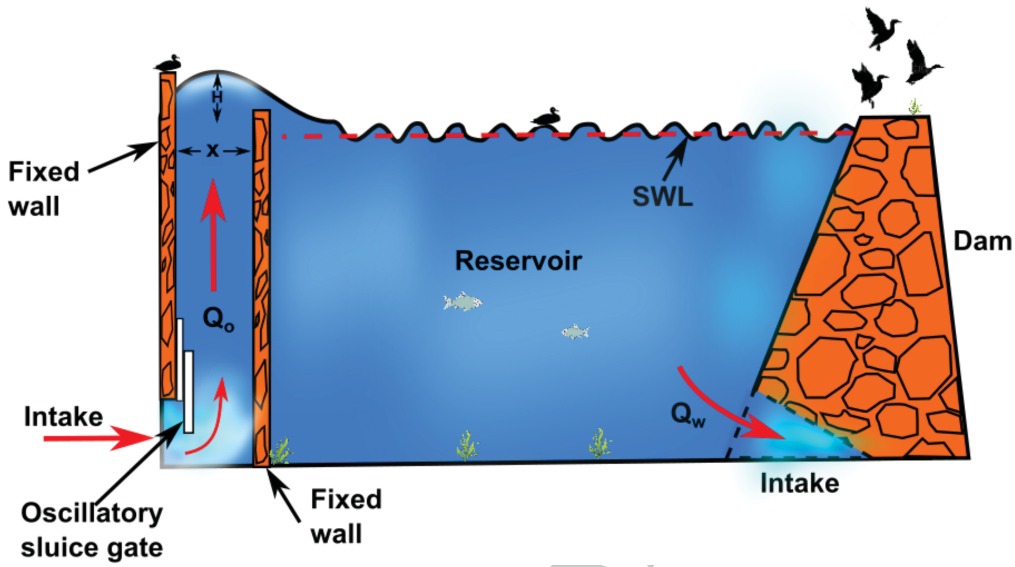


Figure 12: A wave generator by using oscillatory sluice-gate.

always should be the most simple, is mandatory. However the given illustrative choice should not be misconstrued as an attempt to give the definitive and most optimum system, rather it must be observed as a help which will provide important guidance in future efforts to analyze the problem and optimized design.

Having said this, a large number of wave generators imported from the ocean wave energy conversion industry could be potentially used for our purpose, [30], most of these *wave-converters* have an efficiency η in the conversion of *wave-to-electricity* or *electricity-to-wave* as high as $\eta \approx 75\%$, [28], and then the choice of one or other technology will be motivated mostly by the cost, management required, lifetime, etc... However, let us briefly mention some of them which are conspicuous by their simplicity.

2.4.1. Using oscillatory sluice gates

To begin with, let us consider the scheme depicted in Fig. 12. In this, between the dam and the intake of the reservoir two walls are placed. The first wall with a certain cavity on the bottom in which a sluice-gate open and close periodically. At a certain distance x from the first wall there is a second fixed wall, this wall has a height which is a little higher than the still water level (SWL). The function of the two walls is easy to infer. Because of the cavity between both walls, the water flow is accelerated and then it can attain a certain height which will depend on the width x of the cavity. With this idea some estimate can be performed.

First, if the time during which the oscillatory sluice-gate is open is equal to the time in which is closed. Then, on average, during an interval of time t the volume flow when the slice-gate is open Q_c must be equal to the continuous volume flow in the dam Q_d (which is used for the hydroelectric generation)

$$\frac{\Delta t}{2} Q_c = \Delta t Q_d \tag{20}$$

and then

$$Q_c = 2Q_d \tag{21}$$

On the other hand, the velocity inside the cavity, is given by

$$u_c = \frac{Q_c}{A_c} \tag{22}$$

where A_c is the cross section area of the cavity which considering a width x_c and a longitudinal length L_r (equal to the longitude of the reservoir), is given by

$$A_c = x_c \cdot L_r \tag{23}$$

Therefore, taking into account Eq.(21) and Eq.(23) into Eq.(22), the velocity of the water in the cavity yields

$$u_c = \frac{2Q_d}{L_r x_c} \tag{24}$$

On the other hand the volumetric flow of water of the dam Q_d may be expressed as function of the power of the dam W_d and the height (foundation) of the dam H_d as

