GIMA
Geographical Information Management and Applications

Mapping fire-induced water contamination risk in Portugal

Universiteit Utrecht
TU Delft
University of Twente.
Wageningen UR

Joost Schuurman
6866794
j.a.schuurman@students.uu.nl

Colophon

This thesis is submitted in fulfillment of the Master of Science Degree Programme in Geographical Information Management and Applications (GIMA) - Utrecht University (UU), Wageningen University (WUR), Delft University of Technology (TUD) and University of Twente (ICT)

Title:	Mapping fire-induced water contamination risk in Portugal
Date:	03-03-2023
Author:	Joost Schuurman
Responsible Professor:	Ron van Lammeren (WUR)
First Supervisor:	João Carvalho Nunes (WUR)
Second Supervisor	Joana Parente (University of Lisbon)

This master thesis is part of (and supervised by) project FRISCO (Fire-induced RISks of water quality COntamination), founded in 2020, which aims to gauge the vulnerability of Mediterranean surface water resources to fire-induced contamination. Project FRISCO is based in Portugal and consists of scientists from the Universities of Lisbon, Aveiro and Wageningen, as well as representatives from Portuguese water and forest managers. Project FRISCO is funded by the Portuguese Fundação para a Ciência e a Tecnologia (Foundation of Science and Technology).

Acknowledgements

I would like to thank my supervisors, João Nunes and Joana Parente, for their excellent guidance throughout this thesis project. They are deeply involved in this field of study and always give meaningful answers to difficult questions. Moreover, they found time for weekly meetings, keeping my progress on track. And quite importantly, their positive attitude was a significant morale boost, especially during the later stages of this thesis. I would also like to thank Luís Diaz (who is also part of project FRISCO), who was not an official supervisor, but attended many meetings where he provided valuable insights.

Table of Contents

1. Abstract

Wildfires can have severe impacts on humans and nature. One such impact pertains to changes in water quality resulting from the generation and transportation of ash into bodies of water. The quantity and content of this ash can affect the water quality, and thereby the drinking water supply. The Mediterranean region and Portugal specifically, have been, and are increasingly expected to be affected by fire-induced water contamination. Current research has focused on local evaluation of impacts, as well as the global identification of areas at risk. What lacks is the assessment of fire-induced water contamination risk at an intermediate scale, which can be used as a basis for the efficient allocation of efforts mitigating this risk. This study performed a risk assessment of Portuguese reservoirs based on their historical exposure to wildfires, their drinking water dependency and their vulnerability to fire-induced water contamination. A general risk index was established through the creation and combination of hazard and exposure indices, reflecting a reservoirs' drinking water dependency and historical exposure to wildfire respectively. The former was based on data on the yearly water uptake from drinking water facilities at a reservoir. The latter was based on the processing of 32 years of historical data on wildfires and reflects to which extent and frequency reservoirs' watershed areas have been burned. This was followed by further analysis at local scale, consisting of (1) a more relevant method of measuring exposure that includes historic reservoir volumes, as well as (2) an exploration of the vulnerability of several water supply systems. This study has produced a nationwide overview of fire-induced water contamination risk as well as of the degree to which the hazard and exposure concepts contribute to this risk. Numerous differences were found regarding the degree to which individual reservoirs are at risk. These can be ascribed to various regional differences, concerning vegetational, meteorological and land use conditions, as well as local differences as a consequence of water infrastructure design, mitigation measures and the availability of alternative sources. Hence, these results can be used to identify areas at risk, and to evaluate what type of mitigation measures should be implemented and to what extent. Further analysis on exposure has provided an improved method of estimating the exposure of a reservoir to fire-induced water contamination. This measure estimates the yearly probability of the occurrence of significant changes in total suspended sediment concentrations for individual reservoirs. Further analysis on vulnerability has most importantly shown that increasing the size and interconnectivity of water supply systems decreases their vulnerability to fire-induced water contamination. These findings contribute to the understanding of fire-induced water contamination risk in Portugal. Further studies can improve on this work by (1) applying the improved exposure measure and exploring the correlation between reservoir volume and fire size, (2) creating a more detailed hazard measure that possibly includes the dependence on other water sources and (3) assessing and including projections on the possible impact of climate change and its effects on meteorological and vegetational conditions.

2. Introduction

Wildfires can be devastating events that create life threatening situations, destroy buildings and infrastructure as well as natural areas and their ecological habitats; they can produce air pollution with health impacts on local populations and generate various additional expenses (Reid et al., 2016; Diaz, 2012). Besides these direct impacts, there can be relatively long-term consequences that are less straightforward, but can pose similarly serious problems. This applies to soil degradation, vegetation changes and water contamination (Shakesby, 2011; Verkaik et al., 2013; Bodi et al., 2014), the latter of which is the focus of this study. Wildfires can generate large amounts of ash which travels along streams and rivers and ends up in water reservoirs that people depend on for drinking water (Smith et al., 2011; Reneau et al., 2007). The water can become too loaded with fine sediments to be processed by water treatment facilities, leading to a disruption of local water services (Writer & Murphy, 2012; Langhans et al., 2016; Robinne et al., 2021).

The subject is highly relevant in Portugal. Its Mediterranean climate makes the country prone to wildfires. Within the Mediterranean region, Portugal experiences a relatively high wildfire incidence (Catry et al., 2009). In the past, the country has been highly dependent on groundwater sources for their drinking water (Ribeiro, 2007), there are worries that this source is increasingly unsustainable due to increased consumption and future climatic effects (Nunes et al., 2006; Stigter et al., 2017). Over roughly the last 20 years, the country has been steadily increasing their reliance on surface water sources through the improvement of surface-based water collection and distribution infrastructure in general, and the construction of additional artificial reservoirs in particular (Thiel, 2010b; Meneses et al., 2017; Carvalhos et al., 2017). These reservoirs are often located in mountainous areas, as valleys are suitable storage areas. Within Portugal, these mountainous areas are often covered by forests, which contributes to their fire risk (Parente & Pereira, 2016). Consequently, reservoir based water supplies have been under pressure by wildfire induced contamination before. For example, in 2013 and 2017, Lisbons' water supply was threatened leading to costly mitigation efforts such as emergency slope stabilization and water treatment upgrades (Robinne et al., 2021).

The situation becomes more problematic when climate change is considered. Portugal and other Southern European countries will see an intensification of the hydrological cycle, leading to more frequent and longer droughts, as well as more extreme precipitation events (Soares et al., 2015). Drought conditions lead to hotter and longer fire seasons (Calheiros et al., 2021), which is associated with increasing fire occurrence and fire size (Beighley & Hyde, 2018; Turco et al., 2019). In addition, droughts lead to lower water levels in reservoirs, making them more susceptible to contamination as there is less water available to dilute fine sediments (Nitzsche et al., 2022). Moreover, extreme precipitation events can contribute to increased erosion of ashes and sediments, increasing their transport into reservoirs (Paul et al., 2022). In short, climate change contributes to the risk of water service disruption on multiple levels.

The threat of fire-induced water contamination has been extensively studied in local and global contexts, but what is lacking is the application of gained knowledge to identify areas at risk at national and regional levels of scale (Robinne et al., 2021). This study attempts to fill this research gap by performing a national assessment of Portuguese reservoirs and their risk to fire-induced water contamination. It applies the findings of Nitzsche et al. (2022) on the conditions under which reservoir contamination takes place to individual Portuguese reservoirs and includes the potential impact of such contamination events, as well as considers the vulnerability of the water supply systems in these reservoirs.

2.1 Background

The Mediterranean region is particularly associated with wildfires. Its climate causes long and dry summers, with relatively wet winters (Amraoui et al., 2015). Vegetational characteristics promote high-intensity and fast-spreading wildfires due to the typically high surface area to volume ratio (can be read as the density of individual plants and trees) causing vegetation to dry out quickly, as well as the abundance and large accumulations of dead materials (Shakesby, 2011; Pereira et al., 2014). In addition, Socio-economic changes have contributed to the increase of wildfires since the 1960's in the Mediterranean region in general (Shakesby, 2011), as well as in mainland Portugal specifically, where this mostly pertains to rural depopulation, land abandonment and afforestation (Nunes et al., 2016). The former two of which illustrate the reduced management of lands, causing them to be overgrown by mostly scrub vegetation which can strongly accelerate the spread of wildfires (Nunes et al., 2016). The latter illustrates how increased land use, in this case afforestation with the goal of growing the timber industry, can create new areas that offer plentiful fuel for wildfires.

Besides the direct impacts of wildfires on human safety and the built environment, wildfires can also cause more long-term impacts on the health of the affected ecosystem. Soil quality can be severely degraded due to the heat exposure from the fire itself (Varela et al., 2015), as well as the consequential soil erosion caused by rainfall after the fire (Shakesby, 2011). On the other hand, wildfires generate nutrients that can help vegetation recuperate after a fire (Caon et al., 2014). However, this is only the case if these nutrients are not swept away by rainfall and remain in the affected area. Concerning the Mediterranean region, Shakesby (2011) claims: "Despite these instances of enhanced soil nutrient content associated with the fire event itself, the combination of high fire frequency and thin soils in a nutrient-poor ecosystem, typical of many fire-prone Mediterranean areas, causes the risk of soil fertility depletion to be high." (p. 21). This is not to say that the nutritional (and chemical) situation is balanced after a wildfire, even if nutrients remain in the affected area.

Wildfires can cause spikes in different nutrients, as well as in pH levels and other conditions affecting the ecology of the area (Bodi et al., 2014). Typically, erosion takes place when (high intensity) rainfall causes increased land overflow, capturing ashes which flow into bodies of water (Verkaik et al., 2013). The degree of ash capture is generally highest during the first rainfall after a fire after which sources of ashes and sediments are exponentially exhausted by subsequent rain events (Shakesby, 2011). The ecology of the affected bodies of water can be degraded by the inflow of materials and substances produced by the fire. Changes in the balance of nutrients can reduce local populations of fish as well as algae and other vegetation in the water (Verkaik et al., 2013). This is in addition to the influx of ash in large quantities which can, so to speak, smother the water bodies' ecology as it gets covered by a layer of non-transparent sludge.

Another distinction can be made for the type of water contamination that can occur after a wildfire. Much attention has been paid to the mobilization of toxic substances such as polycyclic aromatic hydrocarbons and heavy metals (Smith et al., 2011). On the other hand, there is the concern for mobilization of large quantities of ash. The ash generated by a wildfire descends on the ground and will, in practice, inevitably be mobilized and carried downstream by fresh rainfall. When it is mixed with water, ash acts as fine suspended sediment, creating a turbid, sludgy substance. At a certain threshold, the filtration capacity of water treatment facilities can be exceeded, which causes the facility to come to a halt, which in turn leads to a disruption in the supply of water (Hampton et al., 2022). Part of the work done by project FRISCO (see: colophon) consists of communicating with Portuguese water companies to get a better perspective on fire-induced risks to the water supply. From their talks, the following claims can be made. Portuguese water companies have indicated that the former type of contamination is actually less problematic than would be expected. They can measure the presence of these toxic substances, and have relatively simple means to adapt their treatment process to have these substances extracted. Ash-based contamination, however, is considered to be of larger threat to their treatment facilities as the water becomes too sludgy to be processed at all.

Disrupted water services can have large impacts on the water security of local populations (Robinne et al., 2021). In Portugal, there are enough measures in place to ensure that no one goes thirsty. Yet, responses like additional filtering, upgrading treatment facilities, diverting water or delivery by water trucks can be very costly (Girona-García et al., 2021; Paul et al., 2022). In essence, diverting a bulky, widely-used and essential resource such as water can become extremely expensive. The same goes for other efforts that aim to reduce the quantity of ash to reach the water supply such as the actual fire-fighting efforts and emergency slope stabilization (Girona-García et al., 2021).

Generally speaking, climate change intensifies the risk of wildfires accompanied by water contamination in already fire prone areas, it also creates wildfire risks in areas that were not under threat before. In both cases, water supply systems were often not built to deal with the (increased) threat of wildfire induced contamination. Upgrading these systems requires large investments and takes considerable time to take effect. For these reasons, this is now deemed as a global problem (Robinne et al., 2021).

Regions with a Mediterranean climate, such as Southern Europe, California and Eastern (coastal) Australia, often have developed ways to mitigate wildfires and their impacts as a result of their past experience (Flannigan et al., 2009). Yet, they may still face significant challenges as wildfire seasons may intensify to such a degree that large areas will burn each year (Liu et al., 2010), obstructing the possibility for nature to fully recuperate. Effectively, this is due to increasing frequencies and durations of droughts and heatwaves, which generate more and larger wildfires, especially when they coincide (Parente et al., 2019; Richardson et al., 2022; Ramos et al., 2023). Paradoxically, total burned areas will increase in the short term, as the current state of forests provide large amounts of dry fuel, while in the long-term, generally higher temperatures and longer heatwaves lead to vegetational changes that can transform lush forests to bush- and grasslands with less fuel to be burned by wildfires (Gouveia et al., 2012; Calheiros et al., 2021). As there is less fuel available and therefore less ash to be generated by wildfires, the risk of water contamination decreases. However, this is likely the only positive result of this process.

Calheiros et al. (2021) studied the possible effects of climate change on pyro-regions in Portugal on the basis of the number of extreme days per year. Currently, Portugal can roughly be divided into two major pyro-regions where the Northern half of the country, mountainous and densely forested, still has a relatively smaller number of extreme days compared to the more arid plains in the South. Their projections show that the Southern pyro-regime will move upwards into the Northern regions, triggering the process described in the previous paragraph, the only uncertainty being the degree to which this process will happen. This puts Northern Portugal at the cusp of major changes in fire trends which will transform its landscape gravely, but not before triggering increasingly large and frequent wildfires that can put major stress on the water supply system. While this study analyzes the current situation, and thus will not consider future effects of climate change, the above description underlines the relevance and urgency of understanding fire-induced water contamination.

3. Theoretical framework

The field of study is currently in the situation where the relation between wildfires and water quality is generally well established. Wildfires generate substances that can and will be mobilized into bodies of water where they affect the physical, chemical, nutritional and metallic properties of the water (Hampton et al, 2022; Paul et al., 2022; Raoelison et al., 2022). These effects, too, have been monitored in Portugal, especially following the 2017 fire season (Sequeira et al., 2020a; Basso et al., 2021). Differences in when (how long after a fire) and to what degree these substances reach and contaminate water bodies are ascribed to geographical (slope and vegetation), hydrological (transportability of substances) and meteorological (precipitation after a fire) properties of the affected area, as well as to the properties of the fire itself (intensity, size, type of burned vegetation) (Smith et al., 2011; Moody et al., 2013; Campos & Abrantes, 2021; Pacheco & Fernandes, 2021).

The implications of fire-induced water contamination have been explored at the global scale, with high risk areas being identified in global studies (Robinne et al., 2016; Robinne et al., 2021; Hampton et al., 2022). What lacks, however, is the application of the gained knowledge in this field to risk analyses at a level of scale between the local and the global.

