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Cost estimation of freeboard requirements in water resources management

A. Solera-Solera & A. Morales-Torres
Universitat Politècnica de Valencia, Department of Hydraulic Engineering and Environment, Valencia, Spain

A. Serrano-Lombillo
iPresas S.L., Spain

ABSTRACT: Freeboard requirements in dams are a usual measure to reduce flood risk in downstream areas and to increase dam protection. However, they reduce reservoir regulation capacity, reducing, for instance, available water resources in a drought situation.

In this article, a methodology is presented to estimate the cost of this kind of risk reduction measure. First, a set of simulations of the water resources system management is made to compare the situation with and without freeboards, in order to analyze the difference in demands satisfaction. Then, the economic cost of the difference in the water supplied between both cases is evaluated.

Finally, this methodology has been applied in a water resources system, estimating the cost of freeboard requirements in its principal reservoirs.

1 INTRODUCTION

Nowadays, there is an important concern to protect people against floods, as floods are one of the most destructive natural disasters. Freeboard requirements in reservoirs are a common measure to decrease flood risk in downstream areas. This free volume of the reservoir can be used for flood routing during a flood event, reducing outflow through outlets and loads in the dam and decreasing hazards in downstream areas.

On the other hand, freeboards imply an important reduction of the reservoir regulation capacity, so they decrease the economic benefits of the reservoir, particularly during a drought period. Therefore, freeboards have an economical cost due to the demands that cannot be supplied as a result of the volume reduction in the reservoir.

In this paper, a methodology to compute the economic cost of freeboards is presented. This methodology is based on the combination of simulations of the water resources system management and an economical valuation of the loss of water supplied due to these freeboards.

This methodology has been applied in a complex water resources system (the Duero River Basin water resources system), it has 14 large dams with seasonal freeboards. The economic cost of the freeboards in each dam has been computed. Furthermore, one of these dams has been analyzed in detail, computing the relation between costs and freeboard configurations.

2 PROPOSED METHODOLOGY

2.1 *Structure of methodology*

The main purpose of the proposed methodology is to compute the cost of freeboards in reservoirs. This methodology has two main steps.

– First, simulations of the water resources system management are performed, in order to analyze the difference in water supplied to each demand when the freeboards are introduced.
– Second, this loss of water supply is economically assessed estimating its effect on the demands that have not been fully satisfied due to freeboard requirements.

This methodology has been focused on estimating the economic cost of freeboards in agricultural demands, since they are the main water demand in the studied reservoirs and they usually have a lower priority than industrial and urban demands, which means they are the most affected by freeboard requirements. However, this methodology can be easily applied with other water uses if the cost of the supplied water is correctly valuated.

2.2 *Simulation of water resources system management*

The first step of this methodology is performing simulations of the water resources system management. This kind of simulations is commonly used for planning and managing water resources systems and is usually divided into the following steps (Andreu and Solera 2006):

1. Design of the conceptual model of water resources system management (the detailed methodology to make this design can be found in (Solera et al., 2010)).
2. Model calibration with historical data.
3. Diagnosis of current situation.
4. Definition of development alternatives in the water resources system.
5. Alternatives simulation, comparison and impact valuation depending on the project objectives.

In the case of this paper, the development alternatives are the introduction of freeboards, so the alternatives comparison consists of estimating the long term cost of freeboards using the difference in the volume supplied when they are introduced. Therefore, in order to correctly apply this methodology, a proper model of the water resources system management is needed. This model may include the main demands of water in the studied reservoirs and must follow the priority rules used in the system for water supply in demands. So, this model must be correctly calibrated, including the objective volume in the reservoir in each month, since these values can produce important changes in the results.

In the model of water resources system management, two simulations are performed in each dam. First, an *initial case* is computed, estimating the water currently supplied in each demand. Second, a *modified case* (introducing freeboard requirements), is also simulated, obtaining the water supplied in each demand with these restrictions.

If the *initial case* already has freeboard requirements, the *modified case* is without freeboards, and the result of this methodology is the benefit of removing the freeboard requirements in the dam, instead of the cost of introducing them.

The main result that must be obtained after these two simulations is the difference of water supplied in each demand between the cases with and without freeboard requirements. This result is basic to obtain the economic cost of freeboard requirements.

2.3 *Evaluation of economic cost of freeboard requirements*

With the simulation of the water resources systems management, the difference in water supplied in the cases with and without freeboard requirements is obtained. To then obtain the economic cost of freeboard requirements in each agricultural demand, the total irrigated area in each water demand must be known.

The main assumption to estimate the cost of the difference in water supply is that the percentage of irrigated area each year in each demand is equivalent to the percentage of the demand that has been supplied. For instance, if an agricultural demand has been supplied with the 70% of the total water needed, then the irrigated area in this demand is the 70%

of the total irrigated area. This assumption seems reasonable, taking into account common practice in irrigation.