$$Q_d = \frac{W_d}{\rho g H_d} \tag{25}$$

which inserted into Eq.(24) yields

$$u_c = \frac{2W_d}{\rho g H_d L_r x_c} \tag{26}$$

A first estimate of the maximum height attained by the oscillatory water flow H in the cavity -as depicted in Fig. 12, may be inferred by equating the kinetic energy of the stream with the gravitational potential

$$H \approx \frac{u_c^2}{2g} \tag{27}$$

Inserted Eq.(26) into Eq.(27), yields

$$H \approx \left[\frac{4W_d}{\rho g^{\frac{3}{2}} H_d L_r x_c}\right]^2 \tag{28}$$

- **Discussion**

To obtain some idea of the height of the waves generated by the cavity predicted by Eq.(28), we assume some typical values for a real medium-large dam as the Ribarroja Dam located in the province of Tarragona, Spain: $W_d = 262.8$ MW; $\rho = 1000$ kg/(m^3); $H_d = 60$ m; $L_r = 362.4$ m. The resulting curve is shown in Fig. 13 as function of the length of the cavity x_c. It is seen that height waves up to 2 meters or thereabouts can be obtained by this method. By comparing with the mild height waves needed for resuspension and control of sediments (see Fig. 5 and Fig. 6) it seems that even considering a large margin of error in the calculations, the technique has certain merit.

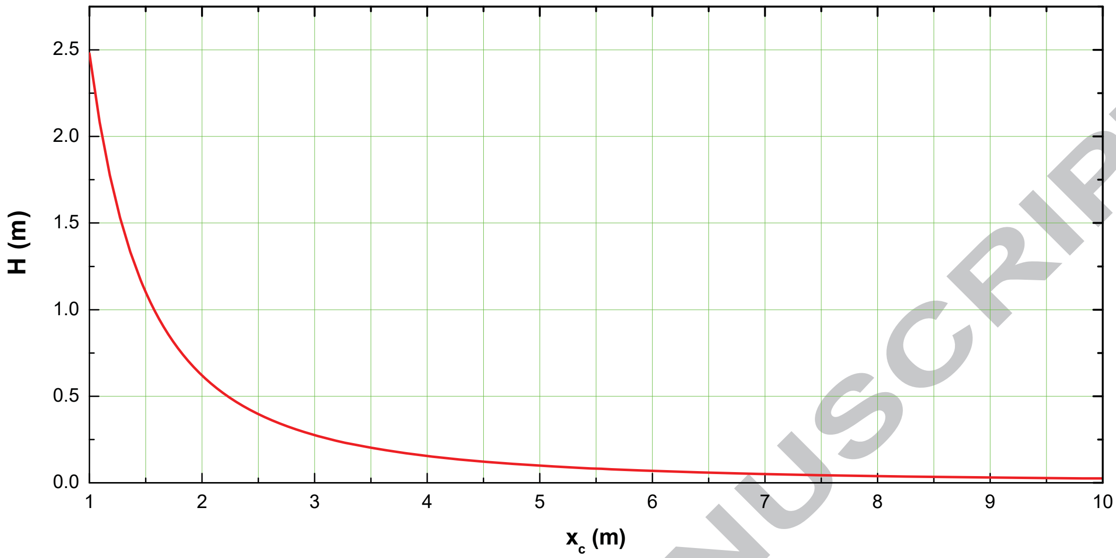


Figure 13: Plot of the wave height obtained at the cavity as function of its width according with Eq.(28).

2.4.2. *Using water wheels, nodding-ducks or technology akin*

Another option for generation of waves on the surface of the reservoir is by the use of mechanical devices which by means of an electrical input of energy can generate the waves. Just for the sake of illustration we have water wheels and nodding-ducks as is pictorially depicted in Fig. 14 and Fig 15, respectively, which are specially conspicuous by their simplicity. The power needed to generate the wave for these devices are given by Eq.(19) and multiplied by the specific efficiency η in the conversion, which for a water wheels and a nodding-duck are around 60% and 70%, respectively, [28]

Finally, is worthy of mention the possibility to develop resonances. In ocean wave energy conversion, designers try to design the PAs with a natural heaving frequency to *resonate* with the ocean wave, [28], in order to obtain a high magnification of the amplitude of oscillation of the PA. Nevertheless because ocean waves are not *monochromatic* in frequency the best they can do is to design a PA with a frequency equal than the highest energy ocean wave.