Robinne et al. (2021) review the current state of wildfire-watershed risk governance at the global scale. The authors highlight the need for increased academic efforts in the field of fire-induced water contamination. They justify this by the foresight of an upcoming global challenge, where climate change will introduce new regions to the dangers of wildfires to their water supply. The authors conclude with the following: “Hence, wildfire-watershed risks (WWR) represent a global challenge that must be addressed through proactive forest and water governance, starting with identification of areas at risk. We must then strategically apply innovative risk reduction strategies to address long-term, large scale impacts from catastrophic wildfires in source watersheds.” (Robinne et al., 2021: p. 1). The identification of areas at risk is the step that this thesis tries to take for mainland Portugal. This step is essential because it forms the bridge between global studies on the problem and the implementation of real-world mitigation efforts.

Identifying fire-induced water contamination risk for Portugal can be done at the level of scale where research units constitute individual rivers and their watersheds. While wildfire risk by itself has been extensively researched, the consequential risk of water supply contamination is still at a younger stage. Currently, studies within Portugal are limited to the evaluation of water quality in individual reservoirs following individual fire seasons (Coelho et al., 2011; Sequeira et al., 2020a; Sequeira et al., 2020b; Basso et al., 2021). These studies are valuable contributions to the field, but lack the spatial and temporal scale to assess fire-induced contamination risk at a national scale. Such a risk assessment can show which watersheds are more exposed to wildfires and are thus more likely to be contaminated. Moreover, the potential impact of this contamination can be examined through the dependence on individual water treatment facilities. To elaborate, a hypothetically large wildfire can have a low potential impact if it takes place in a watershed on which a small part of the population depends. Alternatively, large problems can arise when even average sized wildfires impact watersheds on which entire cities rely. In short, performing a nationwide risk analysis based on the potential exposure to water supply disruption as a result of wildfires, and the potential impact of such a disruption, can give policymakers valuable insights that contribute to the proper allocation of mitigation efforts.

This study explores the risk of fire-induced water supply contamination by building on the results of Nitzsche et al., (2022), which explores fire effects on water quality in reservoirs. The conclusion can be made that there are two main drivers for significant changes in Total Suspended Sediment (TSS) in a reservoir: total burned area as a percentage of the watershed area and reservoir volume in the post-fire-year. As previously discussed, the current study limits itself to ash-based water contamination, which acts as a suspended sediment, making this conclusion highly relevant.

These findings allow for a further analysis that maps the potential exposure to water contamination based on historically burned areas and historical reservoir levels (representing the aforementioned drivers). Historical data can be quantified and applied to individual reservoirs and their watersheds. Combination of these datasets can then be used to identify the relative exposure of reservoirs to fire-induced water contamination. Further combination of the relative exposure with the aforementioned quantification of dependence on each reservoir (or: hazard of water supply being impacted) provides a risk map that reflects each reservoirs' risk of fire-induced water contamination.

Nunes et al. (2018) propose a framework for evaluating post-fire water contamination risk, which describes each stage of post-fire water contamination (Figure 1). The study by Nitzsche (2022) showed that in the case of the selected reservoirs in Portugal, Tier 2 and Tier 3 (the mobilization of contaminants and transport to the water asset) of the framework are relatively irrelevant for risk assessment purposes. The most significant drivers of suspended sediment contamination are fire size (relative to the watershed area) and reservoir volume (relative to its maximum capacity). This implies that the mobilization and transport of contaminants (suspended sediments in this case) is bound to happen sooner or later. The downriver reservoir will eventually receive the contaminants, regardless of how quickly they are mobilized and transported. These parameters, then, are more relevant in river-based water supply systems but are not crucial for reservoir-based supply systems.

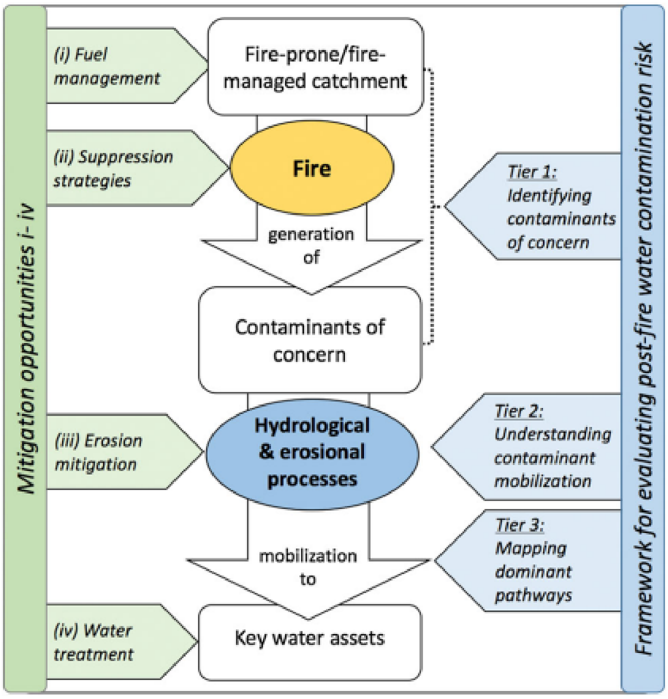

Figure 1, Framework for evaluating post-fire water contamination risk (Nunes et al, 2018, p.2)

Therefore, when this study is placed within the above described framework, a direct connection between the 'fire' and 'key water assets' fields is made. The evaluation of risk for key water assets is based on the probability that fire conditions (burned area as a % of the watershed area), as well as conditions at the key water assets (reservoir volume as a % of the maximum capacity), are such that the situation can lead to reservoir contamination. Additionally, this study expands on the framework by including the potential impact of such contamination to the evaluation of post-fire water contamination risk.

4. Research Objectives

This study explores the risk of water contamination as a result of wildfires in Portugal at a national scale. Conceptually speaking, this study applies the *'risk = hazard * exposure * vulnerability'* framework (Figure 2). This framework is commonly used in studies on natural disaster risks (Peduzzi et al., 2009; Carrão et al., 2016; Ward et al., 2020; United Nations, n.d.), and essentially approaches the question of total risk as a product of the *hazard* (that which poses a threat and the population/assets that would be affected by this threat), the potential *exposure* to this hazard (or: the likelihood that this threat occurs) and the *vulnerability* to this hazard (susceptibility to this hazard and the ability to cope with/adapt to its disturbances).

Figure 2, Risk as a function of hazard, vulnerability and exposure (United Nations, n.d.)

This study applies this framework to individual water reservoirs and their risk of fire-induced water contamination. *Hazard* is represented by the degree of dependence upon a reservoir, *exposure* is represented by the probability of a reservoir being contaminated, and *vulnerability* is represented by mitigation options (such as the availability of alternative supply). However, due to lacking data availability and general complexity, just the exposure and hazard dimensions can be included in the national risk analysis applied to the selected reservoirs.

Historical records of wildfires and reservoir volumes allow an estimation of exposure nationwide. Data on water uptake points, including their consumption volume, can be used to estimate the degree of dependence and therefore the hazard of such an uptake point coming to a halt. There are, however, no standardized options to map vulnerability in terms of available alternatives and mitigation measures due to inherent variability and lack of standardized national data. For example, data on connections between reservoirs, and the transport capacity of these connections exists only in narrative format in Portuguese, making it infeasible for this study to compile this information into a workable, nationally-applicable measure. Additionally, the situation becomes more complex when other options are included such as the possibility to increase filtering capacity (yes or no? And to what degree?) and the expected distance and quantity of water to be transported by truck.

Effectively, the vulnerability aspect cannot be included at the national scale, but this does not mean that there is no knowledge on the subject or that there is no local/regional data that can provide insight on the vulnerability of specific (groups of) reservoirs. This knowledge could add to this study by, for example, showing that a certain reservoir, for which the national analysis produced a high risk factor, is actually relatively invulnerable to fire-induced water contamination because it is connected by canals to other reservoirs. Thus, our risk estimation for this reservoir could be adjusted to more accurately reflect the actual risk. The same principle applies to enhancing the exposure variable for certain reservoirs. Historical measurements of reservoir volumes can provide insight into the probability of having dry, normal or wet post-fire-year conditions; and thus provide insight into the dilution capacity. Yet, these measurements are only publicly available for the larger reservoirs. This means that, for these reservoirs, an additional analysis could be performed that includes this parameter into the exposure index.

The following approach was chosen: the first phase consists of a national risk assessment to get a general insight of reservoirs that are at risk of contamination. The second phase analyzes these results further by exploring specific situations in which additional processes might add to or mitigate the effects of fire-induced water contamination. The flowchart in Figure 3 shows the structure, and how each of the following research questions fits within it.

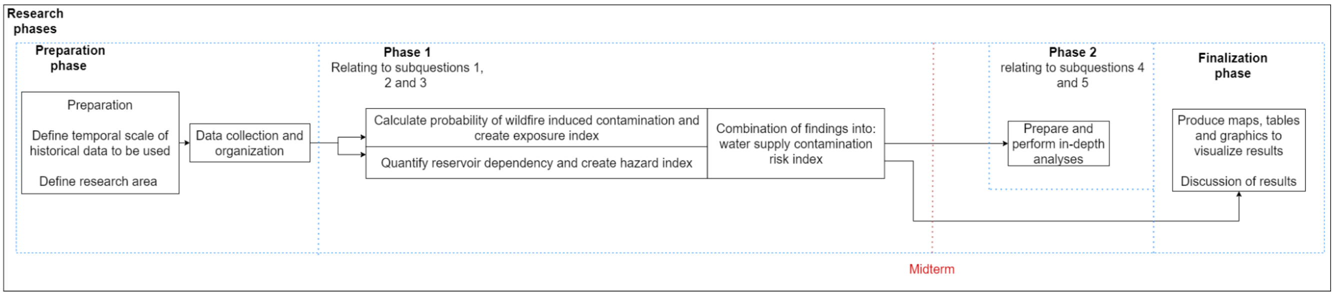

Figure 3, Flowchart of research process

The main question this study answered is to what degree are Portugal's reservoir based water supply systems at risk of fire-induced water contamination? To do so the following questions have been answered to assess risk of contamination of reservoirs at a national scale in Phase 1

RQ1.1 - Based on the post-fire water quality contamination index provided by Nitzsche et al. (2022), what is each reservoirs' yearly probability of being contaminated to such an extent that water services require additional treatment?

RQ1.2 - What would be the hazard of contamination of each reservoir in terms of reservoir dependency?

RQ1.3 - What is the risk of water supply contamination for each reservoir when taking both contamination probability and reservoir dependency into account?

In Phase 2 the following sub questions have been answered to analyze at a more local scale results of Phase 1 by exploring specific situations in which additional processes might add to or mitigate the effects of fire-induced water contamination.

RQ2.1 - How can a more comprehensive assessment of exposure be implemented for a selected area to add local insights on fire-induced water contamination risk?

RQ2.2 - How does adding vulnerability of the water supply network on a local scale to the risk assessment framework lead to added insights on fire-induced water contamination risk?

5. Methodology

As was shortly mentioned before, this study contains two major phases; the first being a quantitative approach to estimating the risk of wildfire induced water contamination for each selected reservoir. The second phase consists of a more qualitative approach to explore additional characteristics of and implications for specific regions and/or reservoirs that stood out in the first phase.

5.1 Preparation and delineation

The main objective of Phase 1 is to create an overview of the general distribution of water supply contamination risk as a result of wildfires in Portugal. This risk is calculated following the “risk = exposure * hazard” framework. Therefore, the specific objectives are to create hazard- and exposure indices that can be combined (or: multiplied) into a ‘water supply contamination risk index’. A step-by-step methodology is provided in the following sections.

5.1.1 Research area & period

The research area is adopted from Nitzsche et al. (2022). The included reservoirs and their watershed areas are shown in Figure 4. Each watershed feeds into a single reservoir at its lowest point. When there is an upstream dam, the watershed is considered to end there as the dam is assumed to retain ashes and sediments.

The year 1990 was chosen as the start of the research period, which applies to the burned areas caused by wildfires in different years. Standardization of the measurement of burned areas was implemented 1990, which resulted in non-uniformity of data between years before and after this change. Data is available until 2021, which is thus taken as the end-year of this study. The total research period is therefore the 32 year period of 1990 to 2021.

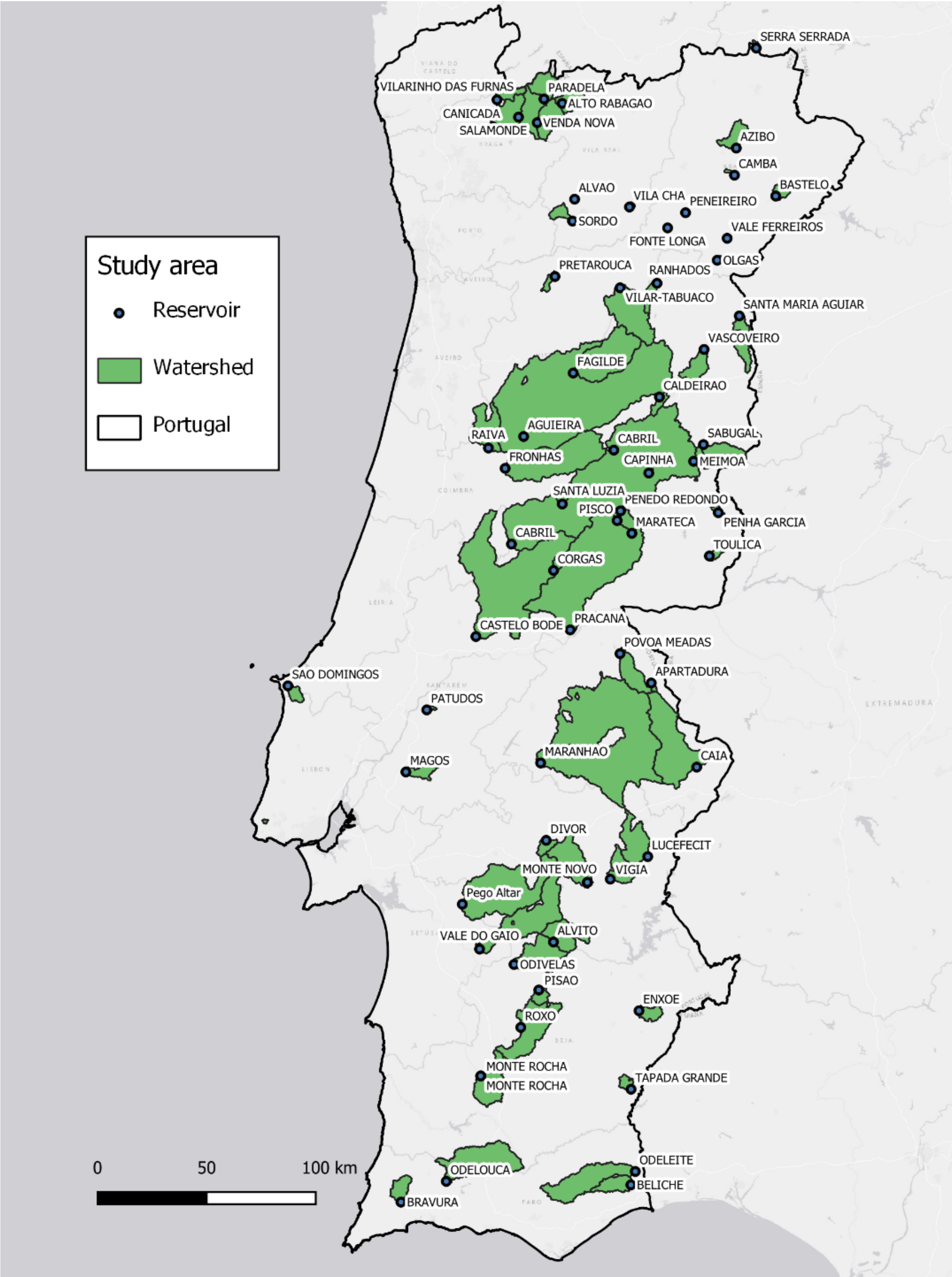

Figure 4, Research area

5.1.2 Data overview

The following overview (Table 1) shows the data gathered for each major step of the research process. It is important to note that later steps can include data that was already gathered for a previous step.

