A Method for Estimating the Risk of Dam Reservoir Silting in Fire-Prone Watersheds: A Study in Douro River, Portugal

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Abstract: Forest fires are an increasing problem over recent decades. The fires, among other consequences, lead to an increase in the soil vulnerability to water erosion and a consequent increase in sedimentation rates. When barriers are present, such as dams or weirs, there is an amplified risk of sediment and ash deposition in their reservoirs, causing siltation. Thus, there is an interest in studying in more detail the risk of siltation of barriers and reservoirs in the Douro River watershed following wildfires. A detailed barrier inventory was lacking for the Douro River, hampering the identification of siltation-prone areas. In order to fill in this gap, an extensive inventory of barriers in the Douro river basin was carried out for the present study. The result was an abundant and reliable dataset on the Douro River barriers, which allowed a prognosis on the watershed siltation risk. The method for calculating the siltation risk relied on the relationship between the frequency of forest fires, the erosion risk and the frequency of reservoirs. The sub-basins with the greater siltation risk are the Tâmega, Corgo, Sousa and Paiva river basins. Most reservoirs with the highest siltation risk were from small dams. The modelling results were compared with stream connectivity and concentrations of stream water phosphorus (associated with the sediments that flow into the rivers due to the fires). With regard to connectivity, only two reservoirs were at high risk of sedimentation due to fires, so the categories of connectivity risk and fire-based sedimentation risk are probably not related. With regard to risk of high phosphorus loadings, in 8 basins the upper classes for fire-based erosion risk coincided with the upper class for phosphorus loadings suggesting that high phosphorus loading could be associated with fire-based erosion. This study works as a simple but reliable example on the assessment and mapping of siltation risk in stream networks intersected by abundant barriers. It allowed for identifying barriers that can accumulate a large quantity of fine sediments and ashes, interfering with water quality and soil erosion as well as with the storage capacity of the respective barriers.

Keywords: wildfire; erosion risk; barrier inventory; water quality

1. Introduction

In Portugal, as well as in other Mediterranean countries, forest fires and burned areas have increased significantly over the last few decades, and often these fires occur again in areas that have been burned before [1,2].
The Mediterranean region climate generally is characterized by summers with a combination of high temperatures and low air humidity [3,4]. Under these conditions, and other biogeographic characteristics, like high wind speeds and heatwaves predominant in summer, the outbursts of wildfires and the manifestation of post-fire erosion are facilitated [5–7]. Furthermore, the fire hazard is constantly amplified [7,8], driven by socio-economic changes, including rural depopulation and abandonment of cultivated land, afforestation with flammable species [6,9], coupled with the ongoing climate change [10,11]. The severity of this increase in Portugal is even greater since it differs from other countries in southern Europe in that it has the highest number of ignitions and the highest proportion of areas burned, especially in the central and northern regions [12].

Wildfires have a significant impact on the soil and water dynamics. Given the partial or complete loss of vegetation cover, wildfires trigger increased runoff, flood event frequency and magnitude, vulnerability of soil to water erosion and increased sedimentation rates in river channels or reservoirs [13–15]. Thus, although there are several causes for soil erosion, the evolving decrease of vegetation cover and infiltration rates has led, in large part, to its exponential increase [16,17].

Forest fires can also cause other serious problems in aquatic systems. According to [18,19], the decrease of infiltration rates and increase of available loose sediment after a wildfire is a consequence from the destruction of vegetation and changes in physical and hydrologic properties of the soil. These changes can significantly increase the amounts of sediment, nutrients and other constituents delivered to streams and reservoirs throughout the watershed [20–22]. These particles and sediments transport can eventually be deposited in dams and weirs reservoirs causing siltation issues [23]. Although soil erosion can sometimes occur even in the third or fifth year after a fire, the greatest effects on hydrology generally occur shortly after the fire. It is therefore necessary to have a quick intervention following the fire events [24].