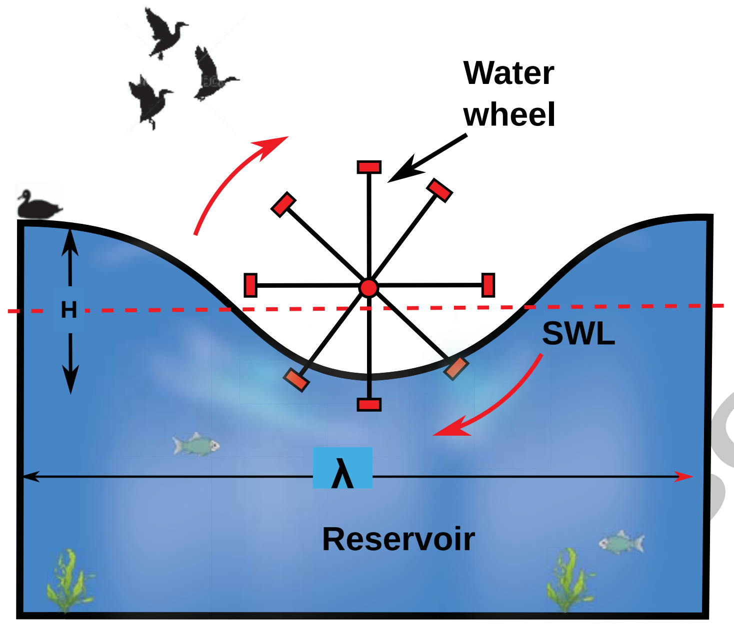


Figure 14: A reservoir wave generator by using water wheels.

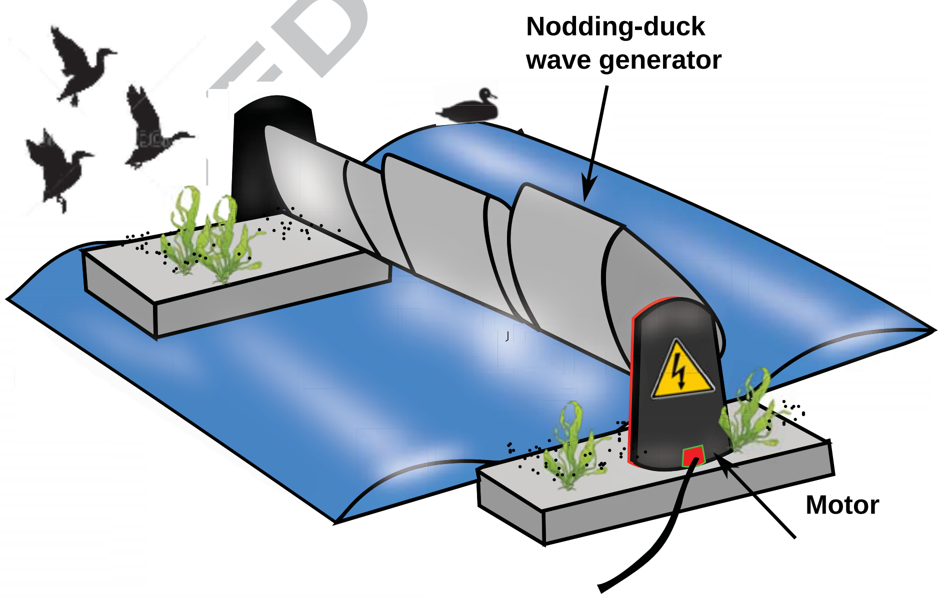


Figure 15: A reservoir wave generator by using nodding-ducks.

For our case, with a stilled reservoir, the waves generated will be highly monochromatic and then with a specific frequency controlled by the operator. This makes that generated wave can be regulated by operators in such a way that the farms of PAs resonate with a substantial magnification of the amplitude of oscillation which can be as high as a factor 5 depending of the damping of the system,[28]. It is easy to see from Fig 5 and Fig. 6, that with this amplification of the amplitude a substantial increase in the probability of the PAs is obtained and without any additional expenditure of power.