	Dataset	Data format (including unit of measurement and period of acquisition where relevant)	Data Source
General data	Watershed areas	Polygon shapefile of watershed areas of individual reservoirs	Calculated by Nitzsche et al. (2022) through Digital Elevation Model (DEM) analysis
	Reservoir areas	Polygon shapefile of individual reservoir areas	Administração Pública (2021)
Phase 1			
Hazard Index	Water uptake points and their yearly uptake volumes	Point shapefile with yearly uptake volume (hm^3) of all surface water uptake points in Portugal in 2018	Agência Portuguesa do Ambiente (2022)
Exposure Index	Historical burned areas	Polygon shapefile with all burned areas for each year within the range of 1990 to 2021	Instituto da Conservação da Natureza e das Florestas (2023)
Phase 2			
In-depth analysis - exposure	Historical reservoir volumes	Table of monthly volume measurements (10^3 m^3) for each individual reservoir within the range of 1990 to 2022	Agência Portuguesa do Ambiente (2023b)
In-depth analysis - vulnerability	Suspended sediment concentrations	Table of monthly measurements of the concentration of total suspended sediments (mg/l) in the Bravura reservoir between 2002 and 2004.	Agência Portuguesa do Ambiente (2023b)

Table 1, Data overview

5.2 Phase 1: RQ 1.1 – RQ 1.3

5.2.1 Hazard index: reservoir dependency

Data on the yearly uptake of surface water uptake points in Portugal is available and allows for an estimation of population dependency on such points. Higher uptake volumes imply that larger populations are reliant on this source, which in turn imply larger potential implications of reservoir contamination. Water uptake volumes are provided in cubic hectometers per year (as measured in 2018).

First, a selection is made on the water uptake points to be included in the analysis. This is done based on a number of conditions. Firstly, water uptake points are excluded if they are not located within the watershed areas used in Nitzsche et al. (2022). Secondly, river based uptake facilities, as opposed to reservoir based uptake facilities, are excluded in the quantitative analysis. Furthermore, where multiple uptake points exist in a single reservoir, they are merged into a single point, and their yearly uptakes are added up. Each point now represents the total uptake from a single reservoir, regardless of there being multiple uptake facilities tapping from the same reservoir. Effectively, this results in a map of each reservoir, the dependence upon this reservoir and its respective watershed area; wildfires occurring within this area can pose a threat to the drinking water uptake from this reservoir.

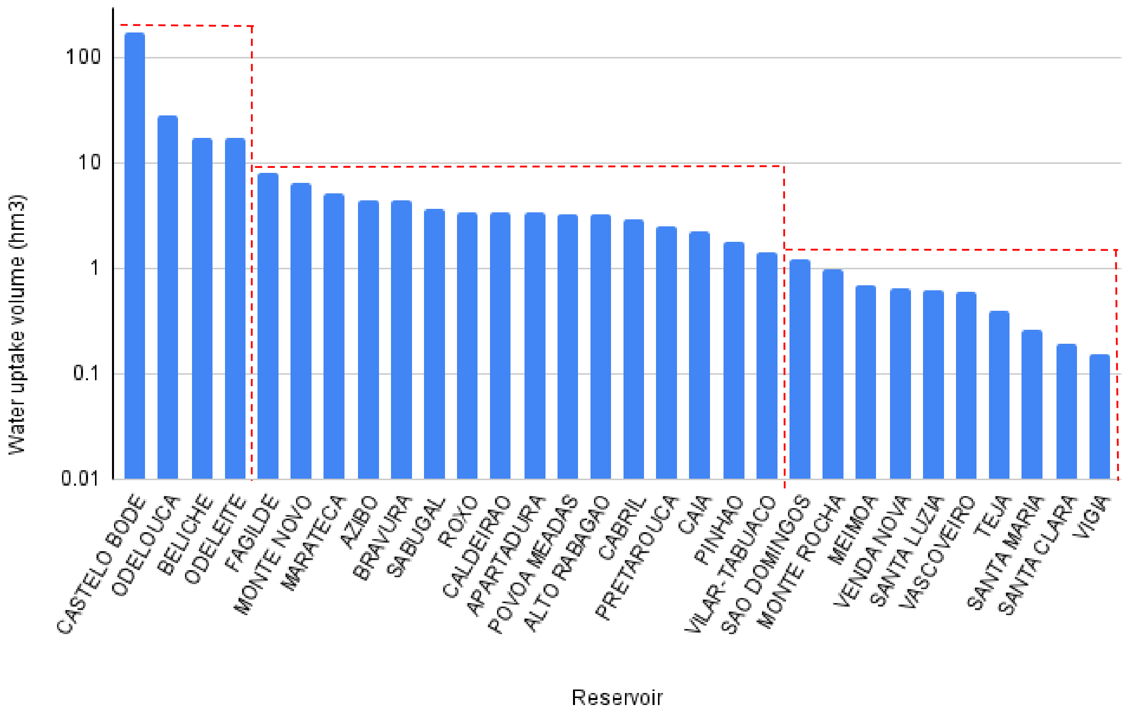

Figure 5, Water uptake volumes in 2018 (hm3) per reservoir on a logarithmic scale

Having organized the water uptake data into single points representing the total water uptake from each reservoir, the values are now normalized into an index. This is done because the index will be used for the calculation of the risk index at a later stage and its contribution should be equal compared to the exposure index. This is in accordance with the risk assessment framework followed by this study (United Nations, n.d.). The decision was made to deviate from a simple linear index due to the exponential distribution of water uptake values (Figure 5); a large share of reservoirs have no or very low amounts of drinking water uptake; a smaller but significant share of reservoirs have an uptake between 1 hm3 and 27 hm3 per year; one single reservoir has an uptake of 172 hm3 per year. Thus, there are three distinct classes of water uptake that the index should reflect.

11^3 = 1331
12^3 = 1728
13^3 = 2197

Figure 6, log base numbers to the third power

A logarithmic function is therefore used to calculate this index. To make the data suitable for such a function, all values must be 1 or higher. As there are a few values ranging between 0.1 and 1 hm3, all values are multiplied by 10. The highest value is now 1722 (172.2 hm3 * 10). Finding the most suitable log() base number to be used is done by comparing *x^3=y* functions and finding for which x, y is closest to 1722 (as can be seen in Figure 6). Log(12) is chosen for the indexation formula.

The uptake volume values are applied to the following indexation formula:

Log(12, "uptake volume") / 3.

The log() function produces values between 0 and 3, which are consequently divided by three to create a normalized hazard index ranging from 0 to 1. Values in this index should be interpreted on the basis of the above discussed methods. It should be noted that the interpretation will be done on the basis of six hazard classes (where each iteration is represented by two classes), in order to provide an additional level of detail. The hazard index is ready to be used in the final risk calculations, which can be found at the end of this chapter.

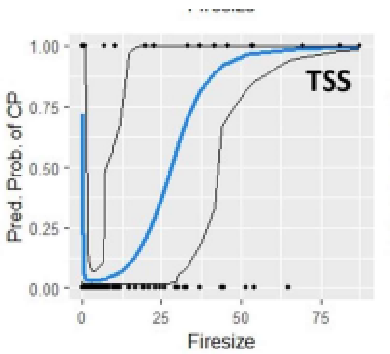

Figure 7, Effect of fire size on the probability of significant changes in total suspended sediments (Nitzsche et al, 2022, p.25)

5.2.2 Exposure index: probability of occurrence of water supply disruption

As mentioned, this study applies the findings of Nitzsche et al. (2022) to the calculation of fire-induced water contamination risk of individual Portuguese reservoirs. This warrants a more precise discussion of this work, and how its results will be used in this study.

Nitzsche et al. (2022) use changepoint analysis to assess fire-induced water contamination events in over 60 Portuguese reservoirs. The authors evaluate the degree and type of contamination along six indicators of water quality: biological oxygen demand (BOD), conductivity (COND), total phosphorus (TP), nitrate (NO3), total suspended sediments (TSS), and pH. The study subsequently attempts, through logistic regression analysis, to identify possible drivers (in terms of wildfire-, watershed-, climatic- and reservoir-based characteristics)

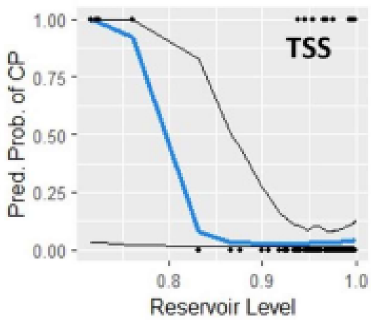

Figure 8, Effect of post-fire-year reservoir levels on the probability of significant changes to total suspended sediments (Nitzsche et al, (2022, p.28) to changes in these substances. Effectively, it provides a comprehensive overview of specific drivers to fire-induced water contamination. It also identifies increased levels of the TSS indicator as a potential threat to the water supply. For this indicator, two drivers have been found to contribute.

The study provides (1) the relationship between burned area as a percentage of the watershed and the probability of significant change in TSS in the reservoir at the bottom of the watershed. This relationship is expressed by a probability curve as can be viewed in Figure 7. It connects fire size to the probability of a changepoint, i.e. a statistically significant change, inTSS concentration (which could, in extension, threaten the water supply). Keep in mind that this is a combination of data from all selected reservoirs. The study also takes into account (2) the relation between reservoir volume in the post-fire-year (this is when the ash actually travels to the reservoir) and the probability of significant change in TSS. This reflects the ability of the reservoir content to dilute the suspended sediment and therefore influences the probability of a changepoint inTSS (Figure 8). Two conclusions can be made: (1) as fire size increases, the probability of changes in TSS increase and (2) as reservoir levels in the post-fire-year decrease, the probability of changes in TSS increase.

Project FRISCO has combined these findings into a cross-tabulation of burned area as a percentage of the watershed and post-fire-year reservoir level showing the probability of significant changes in TSS concentration. As this is ongoing work, there is no official documentation yet, but the team has provided this useful slide with an overview of their tabulation (Figure 9). The left-most graph shows the probability curves of fire size causing a significant change in TSS concentration at five levels of post-fire-year reservoir level. These probability curves were converted to discrete classes and tabulated to reflect the probability of impact by each class of burned area and reservoir level. Note that ‘post-fire-year reservoir level’ was alternatively named ‘fire followed by a drought/normal/wet year’. They chose to exclude the 90% - 100% and the <50% classes due to a need for simplification and because they represent just a small amount of data from Nitzsche et al. (2022). Effectively, this table provides the quantitative conditions that need to be met for a reservoir to be contaminated to such a degree that efforts have to be made to protect the water supply.

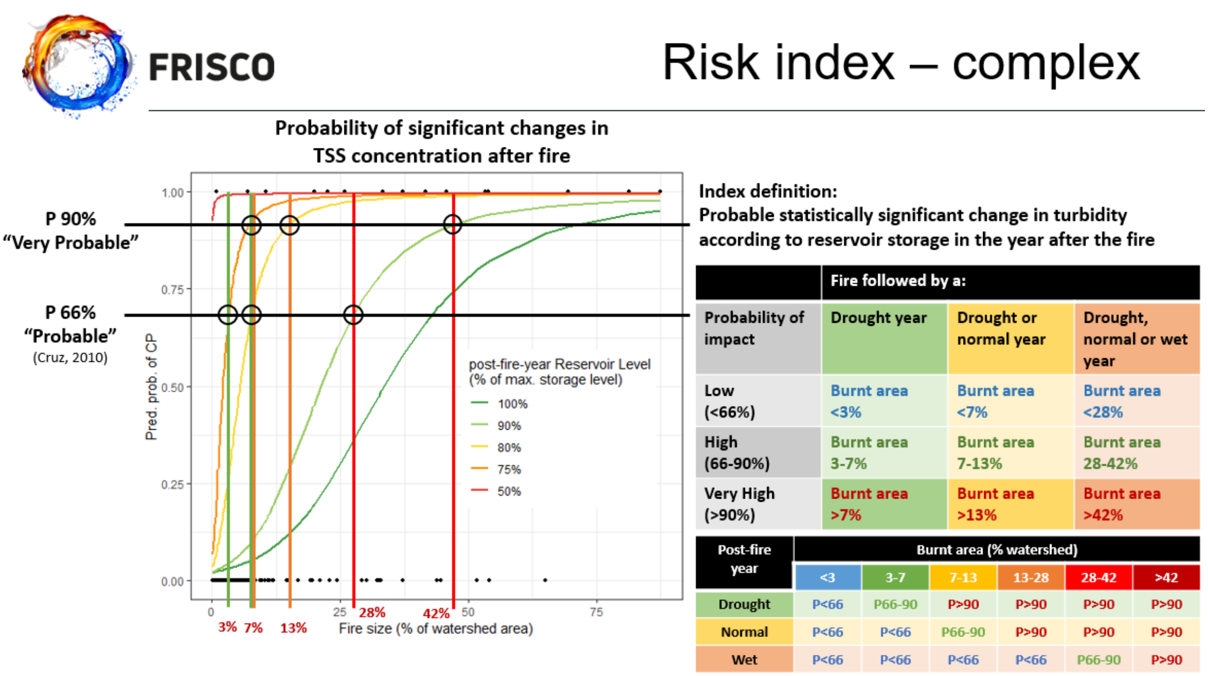

Figure 9, Probability of significant changes in TSS based on findings of Nitzsche et al, (2022). Slide provided by project FRISCO (2020)

Specifically, the probability of impact table in Figure 9 represents the probability of a wildfire causing a significant change in the Total Suspended Sediment (TSS) in a reservoir downstream, while taking into account post-fire-year reservoir level. Looking at the bottom right table (also placed in Figure 10, for the benefit of the reader), one can see that the five burned area classes relate differently to the probability of significant changes in TSS concentration along the lines of post-fire-year conditions. 'Probable (p66-90)' and 'very probable (p>90)' impact classes are reached at a certain burned area threshold. This threshold varies along the post-fire-year drought conditions (or post-fire-year reservoir level). This table allows us to relate the probability of wildfires burning over a certain threshold to the probability of these wildfires actually causing a disruption in water services. To accomplish this, the probabilities of wildfires occurring within a burned area class are added up to reflect the probability of a wildfire burning more area than the threshold value. The result is an overview of each reservoirs' probability of being impacted, following the five burned area classes.