With this assumption, for each demand, the difference in irrigated area in the initial and modified situations can be computed with the following equation:

$$Ai_{NI} = \frac{(Vi_{NF} - Vi_{F})}{Vi_{T}} \cdot Ai_{T} \tag{1}$$

where Ai_T (m^2) is the total irrigated area for demand i, Vi_T (hm^3) is the annual volume of water that the demand i needs, Vi_{NF} (hm^3/year) is the average annual volume of water that is supplied to the demand i in the case without freeboard restrictions, Vi_F (hm^3/year) is the average annual volume of water that is supplied to the demand i in the case with freeboard restrictions and Ai_{NI} (m^2/year) is the area that has not been irrigated in the demand i due to the freeboard requirements.

The result of applying this equation is the average area that has not been irrigated in each demand per year. Adding all these areas, the total non-irrigated area due to freeboards in the water resources system is obtained.

The last step of this methodology is converting the agricultural area that has not been irrigated (m^2/year) to economic terms (€/year). Then a relation between area (m^2) and cost (€) is needed. This conversion depends on local economy and must be analyzed in each case, following recommendations from government, local companies and insurances. Some examples that can be used are the cost of destruction of this agricultural soil or the cost of the crops that can be obtained in this agricultural area. When this conversion is done, the cost of introducing freeboards requirements in the water resources system is obtained.

3 CASE STUDIES

3.1 *Water resources system*

The first case study analyzed in this paper is the water resources system of the Spanish Duero River Basin, which is a complex system with a total annual demand of 4300 hm^3 in an area of 78900 km^2. In this water resources system there are 14 large dams with seasonal freeboards, in order to protect downstream areas against floods. These freeboards are larger in wintertime and lower in summertime.

Since these freeboards are currently in place, the initial case in this analysis is the case with the freeboard requirements in all the dams. Then, the benefit of removing these freeboard requirements has been obtained for each dam, applying the methodology explained in the previous section.

The first step of the methodology is making simulations of the water resources system. In this case, the simulation has been made with the software AQUATOOL (Solera et al., 2007). AQUATOOL is a developing environment for river basin's Decision Support System (DSSs) (or any other water resources system) planning and management. This software is currently being used to develop River Basin Management Plan in Spanish basins. In fact, the water resources system model used in this paper has been used to develop the Duero River Basin Management Plan and it is available on the web page of the Duero River Basin Authority (CHD 2011).

In this model, the water resources system is divided into five subsystems. Figure 1 is a representation of one of the five model subsystems. This model makes a simulation of the water resources system management for 26 years, based on historical data about inflows in the system.

Using this model, the cases with and without freeboard requirements have been computed, obtaining for each demand the difference in water supplied due to these restrictions. The most significant differences in the simulations are when freeboards cause the reservoir to

Figure 1. Representation of the Pisuerga water resources system, which is a subsystem of the Duero River Basin water resources system.

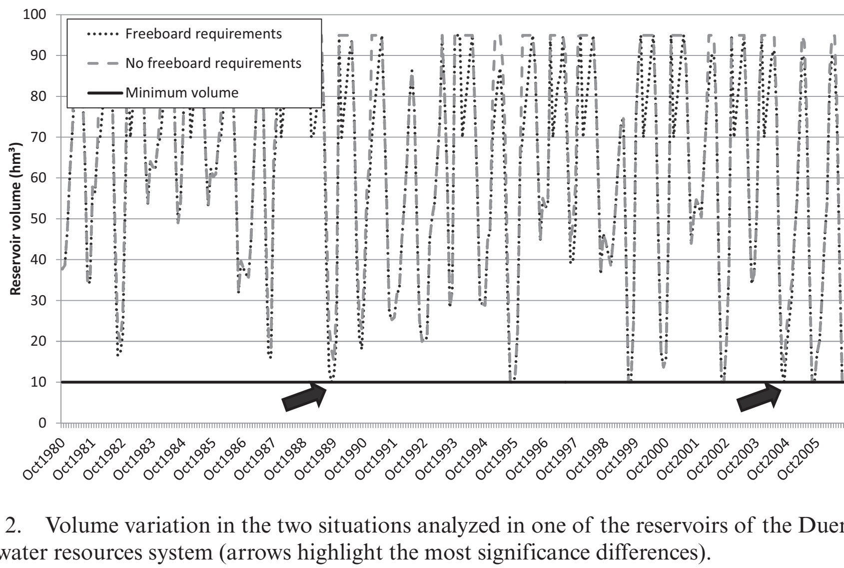

Figure 2. Volume variation in the two situations analyzed in one of the reservoirs of the Duero River Basin water resources system (arrows highlight the most significance differences).

empty and not supply its demands. Figure 2 shows an example of the change in reservoir volume for the studied period. In this case, the situation with freeboards empties the reservoir seven times whereas in the case without freeboards, it is only emptied five times, so in the first case, the water supplied is lower.