2.5. Computational simulation

With the goal to get additional confidence on the discussed technique Computational Fluid Dynamic (CFD) calculations were performed. Although there an overwhelming amount of CFD related software packages (The website CFD-Online(https://www.cfd-online.com/Wiki/Codes) lists over 200 CFD), substantial differences between packages are most related with how meshing is done and what sorts of boundary conditions are provided while solving. Nevertheless because of its superior performance and functionalities for many years, the gold standards in CFD simulation have been Fluent by ANSYS. Therefore, ANSYS Fluent 18.2 CFD software which includes well validated capabilities to deliver accurate results for the widest range of simulations was used in the simulations.

To describe gas-solid flow in fluidized beds, many numerical models have been developed in the last years, such as Lattice-Boltzmann (LBM), Discrete Particle Model (DPM) and the Two Fluid Model (TFM), [35]; but in view of the uncertainty in several parameters, the simplest DPM model for the simulation of fluidized bed in which particles are grouped into parcels, whose the position is tracking like a single representative particle translating into a fast computations and reduced requirements of computer resources, seems preferable. Therefore, the discrete phase model (DPM) using the PISO (*Pressure-Implicit with Splitting of Operators*) scheme for the pressure-velocity coupling and laminar viscous model was used in the simulations.

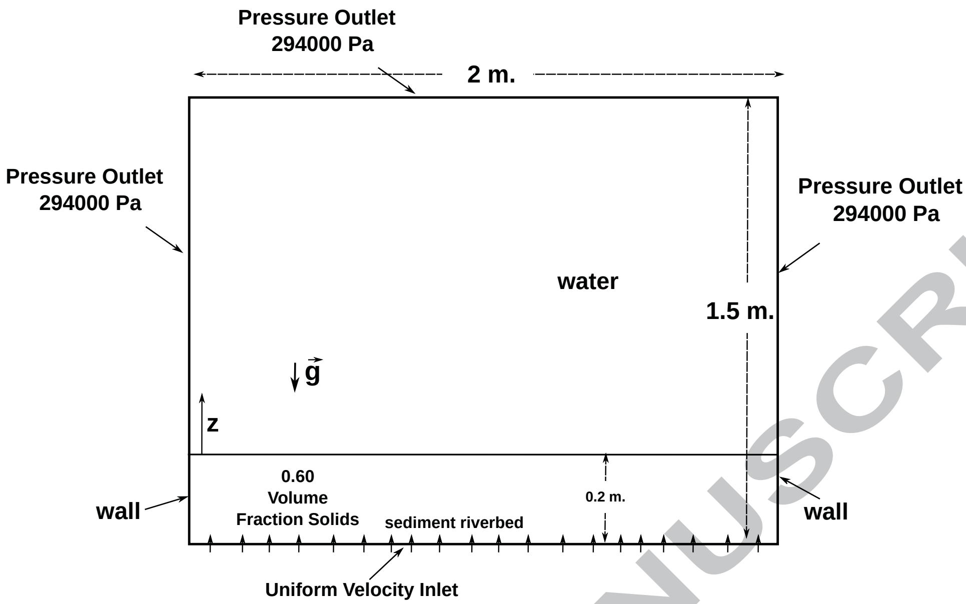


Figure 16: Problem schematics for the CFD simulation.

In order to ensure the independency of the calculations with the grid and time-step, the convergency criteria was taken to be residual RMS error values of 10^{-4}, and the overall imbalance in the domain was less than 1% for all variables, then convergence of the solution was checked at each time step by using the scaled residuals, defined in Fluent after. The mesh resolution independence was checked running an initial mesh and ensuring the convergency criteria of RMS of 10^{-4} and an imbalance in the domain was less than 1%, then, a second simulation was performed using a second mesh with finer cells throughout the domain, then the simulation was run until the convergency criteria and imbalance in the domain were satisfied. The criteria for selection of the mesh was that the contours of volume fraction for two consecutive stimulations were less than a 1%, then the mesh at the previous step was considered accurate enough to capture the result. On the other hand, time step independence was achieved using time-steps of 0.5 s.