Post-fire year	Burnt area (% watershed)					
	<3	3-7	7-13	13-28	28-42	>42
Drought	P<66	P66-90	P>90	P>90	P>90	P>90
Normal	P<66	P<66	P66-90	P>90	P>90	P>90
Wet	P<66	P<66	P<66	P<66	P66-90	P>90

Figure 10, Probability of significant changes in TSS by burnt area and post-fire-year conditions

It should be mentioned that the burned area class of less than 3% of the watershed is not calculated as this class is associated with a low probability of significant changes in TSS concentration, regardless of post-fire-year conditions. Furthermore, calculations are done for the remaining burned area classes, even though they are not necessarily required for the interpretation of results of Phase 1. However, this data is further used in Phase 2, which includes a deeper look into the probability of impact by including reservoir volumes in the post-fire-year as a measure of the probability of post-fire-year (dry, normal and wet) conditions. .

A step-by-step description, mainly performed in QGIS of reaching the exposure index follows. The watershed areas that were established in the *Research area & period* are applied to historical wildfire data from 1990 until 2021. Burned areas from individual wildfires are assigned to the watersheds in which they occurred. Where burned areas cover multiple watersheds, the polygons are split along their borders. Where multiple wildfires occur within the same watershed, their burned areas are merged into a single multiple-feature-polygon. Yearly total burned areas are then calculated for each watershed, as well as the burned area ratio (area burned / total watershed area). This results in an overview of burned area ratio per watershed of the last 32 years, to which the table from Figure 10 can be applied.

The above steps were heavily automated as they have to be performed 32 times, once for each year of study. This was done with the Qgis Graphical Modeler feature, that allows one to queue up multiple operational steps and then to batch-run these steps with the results being joined to an existing table. A concise overview of this model and the operations taken is provided in Appendix 1.

The overview of burned area ratios is compared to the burned area classes. This consists of counting the number of years that can be placed in each respective burned area class. The following steps are performed in Excel as Qgis does not offer a (simple) way to perform this counting action. Five columns are created, representing the number of years in which a wildfire burned 3-7%, burned 7-13%, etc.

The next step involves using return-periods to calculate the probability of wildfires occurring for each class. The return period, otherwise known as the average recurrence interval, can be used to quantify natural hazards (Sanabria et al., 2013). The return period of a natural hazard (exceeding a certain threshold of the phenomenon) can be calculated based on its yearly probability (which can be extracted from historic data) by applying Equation 1 (Coles, 2001; Sanabria et al., 2013):

$$RP = 1 / p \quad (1)$$

Where RP is the return period and p is the yearly probability. An example is provided; in a fictional watershed area, wildfires that burned more than 28% of the watershed occurred in three out of the last 30 years. The yearly probability of such a wildfire occurring is therefore 0.1. In extension, such a fire has a return-period of 10 years (RP = 1 / 0.1) within this watershed. An example is provided; in a certain watershed, wildfires that burned more than 28% of the watershed occurred in three out of 30 years. Such a wildfire can be defined as having a return-period of 10 years. In extension, the claim can be made that the yearly probability of such a wildfire occurring is 0.1.

Thus, Equation 2 is applied to the counted years of occurrence:

$$Pyearly = 1/(years\ of\ occurrence\ / \ 32) \quad (2)$$

Where 32 reflects the total years in the study period. This formula calculates return periods for each burned area class by dividing the counted years of occurrence by the total years of this study period. Dividing 1 by the found return period leads to the yearly probability of such a wildfire occurring. This is done for each burned area class in all watersheds, but in a cumulative manner. The result consists of five columns representing the yearly probability of a wildfire burning more than 3%, more than 7%, more than 13%, more than 28% and more than 42%.

While the probability values already fall between 0 to 1, the index is normalized so that it contributes equally, compared with the hazard index, to the final risk index. This is in accordance with the risk assessment framework followed by this study (United Nations, n.d.). A simple linear-based index is chosen here as the value distribution follows a roughly linear pattern. As it is imperative that the burned area classes remain comparable, the highest value from all classes (logically being in the 'more than 3%' class) is chosen to represent an index value of 1. This is a value of 0.531, meaning that, in this watershed, there is a wildfire that burns at least 3% of the watershed area roughly once every two years. Thus, Equation 3 is applied to all five probability columns:

$$Pindex = Pyearly * (1/0.531) \quad \textit{(3)}$$

Having calculated five indices for the exposure of watersheds to wildfires, the issue arises of how to continue with these findings. There are two options in terms of the continuation with these findings, the issue being that the values will be used in the following steps of the study for the calculation of risk, as well as the further calculations for in-depth analysis 2 in Phase 2. The first option is to multiply the five probabilities into a general exposure measure. The second option is to keep this separation of post-fire-year conditions throughout the remaining steps. The disadvantage of the first option would be the loss of detail regarding post-fire-year conditions. The disadvantage of the second option would be a potentially clouded overview and limitations to general conclusions that can be drawn on its basis.

A solution was found that prevents loss of detail, while providing a solid handle to analyze the contribution of the exposure index to the risk index. Looking at Figure 10, we can see that wildfires burning between 7% and 13% of their watershed area are associated with a 90% or higher probability of significant TSS change in dry post-fire-year conditions; such wildfires are also associated with a 66% to 90% probability of significant TSS change in normal post-fire-year conditions. Higher burned area classes are in turn associated with even higher probabilities of significant TSS changes. Wildfires burning more than 7% or higher should be considered a serious threat because there is already a high probability of such a wildfire impacting water services under normal post-fire-year conditions

Based on this claim, the choice was made to consider the exposure index of wildfires burning more than 7% of their watershed as the base exposure index. It should be noted that the exposure index for more than 7% burned area was readjusted to range from 0 to 1 in order for it to contribute equally to risk as the hazard index. The remaining indices can be used to explore differences in potential exposure to larger or smaller wildfires by comparing to this base index. In addition the remaining indices are used in the Phase 2 analysis of reservoir volumes.

5.2.3 Risk index: combination of hazard and exposure

As *'risk = hazard * exposure'* (vulnerability is left out in this phase), we can now multiply the constructed measures from the previous sections. The hazard of water supply contamination is represented by the hazard index and the degree of potential exposure to wildfires causing significant water supply contamination is represented by the exposure index. The water supply contamination risk index is reached by simply multiplying the hazard and exposure indices. Additionally, an 'Impact vs Probability Matrix' will be created to illustrate the findings. (Dumbravă & Iacob, 2013).

This concludes the methodological part of Phase 1. Maps and samples to be used to illustrate the results in later chapters are based on the dataset created by following the above calculations.

5.3 Phase 2: RQ2.1 – RQ2.2

Phase 2 consists of two in-depth analyses that serve as additions to the results of Phase 1. Firstly, the creation of the exposure index was based on fire size, while Nitzsche et al. (2022) showed that the other main driver of post-fire contamination is reservoir level. Data on the latter was largely unavailable, which is why the choice was made to use an in-depth analysis for those reservoirs that do have this data available. Secondly, the vulnerability aspect of risk was excluded from the national analysis due to complexity and data availability. Therefore, it is valuable to include this aspect in one of the in-depth analyses, even if it only applies to certain areas.

5.3.1 Exposure

As can be recalled from Phase 1, the exposure index is based on the probability of wildfires occurring above certain burned area percentage thresholds. As is shown in Figure 10, the probability of significant changes in TSS also depends on post-fire-year reservoir conditions.

The latter has so far been treated as a means to interpret the results of Phase 1, but purely in a hypothetical manner. Nothing can be said yet about the probability of having either dry, normal or wet post-fire-year conditions. This applies to both the general distribution of dry, normal and wet years, and possible regional differences that might exist within Portugal. Finding a measure that could shed light on this would be a valuable addition to the study as it would improve our understanding of the potential exposure to fire-induced water contamination.

Post-fire-year reservoir volumes reflect to what degree a reservoir is filled and therefore to which degree it is able to dilute ash. Reservoir volume measurements are performed daily, and are performed under supervision once every month, all of which are posted on the SNIRH website Agência Portuguesa do Ambiente (2023b). The most reliable option is to take the monthly, supervised measurements and create a yearly average. To match the data range used for the exposure index, reservoir volumes were included from the same period as is used to estimate wildfire probability: 1990-2021.

One caveat for this analysis, and the reason that it is separate from Phase 1, is that consistent reservoir volume data from the last 32 years is not available for all reservoirs in this study. The scope of this analysis is therefore partly decided by data availability. The other condition used for the inclusion of reservoirs is whether they are used to collect drinking water. There are six reservoirs that conform to the above conditions: Castelo de Bode, Cabril, Vilar-Tabuaço, Beliche, Bravura and Alto Rabagão. Additionally, there are two reservoirs with limited data: Odeleite (1997 - 2021) and Póvoa Meadas (1993 - 2021). This is simply due to the fact that they were not built before 1990. They are still included in the analysis because Odeleite is an important reservoir to consider in the Southern region, and Póvoa Meadas is missing only three years. Their first years are not representative of the post-fire year conditions as they are still being filled up, which is why data is included starting from the month in which they were first filled above 75%. In total, 8 of the 69 reservoirs are selected to be included in the following analysis. Reservoir volume data is retrieved from SNIRH (Agência Portuguesa do Ambiente, 2023b).

For each reservoir, the average yearly volume as a percentage of the maximum volume is calculated based on the monthly measurements. Each year, in this case, ranges from September to July, as September is the month in which the fire season generally transitions into the rainy season. This average is then categorized according to the categories defined by project FRISCO as can be seen in Figure 10. Yearly average volumes below 75% are considered ‘dry’, volumes between 75% and 90% are considered ‘normal’ and volumes above 90% are considered ‘wet’. Similarly to the calculation of return periods regarding burned areas in Phase 1, the return period of each category is calculated for each reservoir, after which it is converted to the yearly probability of having post-fire-year dry, normal or wet conditions.

The result is an overview of the yearly probabilities of post-fire-year conditions and the yearly probabilities of the burned area categories (established in Phase 1) for eight reservoirs. We can therefore calculate the yearly probability of the occurrence of significant changes in TSS for these reservoirs. This is done according to the table in Figure 10. Essentially, each field within this table can be filled in by multiplying the probability of the burned area column with the probability of the post-fire-year conditions row. This results in the probability of each specific combination of conditions for each reservoir. These are then added up according to the probability that these combinations of conditions will actually lead to significant changes in TSS.

5.3.2 Vulnerability

Methodologically speaking, this in-depth analysis is based on literature review, as well as some newly created datasets. This is a narrative analysis and there are no introductions of new methodological concepts. However, a short description on the selection of areas of interest, as well as additionally used data is provided below.

The aspect of vulnerability is evaluated along the lines of two case-studies. The selection of these case-studies depended on certain aspects. Within the last 20 years, Portugal has had a number of devastating fire seasons, the worst of which being in 2003 and 2017 (Trigo et al., 2006; Castellnou et al., 2018). Therefore, sources on contamination events were mostly sought in these years. Geographically, the case studies are limited to reservoirs that are used for the collection of drinking water. As this analysis is relatively explorative, and as Portugal lacks centralized documentation on mitigating wildfire induced water contamination, this analysis is limited by the availability of information.

Case-study 1 - Castelo de Bode and Ansião
Case-study 1 explores the impact of the 2017 wildfires on two water supply systems within the Castelo de Bode watershed. This analysis is based on a review of academic studies and local newspaper articles pertaining to the situation after the 2017 wildfires. Further, it is supported by the presentation of the geographical situation of these two water supply systems within the watershed, as well as an overlapping map of the burned areas in 2017.

Case-study 2 - Algarve
Case-study 2 explores the vulnerability to fire-induced water contamination of the water supply systems in the Algarve. As the water supply infrastructure in this region has seen extensive development in the last decades, an intertemporal comparison is made between the impacts of the 2003 and 2012 wildfires. This analysis is based on a review of academic studies and documents from the local water supply utility, as well as additional data retrieved from SNIRH (Agência Portuguesa do Ambiente, 2023b) on reservoir volume and water quality. Further, it is supported by the presentation of the geographical situation of the region in terms of hydrology and water supply.

6. Results

6.1 Phase 1 - Hazard, exposure and risk indices: RQ1.1 – RQ1.3

6.1.1 Hazard Index

The hazard index reflects the dependency of individual reservoirs and their watersheds for the collection of drinking water. The index shows the potential impact if a wildfire were to occur that contaminates the reservoir. A visualization of the hazard index can be viewed in Figure 11. Notice that some watersheds have a value of zero; the reservoirs collecting water from these watersheds are not used for the drinking water supply. The six-class classification of the values reflects the logarithmic data scale used for this index, representing each logarithmic iteration with two classes for added detail.

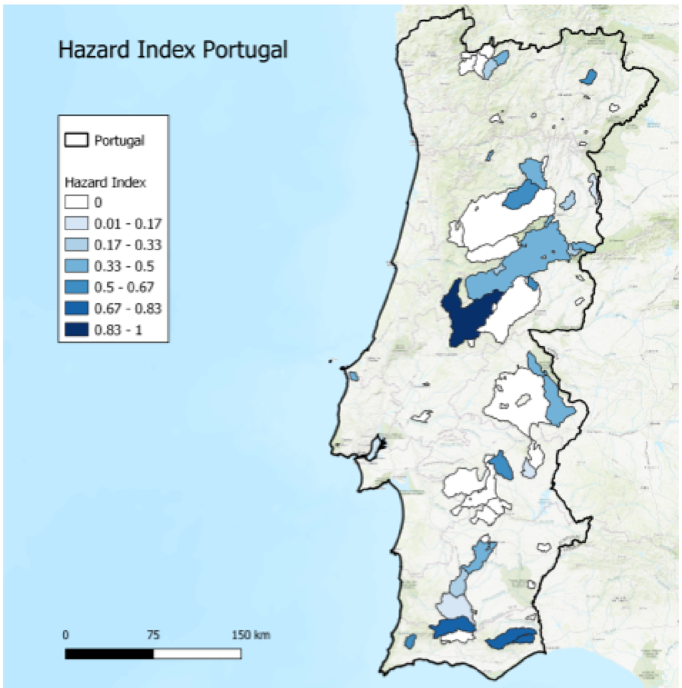

Figure 11, Hazard Index Portugal

One can find the reservoirs in the following discussion in the map of the research area (Figure 4). The Castelo de Bode reservoir scores highest on the hazard index. Within the central region, a number of additional reservoirs can be found with intermediate scores. Additionally, the southern region stands out with three reservoirs in the second-highest class: Odelouca, Odeleite and Beliche. The northern cluster scores relatively low on the index, reflecting the low degree of drinking water uptake from these reservoirs.