The siltation risk of the reservoirs shorten their life expectancy and effectiveness [23,25–29]. This natural phenomenon induced by water erosion is linked to watershed characteristics in terms of topography, lithology, vegetation cover, hydrology, and also human activities that may promote or amplify soil loss [30–32].

Reservoirs siltation can bring numerous socio-economic and ecological problems: water treatment costs for human supply may increase due to increased turbidity [23]. Many cases have been recorded where reservoir siltation rendered water storage structures useless in a few decades due to sedimentation problems, which were observed predominantly with small to medium-size reservoirs [33] and due to problems with the functioning of hydroelectric turbines [34].

The maintenance of hydraulic infrastructure is recommended after the first rain events following a forest fire. Namely, the cleaning of sediments and debris deposited upstream of the hydraulic passages and possible obstructions that prevent the normal operation of the passage. Neglecting sediment management can result in flooding, siltation, sediment entrainment and infrastructure erosion [35].

Another issue that comes from the reservoirs siltation is that they are the most important factors in inhibiting sedimentary feeding on the coast. According to [36], the hydroelectric and hydro-agricultural uses of the hydrographic basins that flow into Portugal are probably responsible for the retention of more than 80% of the volumes of sand that were transported by rivers in a natural regime. In [37], it is stated that the construction of these barriers is directly interconnected with the lack of sand supply on the coast and the respective consequence of coastal erosion and retreat of the coastline.

The risk of siltation also varies according to the size of the barriers. In a study made in the United States of America, in medium-sized reservoirs, the annual storage loss was 2.7% per annum, and the medium rate of sedimentation was 1.5%. For large-sized reservoirs, the rate of sedimentation was only 0.16% per annum [38].

The rate at which a reservoir silts up depends on the amount of silt carried by the river which feeds it, which is a function of the rate of soil erosion of the river’s catchment area. Where that catchment is forested, the soil is not easily eroded due to the network of roots underlying the forest floor and is also protected from the effects of wind and rain by the forest canopy above [39]. In those areas
where forest cover has been depleted, however, the rate of soil erosion increased drastically [39]. Thus, as the Mediterranean is an area with a high frequency of fires, it leads to an increase in deforestation. Given the deforestation, rivers in the region are at risk of transporting more inorganic matter and consecutively increasing the sedimentation risk in the river channel, blocking it during storm events and promoting an intensification of fluvial erosion and hydromorphological changes [18].

The intensification of these phenomena is promoted by different anthropogenic sources and climate change, together with an increasing dam construction related to the storage effort of running waters to compensate the increasing deficit periods. In addition to the ecological and socioeconomic inconveniences associated with dams and weirs, they have an enormous anthropogenic impact with regard to the amplification of siltation, which already exists, and all the consequences arising from this phenomenon [40].

This study aims to assess the siltation risk in the barrier reservoirs originated from the incidence of forest fires and soil erosion. After knowing the areas with the highest siltation risk, it will be possible to test how they influence water quality or the connectivity of riverside habitats. Do the highest siltation risk areas affect water quality and connectivity? Is it related to the highest siltation risk areas?

There are very few studies of this kind because detailed inventories of barriers are not common, and Portugal is no exception. Officially, about 250 large cataloged dams in Portugal, with a height of more than 15 m or storage of more than 1 hm$^3$ (1 million cubic meters), with more than 50 in the Douro [41]. Clearly, this is not a value that comes close to the reality of the Douro watershed, but until then there was no inventory that would come close to reality in terms of bringing together the georeferencing and characterization of the dams and weirs of this watershed. Thus, through the unprecedented and massive georeferencing carried out by MAVA foundation pour la nature [42], it is now possible to begin the study of this basin with greater reliability. Consequently, it is now possible to assess the risk of silting in an unusual situation of availability of abundant and reliable data.