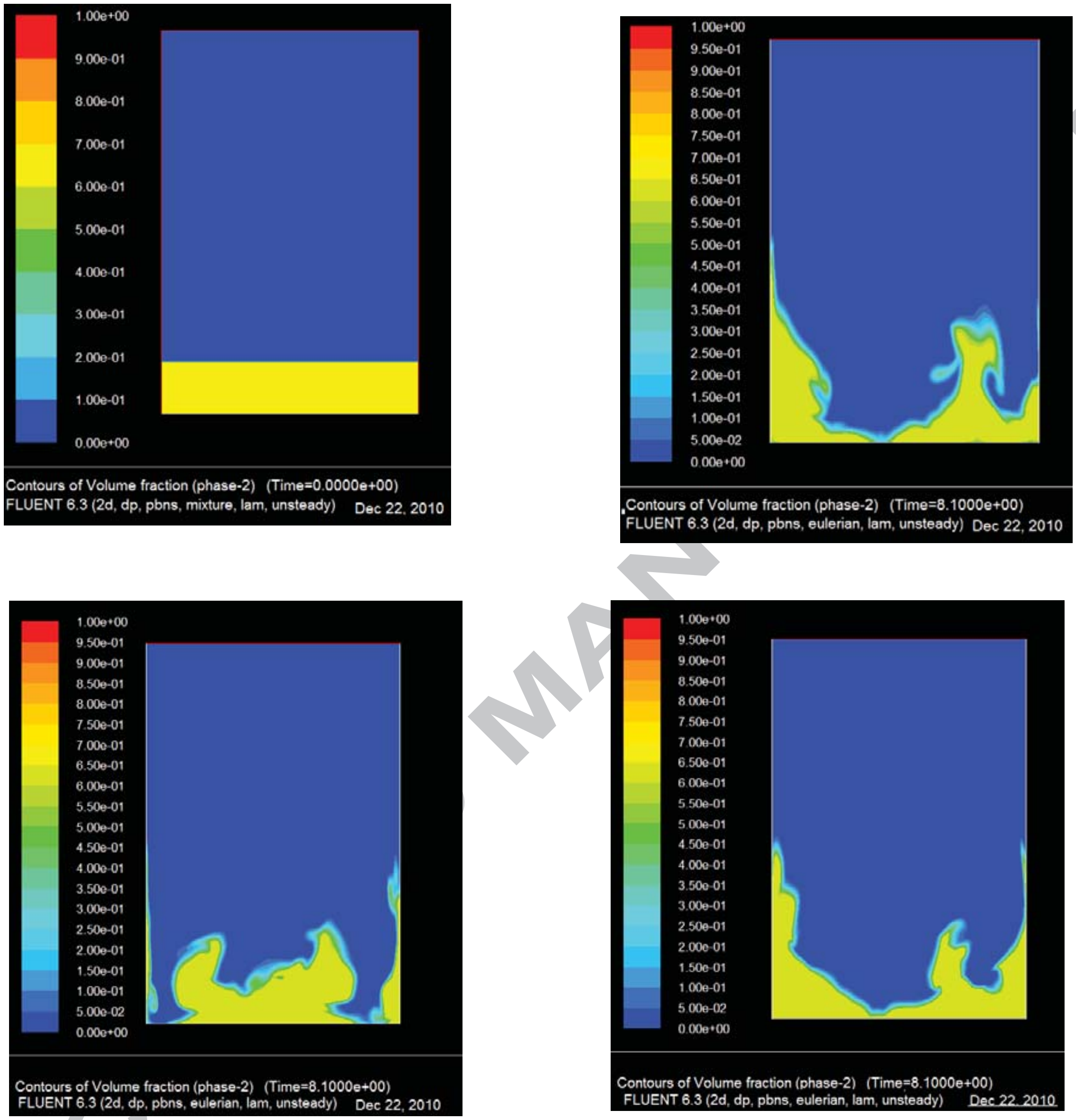


Figure 17: Top left: the initial still condition of the bed before the injection of water starts. Top right: after 8.1 seconds and $\Gamma = 50$. Bottom left: after 8.1 seconds and $\Gamma = 100$. Bottom right: after 8.1 seconds and $\Gamma = 200$.