6.1.2 Exposure Index

Following the burned area classes as described in the methodology chapter, five indices are created (Figure 12). Each index thus reflects the watersheds' likelihood to be burned above the predefined percentages of its total area. A five-step equal interval classification was chosen as this is a simple linear index. Once again, there are some watersheds with a value of zero. These watersheds have not seen any wildfires burning more than 7% of its area in the last 32 years. Naturally, the overview shows the decline in likelihood as burned area percentages increase. Furthermore, the central region scores high across the board, meaning its watersheds are relatively fire-prone. The watersheds in the northern region score relatively high on the smaller burned area classes, but are barely represented in the classes of >13% burned area and above. Oppositely, watersheds in the southern region score relatively low on the smallest burned area class, while still being represented in the higher burned area classes.

As discussed in the methodology chapter, the “burned area >7%” exposure index was chosen to be used for the calculation of the risk index, requiring it to be re-normalized (Figure 13).

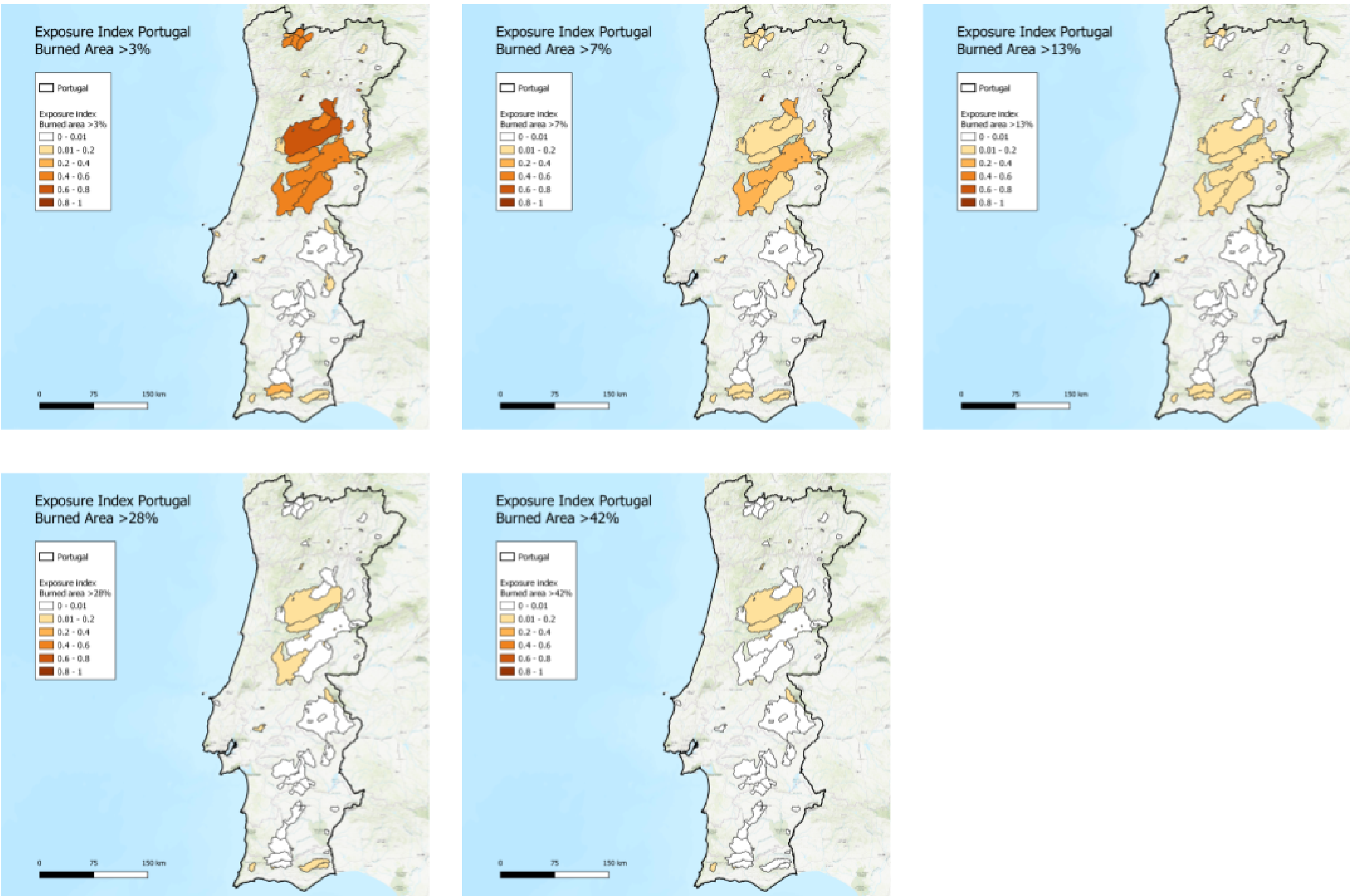

Figure 12, Exposure indices based on burned area classes

6.1.3 Risk Index

The risk index was created by multiplying the hazard and exposure indices and can be viewed in Figure 14. A five-class equal interval classification was chosen to reflect the differences in risk in a detailed manner. Watersheds with a value of zero also scored zero in the hazard index and/or exposure index. After all, if there is no potential exposure to a hazard, there is no risk. Similarly, there is no risk if there is no dependence on a watershed. The remaining watersheds are considered, to a different degree, to be at risk of fire-induced water contamination.

A meaningful discussion of these reservoirs requires a more in-depth look at these outcomes, which is done by means of an Impact vs Probability Matrix (Figure 11). Included are those reservoirs that are used for drinking water consumption and have been exposed to wildfires burning 7% or more of the watershed in the last 32 years. This matrix shows the relation between the exposure and hazard indices. The quadrants represent which type of risk applies to each watershed. High values on the hazard index represent watersheds with a high potential hazard and therefore high potential impact. High values of the exposure index represent watersheds that are relatively exposed to the hazard. This graph is valuable as it provides a more meaningful comparison of the studied reservoirs and in which way they are specifically at risk.

This is well illustrated by the two reservoirs at the highest risk. The large Castelo de Bode reservoir scores highest as it is most relied upon for drinking water uptake, while having an intermediate exposure score. The Pretarouca reservoir, which is relatively small, has experienced the most years in which more than 7% of the watershed area was burned, while having an intermediate hazard score. Accordingly, they occupy different positions in the Impact vs Probability Matrix (Figure 15), despite having similar risk scores.

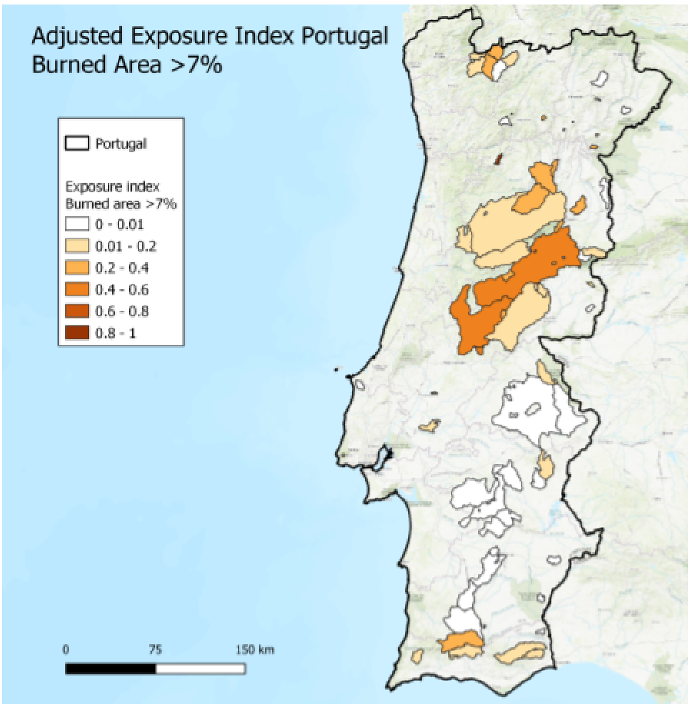

Figure 13, Adjusted Exposure Index

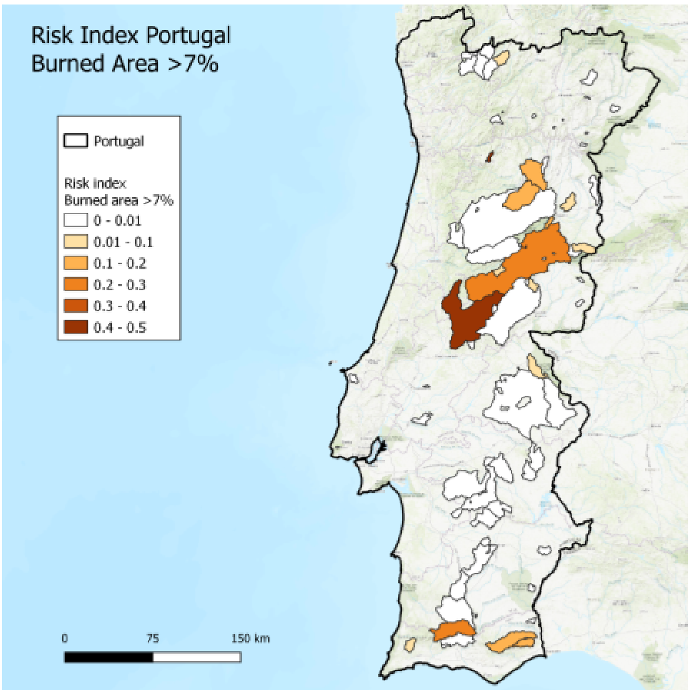

Figure 14, Risk Index

Figure 14 exposes certain areas of interest. Foremost, the high risk Castelo de Bode reservoir and the adjacent Cabril reservoir. Both are important sources of drinking water, and are located in the fire-prone central region. Within this region, a number of reservoirs can be found with intermediate risk scores. These have similar scores in the exposure index as they are in the same fire-prone region, but are significantly less depended on for the uptake of drinking water. Further, the southern region stands out with four reservoirs at risk: Odelouca, Odeleite, Beliche and Bravura. Their location in the “low probability & high impact” quadrant (Bravura to a lesser degree)(Figure 15), reflects the high dependence on these reservoirs as well as the less frequent occurrence of contamination events. What should further be noted is the lack of risk in the northern reservoirs.

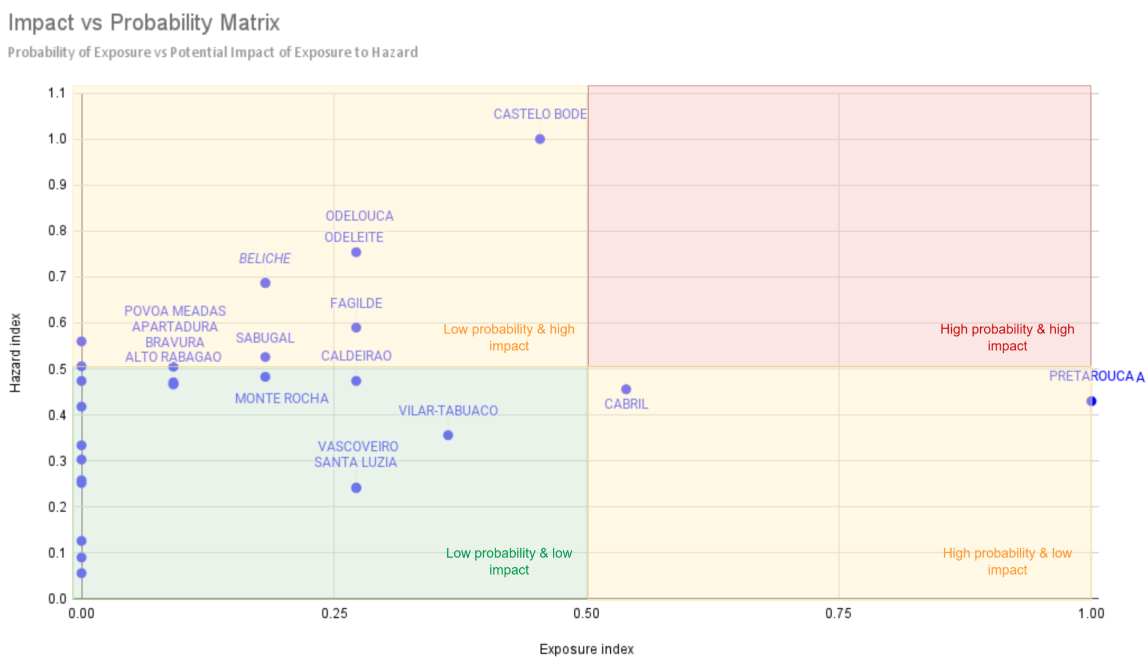

Figure 15, Reservoirs placed in an Impact vs Probability Matrix based on their Exposure and Hazard indices

6.2 Phase 2 - In-depth analyses: RQ2.1 – RQ2.2

6.2.1 In-depth analysis 1: Exposure

The purpose of the first in-depth analysis is to create, for eight reservoirs, an improved measure of exposure compared to the exposure index created in Phase 1. This measure is additionally based on the distribution of dry, normal and wet post-fire-year conditions in the period between 1990 and 2022. This distribution can be viewed in Figure 16 for the eight selected reservoirs. Note that no claims should be made about regional differences based on this data, as this is not a representative selection of reservoirs. There are, however, some observations to be made. The Castelo de Bode reservoir appears to be the most stable, with normal conditions in roughly 90% of the observed years. Just the Odeleite and Bravura reservoirs appear to have experienced wet conditions during the observed years. This is likely due to the fact that yearly averages were created, while reservoirs might only tend to be filled above 90% during the few rainy winter months, after which their levels descend below this threshold. The same likely applies to the apparent abundance of dry post-fire-year conditions. Hence, while the definitions of post-fire-year conditions (dry, normal, wet) made by project FRISCO were applied, this terminology might not be appropriate as they indirectly reflect the climatic conditions, rather than directly reflecting the reservoir conditions. Instead, use of a terminology such as ‘moderate, high and full storage capacity’ would be more appropriate in future work.