The next step is computing the area which cannot be irrigated because of the water free-board requirements. This area has been computed for each demand using Equation 1. Then the average area which cannot be irrigated in each demand is obtained. When all these areas are added, the total annual agricultural area in the water resources system which cannot be irrigated due to freeboard requirements is obtained.

Finally, the non-irrigated annual area must be converted to an annual cost. In this case, this cost has been estimated using the recommendations of PATRICOVA (COPUT 2002) which provides a cost for the total destruction of agricultural soil by flooding in Spain, based on the current cost of this soil. The assumption here is that the damage caused by flooding is the loss of one year's crop, which is equivalent to the loss caused by not irrigating. For cereals and corn, which are the most common irrigated crops in this basin, this cost is 3414.3 €/ha. Furthermore, this cost is similar to the benefit of the production of these crops in a hectare during one year (JCYL 2011).

Then, the economic benefits of removing freeboard requirements have been obtained for the 14 reservoirs in the system, obtaining only significant benefits in 4 dams. The obtained results are shown in Table 1.

The cost obtained for the water which cannot be supplied is always between 0.18 y 0.5 €/m^3, which is the usual range of cost of water defined by the Spanish government (CHG 2010).

3.2 *Individual reservoir*

Finally, the methodology has been applied in detail to one of the dams, in order to analyze how different configurations of freeboard requirements produce different costs. The chosen dam is Dam A, which has the highest costs of freeboard requirements (Tab. 1).

In this dam, two different freeboard configurations have been analyzed:

– On one hand, using the same configuration of the seasonal freeboard requirements that are currently established, the cost of applying different percentages of these freeboards has been computed. The results are shown in Figure 3.
– On the other hand, the cost of applying the same freeboard during all the year has been obtained. This is equivalent to a change in the Maximum Legal Level, so the cost produced in the water resources system of establishing different Maximum Legal Levels is obtained. In Figure 4, the obtained costs can be seen.

Table 1. Benefit of removing freeboard requirements in four reservoirs of the River Basin Duero.

Dam	Benefit of removing freeboard requirements (M€/year)	Difference in water supplied (hm^3/year)	Cost of non-supplied water (€/m^2)
A	0.528	1.21	0.44
B	0.061	0.48	0.35
C	0.117	0.31	0.38
D	0.163	0.48	0.34

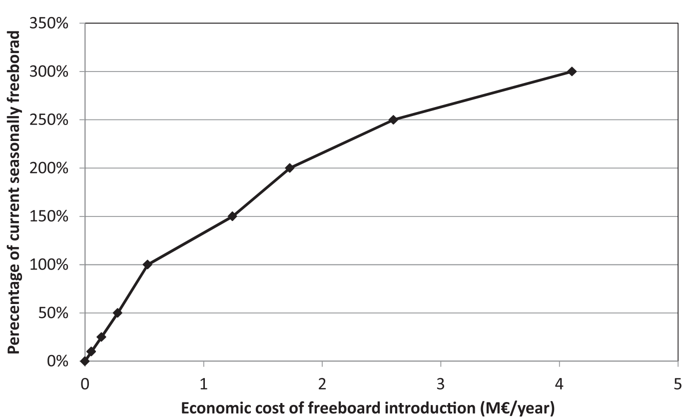

Figure 3. Economic cost of applying a percentage of the current seasonal freeboards.

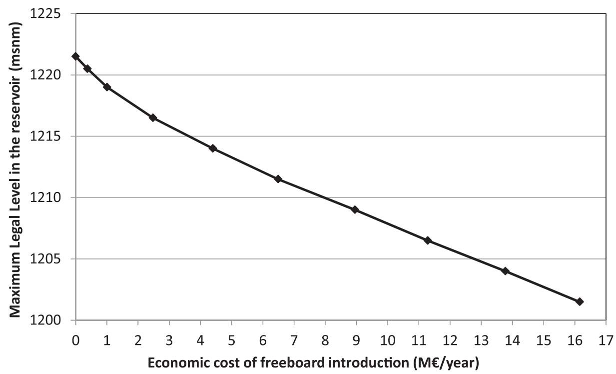

Figure 4. Economic cost of reducing the Maximum Legal Level.

4 CONCLUSIONS AND FUTURE RESEARCH

In this paper, a simple and organized methodology has been presented to compute the cost of freeboard requirements in the water resources system. This methodology is mainly based on simulation of the water resources system management, so in order to apply it correctly, it is very important to have a good water resources system management model, which represents the real rules of demand supply.

The study cases have shown that freeboard requirements can produce an important cost on water resources system, so it is important to correctly justify them. In this sense, an interesting future line of research is comparing the obtained costs with the economic flood risk in downstream urban areas, which can be computed using the methodology proposed in the SUFRI project (Escuder-Bueno et al., 2011). This flood risk is expressed in the same units (€/year), so it can be easily compared with the freeboards cost to get the best configuration of freeboard requirements. The main objective must be minimizing flood risk in downstream areas and freeboard requirements cost.

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