This study is an original work, a precursor of specific and detailed studies on the siltation consequences when knowledge of the risk in each area of the Douro is available. This work can only be carried out due to the inventory of barriers prepared, thus allowing to estimate the risk of silting up both in the barriers and in the surrounding sub-basins. Before these data that we now have about the distribution of barriers, it was not possible to do the task with the certainty.

2. Materials and Methods

2.1. Study Area

The Douro River is located in the North-West Iberian coast (Figure 1) and is the river with the largest hydrographic basin on the Iberian Peninsula. The Douro River headwaters rises up to 1260 m in Spain, in the Urbion Mountains (Cordillera Ibérica). Throughout its watercourse, it is heavily controlled with dams (1201 barriers were inventoried [4]), and debouches into the Atlantic coast in Portugal, close to Porto town.

The population living in this area reaches two million, distributed within 74 municipalities. The catchment comprises 22 main tributaries in Portuguese territory. Of these, Águeda, Rabaçal, Tuela, Sabor, and Tâmega sub-basins are transboundary river basins, while the Côa sub-basin corresponds to a frontier river basin [43].

The Portuguese Douro River Basin covers an area of approximately 19,000 km$^2$. A large number of surface water bodies are distributed within the catchment, namely 361 rivers, 17 reservoirs, three transitional waters and two coastal waters. The available surface water resources approach 8023 hm$^3$/year, 67 large dams, and a huge number of small dams or weirs stored a portion of this water (1594 hm$^3$). These dams cause an increase in hydro-morphological pressures on surface waters. These pressures may have an impact on changes in the state and ecological potential of water bodies, namely due to changes in the level of river continuity, changes in solid transport (siltation), among others [10].
namely due to changes in the level of river continuity, changes in solid transport (silting), among others [10]. The whole region has great climatic diversity, reflecting its great extension and great variety in morphological terms. According to the Koppen–Geiger classification, the climate in the Douro watershed is temperate, with an average annual temperature of 13° C. Average rainfall in the catchment approaches 999 mm/year, varying between 541 mm and 1 773 mm and the average annual relative humidity in the region is 71%, ranging from 58% in July to 82% in January (https://www.ipma.pt). Despite its strong inter annual variability, river flow presents a normal pattern for the latitude, with weaker flows during summer and stronger flows during winter, in agreement with the regional annual precipitation cycle [44].

The catchment is widely characterized by great climatic, morphological and substrate variations creating a heterogeneity of habitats that support a high diversity of fauna and flora.

According to the danger of the forest fire map prepared by the Portuguese Institute for Nature Conservation and Forests (ICNF) [45], the hydrographic region of the Douro River presents a very high risk of forest fire in a large part. Portugal has the highest density of wildfire ignitions among southern European countries, with population density, human accessibility, land cover and elevation sharing important roles in the spatial distribution of fire ignitions [46]. With forest fires, serious environmental consequences occur, such as soil erosion and ash entrainment and leaching with a high risk of altering water quality [47].

2.2. Methodology

A preliminary inventory of the transversal barriers in the Douro basin was carried out together with their characterization and information about their permeability. The identification of the most significant transversal obstacles was carried out based on military maps available at the 1:25,000 scale, orthophoto maps (http://www.dgterritorio.pt/) and satellite images provided by Google Earth.
Georeferencing essentially covered water lines with order numbers up to 5 (Strahler’s classification). Thus, a total of 1201 transversal obstacles were georeferenced and these distribution is illustrated in Figure 2. Barriers were found in 29 Douro river sub-basins. These basins were divided according to the main tributaries of the Douro river basin.

This work focuses on making use of this extensive inventory, in one of the main hydrographic basins in Portugal, being able to estimate the siltation risk for georeferenced barriers that may have been influenced by forest fires and soil erosion.

The workflow portrayed in Figure 3 indicates all the procedures for obtaining the siltation risk that can occur in the barrier reservoirs. For this, it was necessary to collect data such as the aforementioned georeferenced barriers, forest fires that occurred in recent years (from 1990 to 2018), and erosion risk.