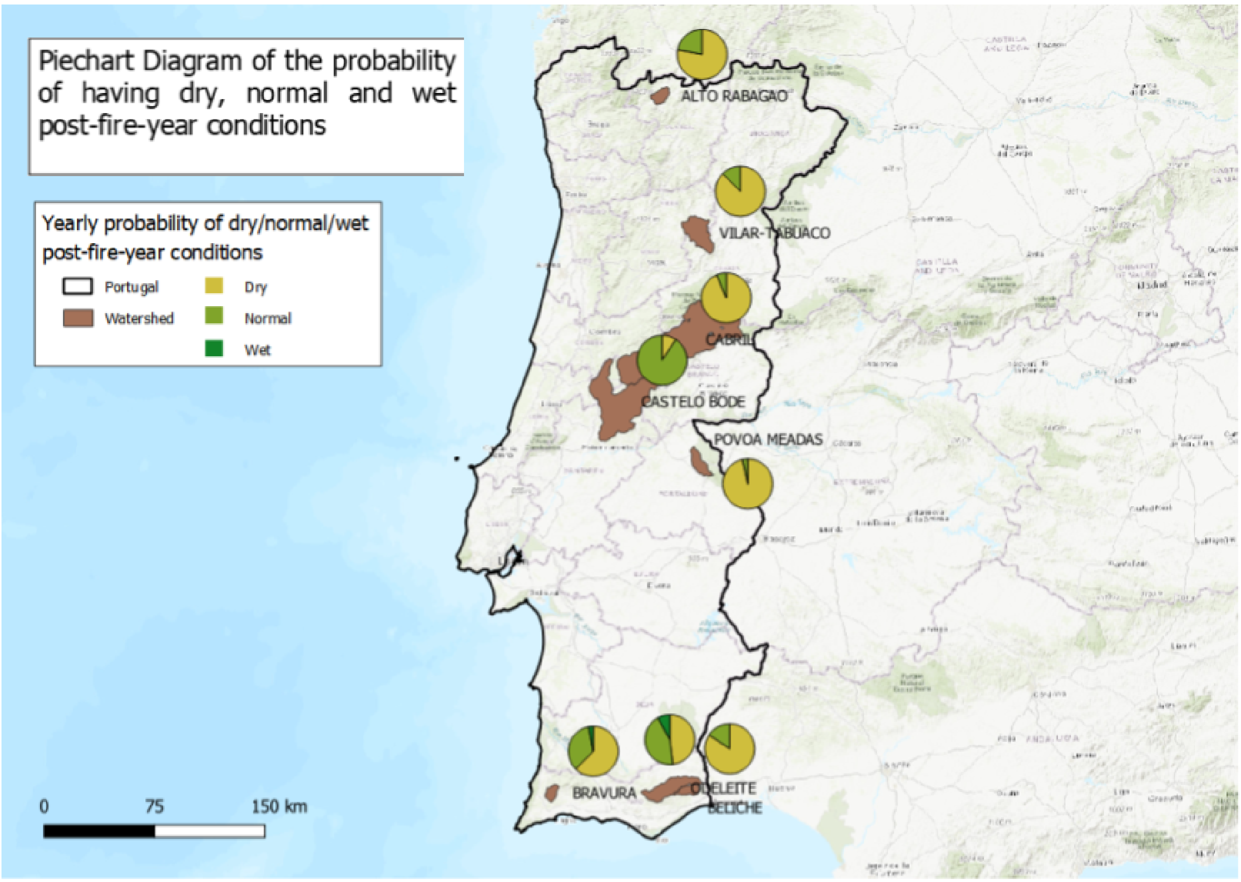

Figure 16, Post-fire-year conditions 1990 - 2021

The improved exposure measure, which essentially fills in each cell in the table in Figure 10, is created by combining the probabilities of post-fire-year conditions with the probabilities of the occurrence of each burned area class for these reservoirs. The table in Figure 17 shows the probability of the occurrence of each combination of these class variables as well as the adding-up of these probabilities following the classification of there being probable or very probable significant changes in TSS (the two rightmost columns of each reservoir). Effectively, for eight reservoirs, a more precise measure of exposure is created by the application of both significant drivers found in Nitzsche et al. (2022). This measure proves especially useful in terms of interpretation. The Vlilar-Tabuaco reservoir, for example, has a roughly 0.11 yearly probability of having very probable (P>90) significant changes in TSS. The same claim in other words: each 9.1 years (1/0.11=9.09) the conditions occur wherein significant changes in TSS are very probable. Furthermore, it has a roughly 0.26 yearly probability of having probable (66<P>90) significant changes in TSS and a respective return period of 3.8 years (1/0.01=3.84).

Yearly probability of impact (significant changes in TSS concentrations)								
Castelo de Bode	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0.125	0.063	0.031	0.063	0		Total
yrlyprobdry	0.094	0.012	0.006	0.003	0.006	0	P>90	0.102
yrlyprobnormal	0.906	0.114	0.058	0.029	0.058	0	66<P>90	0.07
yrlyprobwet	0	0	0	0	0	0	P<66	0.114
Cabril	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0.094	0.125	0.063	0	0		Total
yrlyprobdry	0.938	0.089	0.118	0.06	0	0	P>90	0.182
yrlyprobnormal	0.063	0.006	0.008	0.004	0	0	66<P>90	0.097
yrlyprobwet	0	0	0	0	0	0	P<66	0.006
Vilar-Tabuaco	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0.281	0.125	0	0	0		Total
yrlyprobdry	0.875	0.246	0.11	0	0	0	P>90	0.11
yrlyprobnormal	0.125	0.036	0.016	0	0	0	66<P>90	0.262
yrlyprobwet	0	0	0	0	0	0	P<66	0.036
Beliche	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0	0	0.031	0.031	0		Total
yrlyprobdry	0.844	0	0	0.027	0.027	0	P>90	0.064
yrlyprobnormal	0.156	0	0	0.005	0.005	0	66<P>90	0
yrlyprobwet	0	0	0	0	0	0	P<66	0
Odeleite	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0	0.031	0	0.031	0		Total
yrlyprobdry	0.48	0	0.015	0	0.015	0	P>90	0.044
yrlyprobnormal	0.44	0	0.014	0	0.014	0	66<P>90	0.017
yrlyprobwet	0.08	0	0.003	0	0.003	0	P<66	0.003
Bravura	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0.031	0	0	0	0.031		Total
yrlyprobdry	0.625	0.02	0	0	0	0.02	P>90	0.032
yrlyprobnormal	0.344	0.011	0	0	0	0.011	66<P>90	0.02
yrlyprobwet	0.031	0.001	0	0	0	0.001	P<66	0.012
Alto Rabagao	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0.188	0.031	0	0	0		Total
yrlyprobdry	0.781	0.147	0.025	0	0	0	P>90	0.025
yrlyprobnormal	0.218	0.041	0.007	0	0	0	66<P>90	0.154
yrlyprobwet	0	0	0	0	0	0	P<66	0.041
Povoa Meadas	*BA% class*	3-7	7-13	13-28	28-42	>42		
post-fire-year conditions		0	0	0	0	0.031		Total
yrlyprobdry	0.966	0	0	0	0	0.03	P>90	0.032
yrlyprobnormal	0.034	0	0	0	0	0.002	66<P>90	0
yrlyprobwet	0	0	0	0	0	0	P<66	0

Figure 17, Improved exposure measure – yearly probability of having "probable" (66<P>90) and "very probable" (P>90) significant changes in TSS concentrations

6.2.2 In-depth analysis 2: Vulnerability

This section introduces the vulnerability of reservoir based water supply to the risk assessment framework. Within this framework, vulnerability represents the susceptibility to the presented hazard and the ability to cope with/adapt to its disturbances. In other words, when a contamination event does occur, what measures can be taken to protect the continuation of water supply to the affected areas? This can be studied by considering past contamination events and evaluating whether water supply was disrupted and if so, what actions were taken to safeguard the water supply.

The objective, therefore, is to evaluate how fire-induced water contamination is countered in different places in Portugal as well as to get a general view of how water supply systems are affected when contamination events take place. A number of regions and specific reservoirs are selected and discussed in terms of mitigation methods and availability of alternatives. This analysis consists of two case-studies which can subsequently be discussed in terms of mitigation options and the availability of alternatives.

6.2.2.1 Case-study 1 - Castelo de Bode and Ansião

While this study has so far limited itself to the fire-induced water contamination risk of reservoirs, this case-study includes the river-based water supply of Ansião. This choice was made as it offers the means to compare the vulnerability of a relatively small water supply system to the much larger Castelo de Bode system. This choice is also justified by the claim that water quality in rivers is similarly affected by wildfires as reservoirs, although less can be said about the degree in which this process occurs.

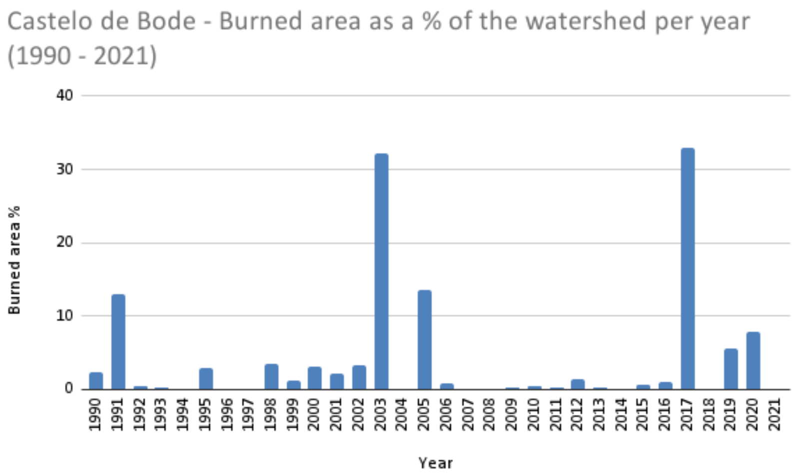

Figure 18, Burned area as a % of the total watershed area for the Castelo de Bode watershed

Castelo de Bode

The Castelo de Bode reservoir is one of the largest reservoirs in Portugal, and the most crucial as it features the most productive reservoir based water treatment facilities supplying Lisbon and its surrounding municipalities. This has been reflected in the high hazard and risk indices produced in Phase 1. Its importance warrants a further exploration into its vulnerability to wildfire induced water contamination.

Wildfires burned nearly 33% of the watershed area of the Castelo de Bode reservoir; the highest percentage in the last thirty years (Figure 18). The year of 2003 was a close second but preference was given to evaluate 2017 as there is more literature available for this year. However, it should be noted that Coelho et al. (2011) observed a number of spikes of Total Suspended Sediments exceeding 5mg/L in the reservoir at the end of 2003, possibly as a consequence of the wildfires that occurred that summer. Relating this to the work of Nitzsche et al. (2022) and project FRISCO, this possibility can likely be confirmed. The 2003 and 2007 fire seasons fall within the 28-42% burned area category, which is associated with probable changes in TSS at wet post-fire-year conditions and highly probable changes in TSS at dry and normal post-fire-year conditions (Figure 10). Strong impacts on the water quality of the reservoir would thus be expected.

Concerns about the water supply from the Castelo de Bode reservoir were raised after the 2017 fires. Figure 19 provides an overview of the situation. These concerns caused the Portuguese Environment Agency to implement emergency slope stabilization (Agência Lusa, 2020). The main goal of slope stabilization efforts is to reduce the susceptibility to erosion and therefore reduce the degree of sediment runoff. In practice, this consists of identifying areas most susceptible to erosion, after which they can be adapted with the construction of micro-dams, sediment retaining structures, retention basins, compost piles and barriers of shredded vegetational material (Agência Lusa, 2020). Strategic placement of such constructions can decelerate the ash runoff in the period after the fire, reducing short-term heavy influxes of suspended sediments (Girona-García et al., 2021). The Portuguese Environment Agency has claimed that their efforts have done just this, and prevented large quantities of ash from reaching the reservoir (Agência Lusa, 2020).

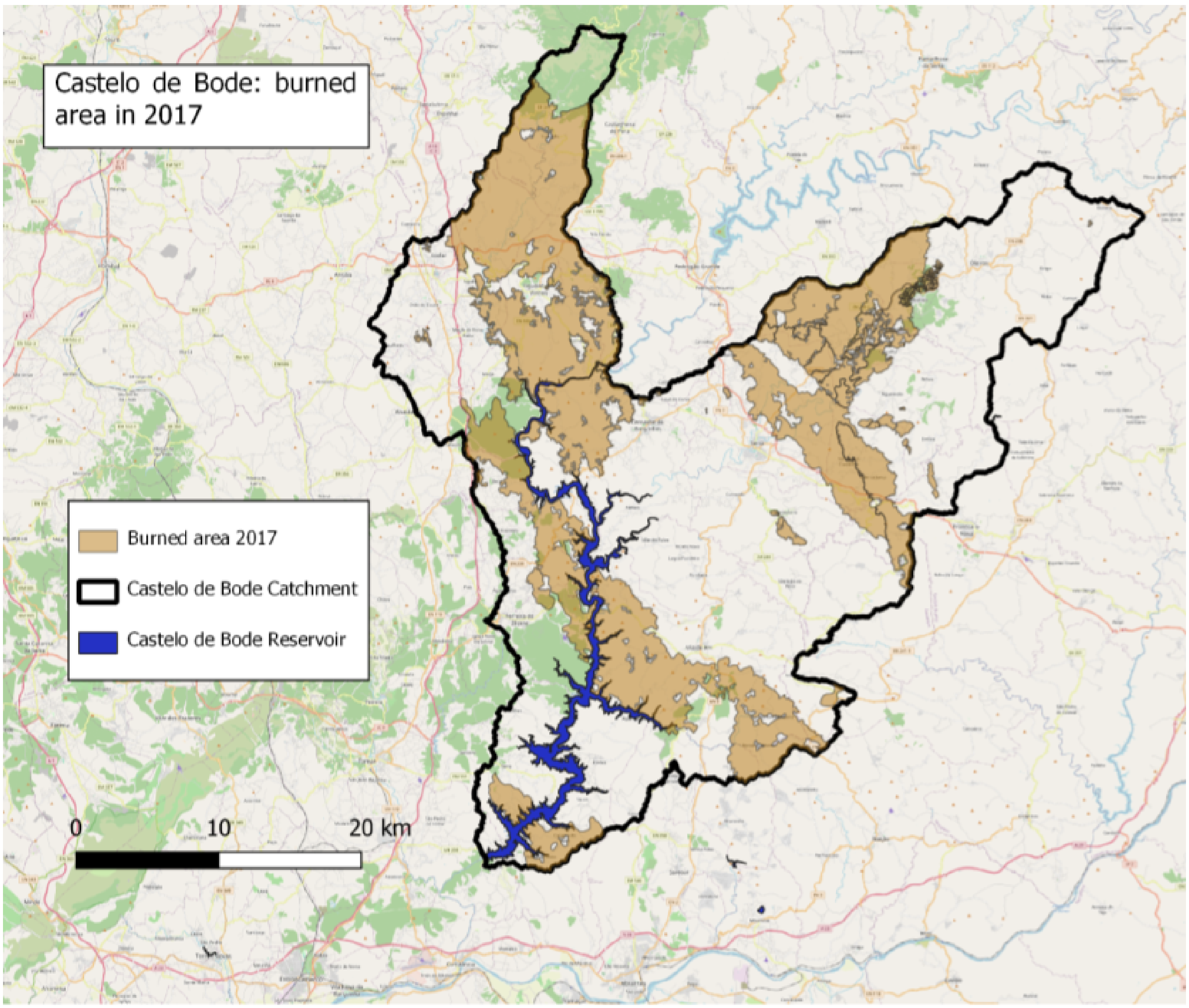

Figure 19, burned areas in the Castelo de Bode watershed in 2017

Later evaluations of this fire year and its effects on water quality showed increases in nutrient and sediment concentrations at the reservoir inlet (Basso et al., 2020). However, the overall quality of the water in the reservoir appeared to remain relatively stable. Water quality data from SNIRH shows that the total suspended sediment did not increase above 2mg/liter in 2017 or the years thereafter. This is somewhat confirmed and explained by a later study from Basso et al. (2021). They conclude that the wildfires of 2017 did not pose a threat to the quality of the water supply because the reservoir contained enough water to properly dilute the influx of sediments (although small adaptations to the treatment process might be necessary due to high degrees of TSS on the surface). However their model did not include the implementation of slope stabilization measures, meaning that these efforts could attenuate their conclusions.