2.5.1. problem description

The problem to be considered is shown schematically in Figure. 16. A rectangular box is of side 0.5 meters and width 2 meters. Gravity acts downwards. A the bottom side, the computation mesh consists of 24.600 cells. In the bottom of the box a region of 0.2 meters of granular material was placed simulating the river bed with a volume fraction of 0.60. The left, right and top side was fixed as a boundary outlet pressure with 294000 Pa corresponding to a reservoir depth 30 m. The bottom side was fixed as an inlet velocity where water was injected. The velocity of the water injected was calculated considering a wave of 30 cm of height and a plausible wavelength of 3 meters which according with Eq.(15) corresponds to a period of 4.53 seconds. For the Illustrative example, particles of 10μm were simulated. Fig. 17 shows the dispersion of the riverbed: Top left is the initial still condition of the bed before the injection of water starts. Top right the dispersion of the bed after 8.1 seconds the injection of water starts for $\Gamma = 50$; bottom left for $\Gamma = 100$; and bottom right for $\Gamma = 200$. It is seen that even considering several unavoidable mistakes from several simplifying assumptions, the dispersion of riverbeds by inducing mild waves at the surface of the reservoir and the use of point absorbers -or technology akin, has merit of being considered.

3. Ecological issues

Although for this preliminary work, the proposed method only was assessed from an engineering standpoint, nevertheless some ecological issues related to sediment resuspension should be at least briefly analyzed.

Various studies suggested that sediment resuspension determine the sites and rates of organic matter mineralization in shallow environments and that resuspended organic material could exert an enhanced demand on dissolved oxygen with direct negative consequences for water quality and indirect in ecosystem integrity. For example, the study by Almroth et al.[32] demonstrated that increased oxygen consumption as a result of sediment resuspension could lead to spreading of anoxic/suboxic bottom water conditions, and thus indirectly to increased benthic release of phosphate, ammonium and iron. Thus, the continuous disturbance of the reservoir bottom for resuspending the sediments, although can have the advantage of preserving the sediment flow across the dam and replenishing the riverbeds with sediments downstream, can also keep a state of anoxic conditions in the water column affecting the lake plant and animal communities. Recent research on the effect of transference of element from sediments to the water column by disturbance of the lake bottom can be also found in the works by Puttonen et al (2016), [33] and Ji et al. (2017),[34].

It is interesting to note that the proposed method is controllable by two different ways, namely: on one hand by a *passive* way and on the other one by an *active* way. The *passive* way is the self-control of resuspension of the riverbed without any intervention from operators or external management. This is due to the fact that the water flow injected by the PAs only resuspend the riverbed standing on the pressure manifold or velocity distributor (see Fig. 2), and then once is totally resuspended the given thickness of the riverbed, the induced water flow is not creating any erosion on the riverbed located beneath the pressure manifold and the water flow is now only preventing the settling down of new sediment.

The *active* way is referred to the control of the intensity of resuspension by controlling the parameters of the surface wave, i.e., the period and/or the amplitude of the wave, so the intensity of resuspension is controlled by controlling the wave generator as is pleased by operators. Therefore, the proposed technique with the use of surface waves presents unique features worthy of being considered for resuspension and control of sediments taking into account environmental issues.

4. Summary of results and conclusions

A new promising method has been proposed for the resuspension and control of sediments in reservoirs by inducing mild waves on its surface and using point absorbers or technology akin to transform the wave energy spreading through the surface of the reservoir into a continuous injection of water flow in the riverbed. Some interesting conclusions are resulting from this preliminary work as follows:

(a) Generation of waves and use of wave converters could be a very efficient method for riverbed resuspension and control, where preliminary estimations show that, more than 50 times of riverbed area could be resuspended in comparison with the area of the point absorber for practical waves.

(b) Wave generation could be performed by using dedicated oscillatory sluice gates or conventional technology used in ocean energy conversions (e.g., water wheels, nodding-ducks). For this last case, an electrical power around 0.5 kW per meter-width of the reservoir will be required, which compared with the power output of a large dam is negligible.

(c) The proposed technique can help to solve or mitigate the problem of settling down of sediments in reservoirs which affect the delta of rivers and limiting the life of the dam.

Because the hydraulic/sediment interaction and sediment transport is so complex involving so many parameters, the theoretical predictions using an idealized model as well as computational simulations as presented in this manuscript are only a crude approximation of real situation, and and as such, they only provide important guidance in future efforts to analyze the problem and to encourage a further research of the subject.

Therefore, as imperative next research step, 3D movable-bed modeling by using laboratory techniques are required.