![Figure 2. Spatial distribution of barriers within the Portuguese side of the Douro River Basin.](image1)

![Figure 3. Workflow of the risk of silting of the Dam or weirs reservoirs.](image2)
The forest fire data were obtained through the ICNF (http://www2.icnf.pt/portal/florestas/dfci/inc/mapas). These data were assembled, displayed and processed in ArcMap computer program [48]. For each year, a raster map was drawn with the reclassification of the fire location set to 1. This procedure was done for all the years of fire registrations. Subsequently, the raster maps were overlayed and the fire locations added using the Math Algebra Tool of Arcmap. From here, we obtained the fire frequency of fires (FF) in each location.

The Erosion Risk (ER) was obtained from a previous work published by the present research group [49], at the time elaborated on the scale of mainland Portugal and currently clipped to the Douro River watershed. The method used to estimate erosion was the well-known Universal Soil Loss Equation, which is based on the assessment and combination of various parameters: rainfall erosivity, soil erodibility, hillside slope and length, land cover and landscape management practices. The soil losses derived therefrom were used to produce a map of soil erosion risk at the scale of Douro River basin, using the appropriate tools of Arcmap version 10 software, namely the tools to handle raster maps.

The fire frequencies and soil losses were further processed in Arcmap to obtain average values for each sub-basin of Douro, using the Zonal Statistic as Table Arcmap tool. The sub-basin limits were obtained from Copernicus (https://land.copernicus.eu/imagery-in-situ/eu-hydro). The combination (product) of FF and ER is a proxy to the risk fire sediment export towards the stream channels and dam reservoirs. In addition to these data, the Reservoir Frequency (RF) was calculated, considering the barrier locations within the sub-basins, using the Arcmap Tabulate Intersection Tool. The fire sediment transport risk when associated with the dams or weirs frequency, allowed to obtain the siltation risk, according to the simple calculation of Equation (1):

\[
SR = FF \times ER \times RF
\]

From here, it was possible to obtain a general overview on the siltation risk that can occur in the barrier reservoirs due to transport of sediments and ashes caused by wildfires and soil erosion. These aspects are relevant for catchment management since they have also consequences for water quality and habitat impoverishment as a consequence of siltation.

3. Results

Considering the frequency of wild fires and inherent soil erosion, it is possible to analyze their spatial distribution in Figure 4: (a) depicts the frequency of forest fires over a period of 28 years (between 1990 and 2018). For this period, there is a wide variation in the recurrence of fires: from virtually non-burned areas to a recurrence less than 3 years; (b) illustrates the distribution of soil loss in the Douro river basin, where we can observe an intensification of erosion closer to the main watercourses, related to the topography and drainage density.

Through the burnt areas across the watershed, it is possible to identify the risk of sediment and ash transport within the watershed. However, in order to obtain the risk of incoming sediment load, it was necessary to calculate the reservoir frequency by sub-basin (https://land.copernicus.eu/). Figure 5 shows the risk of dam reservoir silting results by sub-basin. This risk ranges from values close to zero (very low risk) to values up to 90,000 (very high risk). The grey color represent sub-basins that do not present obstacles, and therefore present a limited risk of silting. It is clear that the areas with the highest concentration of obstacles present a greater siltation risk, such as the northwest and southwest areas of the basin.

The Douro River is also characterized by its enormous slopes and evident differences in altitude, which alone are an enormous risk of natural erosion. When the soil is exposed due to forest fires, the steep slopes facilitate the drainage of precipitation into the water lines, contributing to the transport of sediments and affecting water quality. The frequency of dams per water line or sub-basins is the parameter that allowed us to obtain the risk of siltation. As shown in Figure 5, the areas with the highest
incidence/concentration of barriers are the areas with the highest risk of silting. The basins where there is a greater siltation risk are the Tâmega, Corgo, Sousa and Paiva river basins. Table 1 shows the 20 barriers with the highest siltation risk. It appears that the basin with the highest number of barriers represented is the Corgo River basin, followed by the Paiva River. They are all small barriers, more specifically weirs. Of these, about 70% are constructions in Riprap and practically all are in forest or semi-natural areas.