Ansião

In 2017, the water supply of the municipality of Ansião, located near the Castelo de Bode reservoir, was disrupted due to wildfire induced water contamination. Figure 20 provides an overview of the situation. Ansião is supplied by a water treatment station located on the Alge river (Ribeira de Alge), which flows into the Castelo de Bode reservoir. Its catchment area consists (at least upstream of the treatment station) largely of densely forested hillscapes. As can be seen, around 80% of the area upstream of the treatment station was burned in 2017.

According to news sources, the water treatment facility was shut down on two occasions as a consequence of heavy precipitation, the first of which being the first significant rainfall after the fire (Rádio Renascença, 2017; Diário de Notícias, 2017). This rain caused the river to overflow its normal banks and reach areas of ash-laden burned forest. In addition, it is important to note that the degree of ash transportation decreases exponentially over time, meaning that the first rainfalls after the fire captures the largest amount of ash (Shakesby, 2011). Essentially, a short but heavy influx of disproportionally ash-laden water reached the facility, causing it to shut down. However, this does not explain the second contamination event in December, almost half a year later. As Nunes et al. (2018) mention: “the remobilization of contaminants inside the stream network (...) can lead to a lagged post-fire response.” (p.4). Essentially, high intensity rainfall can lead to turbulent water flow in rivers and streams. This can cause previously deposited ashes on the stream bed to be resuspended and rejoined to the water flow.

To resolve the need for clean drinking water, the municipality had to resort to the installation of temporary small reservoirs, to be filled by water trucks coming from elsewhere. This situation persisted for multiple days on the first occasion, yet was quickly resolved on the second occasion.

Having two separate events of heavy rainfall causing facility shutdowns within one year shows the vulnerability of a small system such as this. The treatment facility is located halfway a roughly 30 kilometer long river, meaning that it has a rather small catchment area which can be significantly burned by a single fire. This situation led to total shutdown of the water treatment facility after a single fire and a single rainfall event, after which the ‘last resort’ measure had to be taken to bring water by truck. This shows that, under the right circumstances, a small system can be very vulnerable to wildfire induced water contamination.

The evaluation of two water supply systems that differ in size, despite being in close proximity to each other, shows the advantage of a very large system in terms of its vulnerability to wildfire induced water contamination. By itself, its sheer size is able to mitigate the effects of wildfires that burned over 30% of the total watershed area. Furthermore, it highlights the willingness of the authorities to protect this drinking water source. While slope stabilization efforts can be effective, they can be quite costly and difficult to organize. To maximize their effectiveness, they should be implemented before the first significant rainfall (Agência Portuguesa do Ambiente, 2023c). This means that the selection of areas susceptible of erosion, the organization of construction crews and materials and the construction itself will have to happen within months or even weeks after a fire.

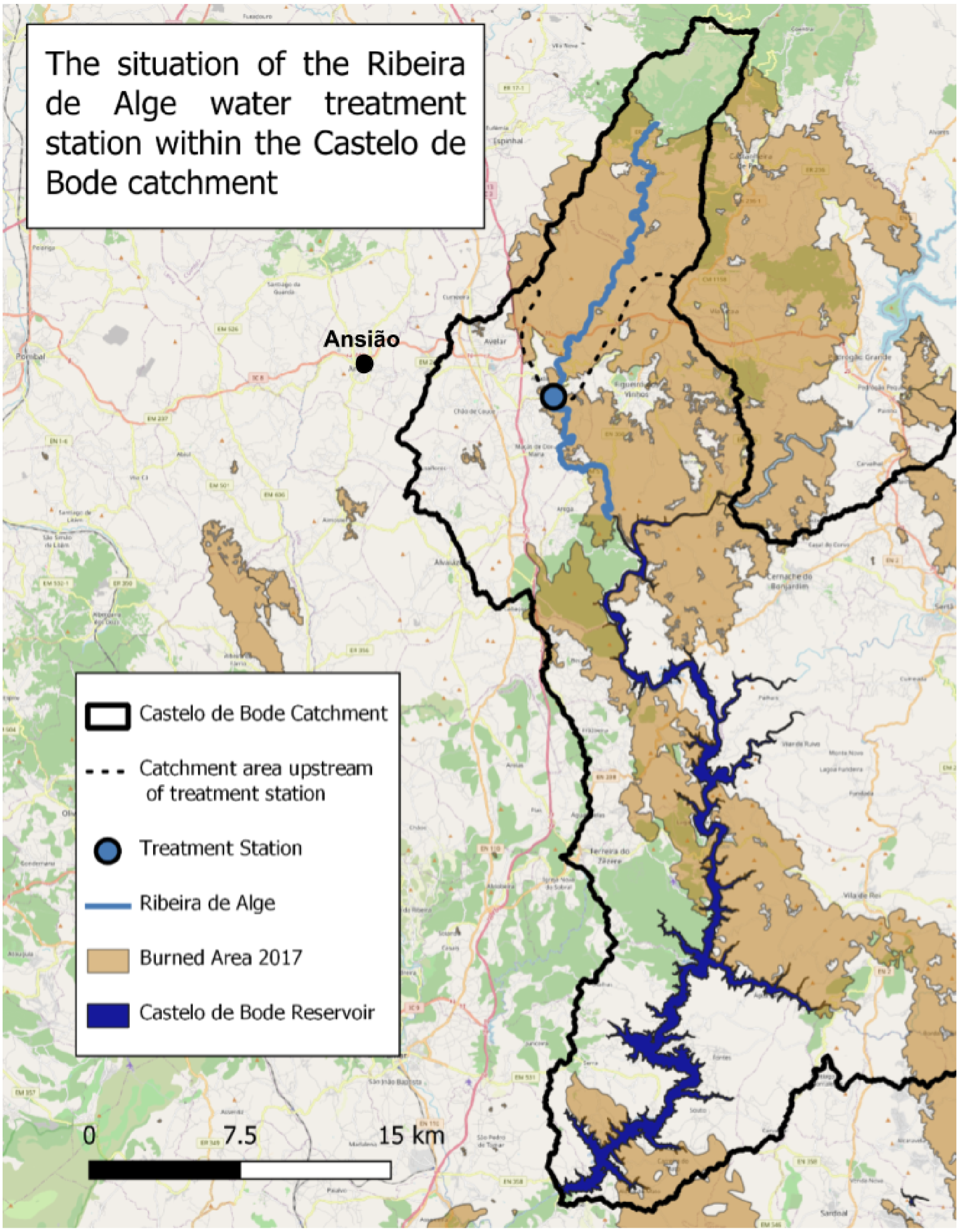

Figure 20, The situation of the Ansião water supply system within the Castelo de Bode watershed

6.2.2.2 Case-study 2 - Algarve

The Algarve region covers the southernmost part of Portugal. It experiences relatively dry conditions compared to the central and northern regions of Portugal (Santos et al., 2017). While drier conditions are generally associated with a higher fire probability, the region is less forested and contains more scrub vegetation (Parente & Pereira, 2016). As a consequence, there is less fuel for wildfires to burn through and therefore less ash generation. Although this somewhat reduces the potential water contamination as a result of wildfires, concerns have also been raised about the water supply in absolute terms. Currently, the bulk of drinking water in the region is supplied by four major reservoirs (Figure 21).

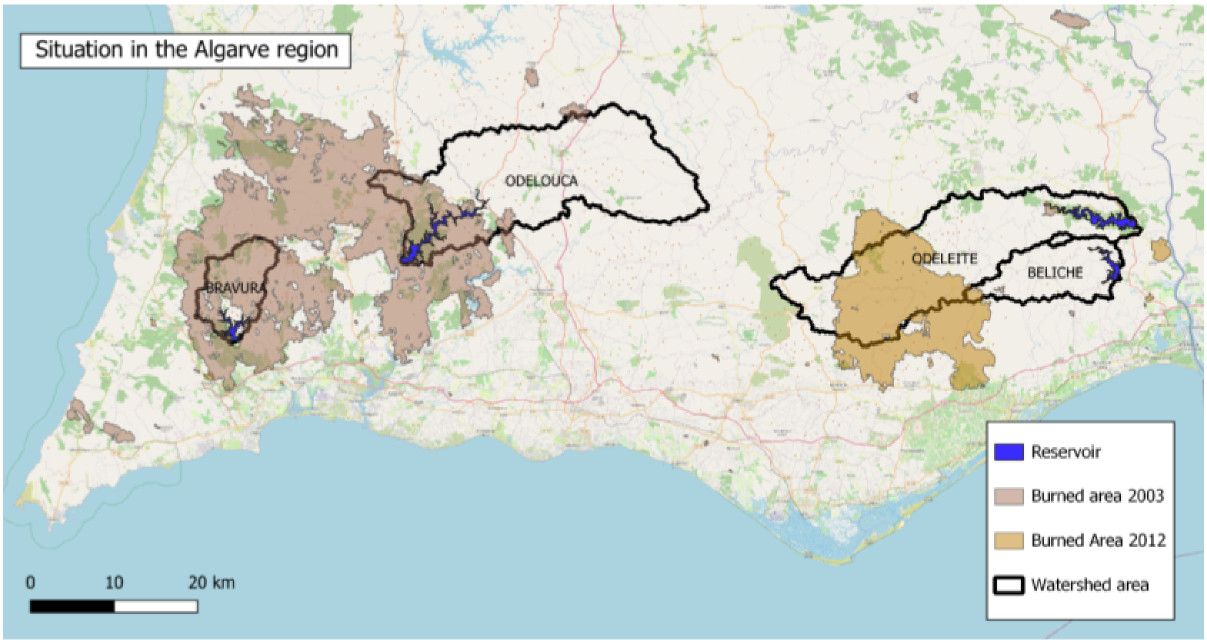

Figure 21, Reservoirs with drinking water uptake in the Algarve and burned areas in 2003 and 2012

The region generally receives most of its rainfall in a short winter period, which is followed by a long and dry season (Nunes et al., 2006). Contrarily, water consumption strongly rises during the dryer period when population peaks as the region sees a high degree of summer tourism (Stigter et al., 2007). This imbalance in water supply and consumption has led to a strong need for large-scale water storage, as well as the need for improved manageability of the system (Nunes et al., 2006). Water storage capacity in the region has been steadily developed in the last 30 years. The large reservoirs of Odeleite and Odelouca were put into operation in 1997 and 2012 respectively. Additionally, large parts of the Algarve have been increasingly integrated into a single water supply system, with the aim of increasing its interconnectivity and manageability, thereby decreasing local vulnerabilities. This process provides an opportunity to examine how changes in the water supply system can reduce its vulnerability to fire-induced water contamination as well as, in this case, drought conditions.

The western part of the Algarve region experienced disastrous wildfires in 2003, as can be seen in Figure 21. It is important to note that the Bravura reservoir was the only reservoir used to collect drinking water in the western Algarve, as the Odelouca reservoir was not constructed at this time. In this year, 81% of the watershed area of the Bravura reservoir was burned, leading to considerable increases of total suspended sediment concentrations in the months after the fire (Figure 22). Thiel (2010a) examined the context in which this took place. While the reservoir based water supply in the region was rendered nearly inoperational, there was no acute emergency as it was possible to increase the use of aquifers as a drinking water source. However, the vulnerability of the water supply was exposed; the main source was largely and lastingly compromised, forcing the emergency solution of aquifers which can be quite unsustainable as these replenish slowly.

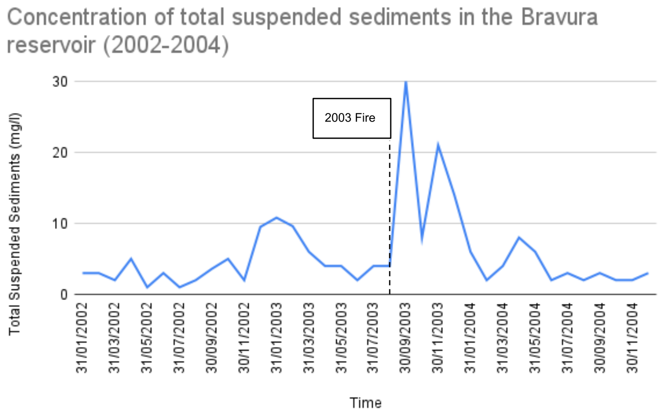

Figure 22, TSS concentrations in the Bravura reservoir (2002-2004)

Two years later, in 2005, the Algarve region experienced a serious drought, leading to some of the lowest reservoir levels in the last 20 years (Figure 23). Similarly, aquifers showed low water levels, underlining the unsustainability of relying on such sources (TVI Notícias, 2005). As a result, sixteen municipalities, with a total population of nearly 12.000, were forced to use water trucks to maintain supply. Additionally, emergency funds were raised for drilling into smaller aquifers and tapping into different surface sources. Lastly, the conditions in 2005 accelerated the construction of the Odelouca reservoir, as the European Commission declared that in this case, public interest overrides their environmental concerns (Thiel, 2010a).

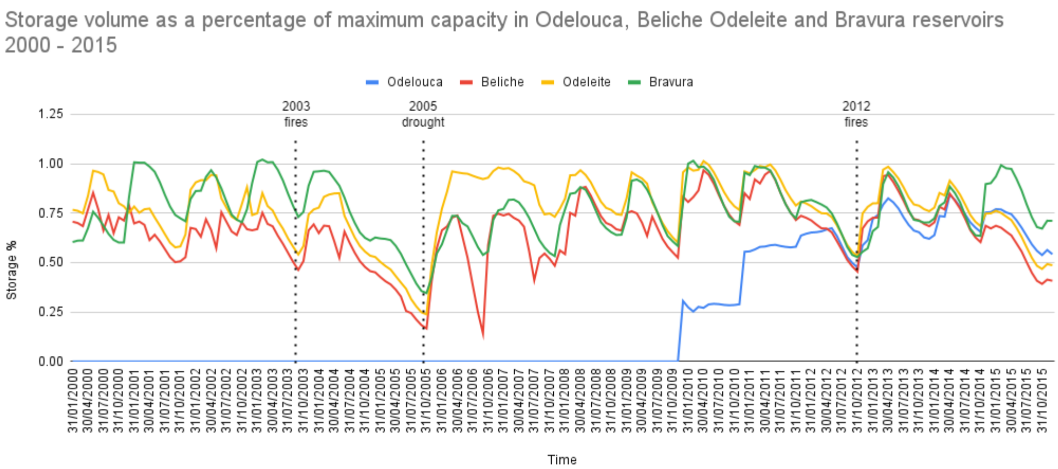

Figure 23, Storage volumes (% of total capacity) in the reservoirs of the Algarve (2000 - 2015)

The quick succession of two difficult years led the local water supplier, Águas do Algarve, to reconsider the water supply system of the Algarve (Pires, 2016). This was mostly done from the perspective of vulnerability to drought, but its effects are similar in terms of vulnerability to fire-induced water contamination. Besides increasing the general storage capacity in the region by continuing construction of the Odelouca dam, Águas Do Algarve redesigned their water supply system completely by focusing on interconnectivity and flexibility. The document from Águas do Algarve (2023a) states: “With the completion of this dam, the entire Multimunicipal Water Supply System will remain at a level of reliability much higher than the current one given that, through the Reversible Pumping Stations, it will be possible to reinforce the supply to the Leeward (eastern, red.) in case of need/emergency." (p. 13). The following description of these changes is partially based on the work of Thiel (2010b), and will be illustrated using the map of the current state of the water supply system shown in Figure 24.