NOMENCLATURE

A_d = area of the river bed

A_p = area of the point absorber

A_s = area of the river bed lifted by the point absorber

b = crest width

C_D = drag coefficient

d_p = diameter of particle sediment

g = gravity

h = water reservoir depth

$\bar{H}$ = average vertical displacement of the PA

L_r = width of reservoir

n_s = number of particles per volume

P = power of the wave

P_g = power of the wave generator

Q_c = cavity water flow rate

Q_d = hydroelectric water flow rate

Re_p = particle Reynolds number

t = time

T = wave period

u_{mf} = minimum fluidizing velocity of the bed

u_u = upward velocity

u_d = downward velocity

u_t = terminal velocity

Greek symbols

λ = wavelength

δ = thickness of the sediment bed

η = efficiency in mechanical conversion

ρ = density of water

ρ_s = density of particle

ε = void fraction

ϕ_s = sphericity of particle

ω = wave frequency

Γ = area of riverbed covered divide with the area of the point absorber defined by Eq.(10)

subscripts symbols

s = sediment

p = pressure absorber,particle

u = upward

d = downward

ACKNOWLEDGEMENTS

This research was supported by the Spanish Ministry of Economy and Competitiveness under fellowship grant Ramon y Cajal: RYC-2013-13459.

5. References

[1] Mohammad Akram Gill. 1979. Sedimentation and useful life of reservoirs. Journal of Hydrology, 44, 1-2, pp. 89-95

[2] Michele Caputo, Jos M. Carcione. 2013. A memory model of sedimentation in water reservoirs. Journal of Hydrology, 476, 7, pp. 426-432

[3] Abbas Parsaie, Hazi Mohammad Azamathulla, Amir Hamzeh Haghiabi. 2017. Physical and numerical modeling of performance of detention dams. Journal of Hydrology, In press, corrected proof.

[4] Fatemeh Alighalehbabakhani, Carol J. Miller, James P. Selegean, John Barkach, Mark Baskaran. 2017. Estimates of sediment trapping rates for two reservoirs in the Lake Erie watershed: Past and present scenarios. Journal of Hydrology, 544, pp. 147-155

[5] Mingfu Guan, Sangaralingam Ahilan, Dapeng Yu, Yong Peng, Nigel Wrigh. 2018. Numerical modelling of hydro-morphological processes dominated by

fine suspended sediment in a stormwater pond. Journal of Hydrology, Volume 556, January 2018, pp. 87-99

[6] Jungsu Park, James R. Hunt. 2017. Coupling fine particle and bedload transport in gravel. bedded streams. Journal of Hydrology, 552, pp. 532-543

[7] Xin-An Yin, Zhi-Feng Yang, Geoffrey E. Petts, G. Mathias Kondolf. 2014. A reservoir operating method for riberine ecosystem protection, reservoir sedimentation control and water supply. Journal of Hydrology, 512, 6, pp. 379-387

[8] Taormina R., Kwok-Wing Chau; Bellie Sivakumar. 2015. Neural network river forecasting through baseflow separation and binary-coded swarm optimization. Journal of Hydrology. 529, Part 3, 1788-1797

[9] Olyaie E; Banejad H; Chau K.W; Melesse A.M. 2015. A comparison of various artificial intelligence approaches performance for estimating suspended sediment load of river systems: a case study in United States.Environ Monit Assess. 187, 4. 189, 22 p

[10] Chen X.Y; Chau K.W. 2016. A hybrid double feedforward neural network for suspended sediment load estimation. Water Resources Management. 30,7, 2179-2194

[11] Wang W.C; Xu D.M; Chau K.W; Chen S. 2013. Improved annual rainfall-runoff forecasting using PSO-SVM model based on EEMD. Journal of hydroinformatics. 15, 4, 1377-1390

[12] Wu C.L; Chau K.W. 2006. A flood forecasting neural network model with genetic algorithm. Int. J. Environment and Pollution, Vol. 28, Nos. 3/4.

[13] Chau K.W. 2017. Use of Meta-Heuristic Techniques in Rainfall-Runoff Modelling. Water. 9, 3. 186.