Figure 4. Spatial distribution of forest fire frequency (a) and soil loss (b) of the Douro river basin.

Figure 5. Map of the siltation risk along the main tributaries of the Douro river basin.
Table 1. Some characteristics of the 20 barriers with the highest siltation risk.

| ID  | River Name | Category | Barrier | Type   | Land Use Area         | Siltation Risk Rank |
|-----|------------|----------|---------|--------|-----------------------|---------------------|
| 1436| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 1                   |
| 1437| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 2                   |
| 473 | Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 3                   |
| 479 | Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 4                   |
| 478 | Corgo      | Principal| Weirs   | Concrete| Forest and seminatural| 5                   |
| 477 | Corgo      | Principal| Weirs   | Concrete| Forest and seminatural| 6                   |
| 1238| Corgo      | Principal| Weirs   | Riprap | Agricultural       | 7                   |
| 474 | Corgo      | Principal| Weirs   | Riprap | Agricultural       | 8                   |
| 1236| Corgo      | Principal| Weirs   | Concrete| Forest and seminatural| 9                   |
| 1296| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 10                  |
| 1297| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 11                  |
| 1474| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 12                  |
| 1475| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 13                  |
| 1512| Corgo      | Principal| Weirs   | Riprap | Agricultural       | 14                  |
| 1237| Corgo      | Principal| Weirs   | Concrete| Forest and seminatural| 15                  |
| 1240| Corgo      | Principal| Weirs   | Riprap | Forest and seminatural| 16                  |
| 1234| Corgo      | Principal| Weirs   | Riprap | Agricultural       | 17                  |
| 332 | Paiva      | Principal| Weirs   | Riprap | Forest and seminatural| 18                  |
| 336 | Paiva      | Principal| Weirs   | Concrete| Forest and seminatural| 19                  |
| 333 | Paiva      | Principal| Weirs   | Concrete| Forest and seminatural| 20                  |

4. Discussion

The present paper follows a previous work related to the loss of connectivity in the River Douro catchment [42]. We develop now a model focusing on risk of dam reservoir silting that can occur due to the presence of fire-prone areas in the watershed. Factors such as the fires frequency and the soil erosion, can lead to the accumulation of sediments (and eutrophication, as phosphorus loading to receiving waters increases with soil loss), that can increase the risk of silting up of reservoirs making them useless.

The Mediterranean climate and biogeographic characteristics facilitate the outbursts of wildfires and the manifestation of post-fire erosion [5]. Wildfires are events with a lot of recurrence in the north of Portugal, and severity has increased in the most recent decades, not only in Portugal but also in several countries [50,51]. It is considered that climate change leads to an increase in periods of heat and scarcity of rain, which may influence forest vulnerability [9,52]. The increase in the recurrence of forest fires leads to dramatic consequences on soil erosion and nutrient export deteriorating also the water quality. Phosphorus input is strongly influenced by the burned area, run-off increase (related to soil hydrophobicity) and the river flow [53].

In Figure 4a it is possible to observe the frequency of forest fires in a period of 28 years (1990–2018), which varies between 1 and 10, this is, some areas were burned from one to 10 times in that period. Wildfires can considerably change hydrological processes and the landscape’s vulnerability to major erosion events [24]. According to [54], mountainous areas are highly susceptible to soil erosion when forest fires occur. The results indicate an average soil loss between 1287 and 1404 Mg ha⁻¹.

In mountainous areas, land use changes, such as roads and trails, may also have an important contribution to accelerated erosion [55]. Attention should also be given to changes in the structure of riparian vegetation caused by fires and the effect of any changes on the ability of the riparian vegetation to be an important buffer to soil invading the aquatic system avoiding sedimentation in the river bed.

In addition to the reservoir siltation issue, when we associate these results with the connectivity study of our research group [42], it is possible to verify (Figure 6) whether the areas with the highest siltation risk overlap/cross with some barriers that already presented an enormous risk of fragmentation habitats of fish species in the same areas. More specifically, of the 37 barriers with a very high rate of link improvement, only two are located in areas with very high siltation risk. Thus, it appears that connectivity is not directly related to siltation issues.
Wildfires may cause very substantial changes in soil nitrogen (N) and phosphorus (P) [56–58], that may affect post-fire nutrient exports and concentrations of these constituents in runoff and streams [21,59,60]. In [21], it was mentioned an increase of up to 20% in the concentration of particulate P in burned soil. The increase of available P and N after a fire has implications for water quality and potential eutrophication of water bodies [21]. The high concentration of these nutrients increases the likelihood of eutrophication of aquatic ecosystems, by decreasing of oxygen in the water causing the death of fish and other animals and the increase of toxins that may contaminate the water intended for human consumption [21].

In Figure 6 it is possible to verify that the highest annual concentrations of phosphorus are not directly related to the siltation risk, and of course, other causes may be camouflaged. Soil erosion occurred by the fires is a major contributor of phosphorus to streams. However, bank erosion occurring during floods can transport a lot of phosphorous from the river banks and adjacent land into a stream, lake, or other water body [61]. Beyond stream bank erosion, phosphorus comes from nonpoint sources such as runoff from pasture and croplands and atmospheric deposition [62]. Phosphorus is a common constituent of agricultural fertilizers, manure, and organic wastes in sewage and industrial effluent. It is an essential element for plant life, but when there is too much of it in water, it can speed up eutrophication (a reduction in dissolved oxygen in water bodies caused by an increase of mineral and
organic nutrients) of rivers and lakes [61]. However, Figure 6, shows the existence of eight basins, where the upper classes of both assessment parameters overlap. This indicates that in these areas, phosphorus may have originated in the fires.

5. Conclusions

This paper followed a previous work [42], which focused on the Portuguese Douro River basin. For the first time, it was possible to study some of the effects of the barriers installed along these basins because the work of georeferencing and characterization of them had never been done before. Thus, this step opened the door to the possibility of several studies to be carried out in this context and in the most varied areas, henceforth. The purpose of this article was accomplished. A siltation risk map of the georeferenced barriers was obtained, caused by a series of years of forest fires associated with soil losses. It was found that when the parameters of fire frequency, soil erosion and frequency of barriers are analyzed in conjunction and applied to the Douro sub-basins, it is possible to predict the siltation risk of these sub-basins and corresponding barriers. There was a very high level of risk in the Tâmega, Corgo, Paiva and Sousa rivers. The 20 barriers with the highest risk of silting were identified, which are found in Corgo and Paiva. Of these 20 barriers, it was found that all are small dams, which are located mainly in forest and semi-natural areas.

In order to analyze the relationship between the highest siltation risk areas and water quality and connectivity, the model developed was compared to the connectivity model developed in [42] and to the concentrations of phosphorus (associated with the sediments that flow into the rivers due to the fires) present in the same basins and barriers. The responses to this analysis are inconclusive. In both comparisons, it was demonstrated that there is a little expression when both parameters are overlapped. Thus, either the parameters are not directly related, or there may be other factors that are disguised and do not allow to verify the relationship between them. With this, it appears that more studies must be carried out, in order to understand better the dynamics involved in the silting context of this basin.

This type of planning studies of the territory in relation to the identification of areas at risk of silting up is inexistent. However, these would certainly be an asset in order to prevent the occurrence of silting by cleaning or clearing the reservoirs in those areas, during forest fires, for example. This work now proposes an innovative model for planning and assessing obstacles in a large watershed, including large and small dams. With this model, it will be possible, in the future, to plan new infrastructures, mitigate or remove the old ones to improve ecological impacts and obtain socioeconomic benefits.

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