[14] Liu C; Walling D.E; Spreafico M; Ramasamy J; Thulstrup H.D; Mishra A. 2017. Sediment Problems and Strategies for their Management. Experience from several large river basins. International Sediment Initiative (ISI)-IHP-UNESCO

[15] Spreafico M; Lehmann C. 2009. Erosion, transport and deposition of sediment- case study Rhine. UNESCO-ISI. Report no II-20 of the International Commission for the Hydrology of the Rhine Basin (CHR).

[16] Wang Z.Y; Hu C. 2009. Strategies for managing reservoir sedimentation. International Journal of Sediment Research. 24, 4 369-384.

[17] Kondolf G.M. et al. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents, Earths Future, 2.

[18] Annandale, G. W. 2013. Quenching the Thirst: Sustainable Water Supply and Climate Change, CreateSpace, North Charleston, S. C.

[19] Grumbine, R. E., and J. Xu (2011), Mekong hydropower development, Science, 332(6026), 178179.

[20] Kondolf G.M., Z. K. Rubin, and J. T. Minear (2014), Dams on the Mekong: Cumulative sediment starvation, Water Resour. Res., 50, 5158-5169.

[21] McCully Patrick. Silenced Rivers: The Ecology and Politics of Large Dams. Zed Books, 7 dic. 2001. 359 pages.

[22] EBRO-ADMICLIM project, EU, http://www.lifeebroadmiclim.eu

[23] Falcao, A.F.de O. 2010. Wave energy utilization: A review of the technologies. Renewable Energy and Sustainable Energy Reviews. 14,3, pp. 899-918.

[24] Drew B., Plummer A.R., Sahinkaya M.N. 2009. A review of wave energy converter technology. Proc. IMechE Vol. 223 Part A: J. Power and Energy

[25] Hughes S.A, 1993. Physical Models and laboratory techniques in Coastal Engineering. World Scientific Publishing Co. Pte. Ltd.

[26] Kunii D., Levenspiel O. 1991. Fluidization Engineering. Second edition, Butterworth-Heinemann, Massachusetts .

[27] Haider A., Levenspiel O., 1989. Drag coefficient and terminal velocity of spherical and nonspherical particles. Powder Technology, 58. 63.

[28] McCormick M.E. 2007. Ocean Wave Energy Conversion. Dover Publication Inc. Mineola, New York. McCormick M.E. 2007. Ocean Wave Energy Conversion. Dover Publication Inc. Mineola, New York.

[29] Stroh A; Alobaid F; Hasenzahl M.T; Hilz J; Strohle J; Epple B. 2016. Comparison of three different CFD methods for dense fluidized beds and validation by a cold flow experiment. Particuology. 29. 34-47

[30] Drew B., Plummer A.R., Sahinkaya M.N. 2009. A review of wave energy converters technology. Proc. IMechE. 223. Part A: J. Power and Energy. 887-900.

[31] Wen C.S. The fundaments of aerosol dynamics. World Scientist Publishing Co. Pte. Ltd, Singapore.

[32] Almroth E; Tengberg A; Andersson J.H; Pakhomova S; Hall P.O.J. 2009. Effects of resuspension on benthic fluxes of oxygen, nutrients, dissolved inorganic carbon, iron and manganese in the Gulf of Finland, Baltic Sea. Continental Shelf Research. 29. pp. 807-818

[33] Puttonen I; Kohonen T; Mattila J. 2016. Factors controlling phosphorus release from sediments in coastal archipelago areas. Marine Pollution Bulletin. 108, 1-2. p.p. 77-86

[34] Ji N; Wang S; Zhang L. 2017. Characteristics of dissolved organic phosphorus inputs to freshwater lakes: A case study of Lake Erhai, southwest China. p.p. 1544-1555 Science of the Total Environment 601-602 (2017) 1544-1555.

[35] Van Der Hoef M.A; M. Van Sint Annalabd, Deen N.G; Kuipers J.A.M. 2008. Numerical simulation of dense gas-solid fluidized beds: a multiscale modeling strategy, Annu Rev Fluid Mech, 40. pp. 47-70.

Date: December 24, 2017
Barcelona, Spain,

1 *Title*

Paper title : "**On Resuspension and Control of Reservoir Sediments by Surface Waves and Point Absorbers** "

1. Generation of waves and use of wave converters could be a very efficient method for riberbed resuspension and control
2. Wave generation and conversion is a mature technology unexplored in this field
3. May solve the problem land loss in the river deltas and storable capability of large dams.