Firstly, region-wide connections were established in the low-lying coastal regions. As can be viewed in Figure 21, the water treatment plants (encircled) are located down-river, close to population centers in the south, whereas the reservoirs are located in the more mountainous northern parts of the Algarve. Before 2005, there were already some multi-municipal systems in place. As part of the redesign, connections between these systems were constructed up to the point where all systems were upscaled into a single region wide system. As can be viewed on the map, this was done by the construction of interconnecting (largely underground) canals that connect all four treatment facilities. These are managed by two-way pumps, enabling the transfer of water across the region as required by real-time supply and demand. An important result of these connections is that the entire system can be supplied by the eastern reservoirs if the western reservoirs are affected, and vice versa (Vieira et al., 2011). At least within the last 31 years, it has been extremely rare for both sides to be seriously affected by wildfires in the same year, although we have seen occasions in which either side was seriously affected.

Secondly, connections were established between the reservoirs themselves. These are highlighted by the arrows in Figure 21. One can see the tunnel between the Odeleite and Beliche reservoirs, as well as the connection between the Odelouca and Funcho reservoirs. These connections allow for the transfer of water between reservoirs, thereby enabling management of the distribution of water in the system at its source. The procedure for these transfers when wildfires put stress on quality of the water has unfortunately remained unclear, but might go in either of two directions. When one watershed area is hit by significant wildfires, the decision could be made to either (1) transfer as much water as possible to the unaffected reservoir in an effort to save as much clean water as possible before the suspended sediments reach the reservoir, or (2) to transfer water from the unaffected reservoir into the affected reservoir in an effort to increase its dilution capacity, possibly keeping suspended sediments concentrations low.

In summary, the water supply system of the Algarve region was drastically up-scaled. Since 2005, the large Odelouca reservoir has become operational, small water supply subsystems have been merged into a single larger system and major reservoirs have been connected to accommodate redistribution of water at the source. The president of Águas do Algarve, the local water supply company, claimed in an interview that these implementations have led to the Algarve currently having no water supply problems (Pires, 2016).

It is important to re-emphasize that while these measures were aimed at alleviating drought conditions, they also apply to the systems' vulnerability to fire-induced water contamination. The gained ability to redistribute and divert water throughout the region allows water managers to negate the impact of local water contamination. When a fire causes the contamination of one of the reservoirs, water can be diverted to supply areas that would have been strongly affected in the past. Revisiting the example of the 2003 fire season, water could have been transferred from the unaffected eastern region to supply the municipalities depending on the Bravura reservoir. Similarly, when the Odeleite watershed was hit by a large fire in 2012 (Figure 21) the system was flexible enough to temporarily reduce intake from the Odeleite reservoir. It is clear, then, that the improvements strongly reduced the vulnerability to fire-induced water contamination.

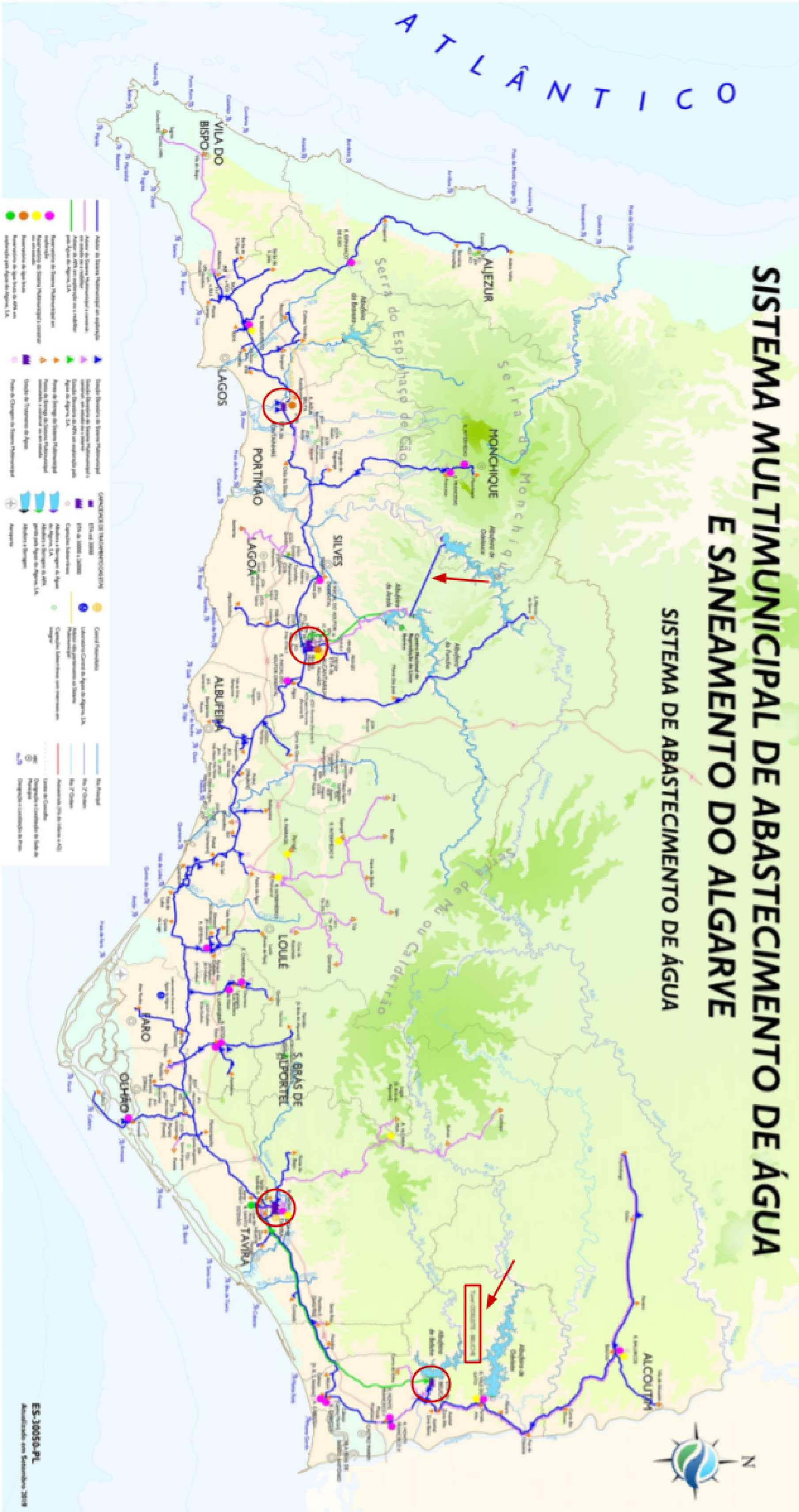

Figure 24, Multimunicipal water supply system Algarve (Águas do Algarve, n.d. b)

6.2.2.3 In summary

The case-studies have provided a multitude of mitigation measures, which differ in terms of urgency (how fast they have to be implemented). In extension, when a contamination event occurs, the urgency of the measures taken reflects how vulnerable a system is. For example, water trucks and local storage reservoirs were used in Ansião to alleviate the immediate threat to the continuation of drinking water supply. Implementation of this measure reflects a high vulnerability of the system as there is apparently no other feasible option besides this last-resort measure. In the Castelo de Bode watershed, emergency soil stabilization was implemented which, as discussed, has to be implemented within weeks or a few months. This means that the water supply could be safeguarded by less urgent, yet still extensive, measures, implying a lower vulnerability of the system. The Algarve poses an interesting situation. The vulnerabilities that were exposed in 2003 and 2005 were addressed firstly with urgent measures such as trucking in water and the increased use of aquifers. Subsequently, a large-scale improvement and expansion of reservoirs and infrastructure was implemented to decrease the vulnerability of the water supply in the region.

Relating the above to the results of Phase 1, it becomes clear that considering the vulnerability of a reservoir based water supply system can add insights to its risk of fire-induced water contamination. For example, estimations of risk were relatively high for the Castelo de Bode reservoir, as well as the reservoirs in the Algarve region. The former was shown to be relatively invulnerable due to its size, which mitigates its risk. The latter were shown to be highly interconnected, which too mitigates the risk posed to these reservoirs.

7. Discussion

7.1 Interpretation of results

7.1.1 Phase1: RQ1.1 - RQ 1.3

By themselves, the hazard and exposure indices provide a broad overview of the national situation in terms of reservoir based water supply and fire propensity. The importance of the Castelo de Bode reservoir is reflected in the former (Figure 11), as this reservoir serves as the main source of drinking water for the metropolitan area of Lisbon. The same can be said about the reservoirs in the Algarve, which cover the increased summer demand of this highly touristic region (Stigter et al., 2007).

The exposure indices (Figure 12) reveal regional differences in exposure to wildfires, each of which show how the central region of Portugal stands out. In addition, the indices show that while the northern reservoirs experience many wildfires, they do not tend to burn large areas. Oppositely, the southern reservoirs are exposed to relatively few wildfires, but when they do occur, they often burn large areas. Similar regional differences are described by Calheiros et al. (2021), who assess the occurrence of 'fire-weather' days in the Iberian Peninsula as well as the contrast between the resulting pyro-regions in the northern and southern parts of Portugal. Differences in fire frequency can be partly explained by climatic conditions, where the relatively dry climate in the south leads to less vegetation density and slower growth. Consequently, the fire recurrence (how often is the same area burned?) of this region is comparatively low as burned areas recover relatively slowly. Parente et al. (2022) show regional differences in fire recurrence, in which the same North-South pattern can be viewed. Thus, despite experiencing more 'fire weather', the southern regions experience lower fire frequencies as a consequence of slow vegetational growth and infrequent fire recurrence. A similar explanation is shown in Parente & Pereira (2016), where fire probability scores are lower in the southern region, while fire susceptibility scores are comparable between North and South.

Moreover, differences in fire frequency can be explained by regional population densities accompanied by the claim that the vast majority of fire ignitions in Portugal and other southern European countries are human caused (Catry et al., 2008; Catry et al., 2009). In other words, increased presence of humans is associated with more frequent fire ignitions. Parente & Pereira (2016) show that population densities in rural areas are generally higher in the northern and central regions compared to the southern regions. This claim is further strengthened by the work of Parente et al. (2018), which shows how frequencies of total, negligent and intentional wildfires decrease as one moves from North to South.

Differences in fire size can be explained by meteorological conditions and land cover types. As is shown in Parente & Pereira (2016), areas with relatively dry meteorological conditions are associated with lower vegetation densities. At the same time, the vegetation that does exist tends to be highly flammable due to the combination of dry conditions and the typically high surface area to volume ratio (can be read as the density of individual plants and trees) causing vegetation to dry out quickly (Shakesby, 2011). Despite lower fuel availability, wildfires do tend to burn intensely and spread fast (Fernandes, 2001). Hence, they are more difficult to control and burn larger areas. As is shown in the Iberian Climate Atlas (2011), the southern region experiences considerably less precipitation and considerably higher temperatures compared to the central region; comparing the central to the northern region follows a similar tendency. Furthermore, the generally low hazard index values in the North could be explained by the precipitation this region receives. The more humid climate allows for water uptake directly from rivers, and a lower need to store water in reservoirs.

The risk index functions as a means to assess risk of reservoir based water supply systems to fire-induced water contamination at a national scale. The frame of this study limits the risk assessment in two ways. Firstly, this study considers risk to the drinking water supply. Reservoirs that were not represented in the hazard index might still be at risk of fire-induced water contamination in terms of ecology and agricultural water supply (Caon et al., 2014; Campos & Abrantes, 2021; Nitzsche et al., 2022). Secondly, reservoirs that were not represented in the exposure index are implied to be at no risk of fire-induced water contamination as they did not experience years with above 7% burned area in the last 31 years. However, this claim is not watertight as these reservoirs could still be affected in combination with dry post-fire-year conditions (Figure 10). The risk index provides a quantitative measure of fire-induced water contamination risk for reservoirs that comply with both conditions. In addition to this measure, the results also show what type of risk is posed to a reservoir. The impact vs probability matrix (Figure 15) reflects the contribution of hazard and exposure to the risk value of each (relevant) reservoir. This allows for a more in-depth evaluation of individual reservoirs.

7.1.2 Phase 2: RQ2.1 - RQ2.2

The first in-depth analysis (RQ2.1) showed how the exposure measure could be improved for a number of selected reservoirs. Ideally, this would have been done for all reservoirs, but this was not possible due to the unavailability of public data on reservoir volumes. However, it does show how the findings of Nitzsche et al. (2022) can be optimally applied to the risk assessment. Whereas the national risk index reflects the yearly probability of wildfires burning more than 7% of a watershed area, the adjusted exposure measure estimates the yearly probability of a reservoir experiencing significant changes in TSS. It does this by estimating the probability of each combination of burned area classes and post-fire-year conditions. Following the table of Figure 10, the probability of each combination is added up according to their associated level of probability of impact (P<66, P66-90, P>90). The resulting values are highly useful as they show the yearly probability of having “probable” and “very probable” impact on TSS concentrations. In short, combining the probabilities of the two significant drivers of changes in TSS provided by Nitzsche et al. (2022) provides a precise estimate of the chance that a reservoir is significantly affected by fire-induced water contamination.

The second in-depth analysis (RQ2.2) includes vulnerability to the risk assessment framework. Foremost, it shows that the size of a system is an important aspect in terms of its vulnerability to fire-induced water contamination. The case-studies showed how wildfires can quickly and heavily disrupt small water supply systems. Ansião and Bravura both had wildfires that burned around 80% of the watershed. Such percentages are more easily reached in systems with a small watershed. As wildfires will become larger and more frequent in the future, the vulnerability of smaller systems will only increase, making improvements to treatment infrastructure within this system relatively futile. In contrast, Case-study 1 showed how the sheer size of a reservoir defines its capacity to cope with contamination events, whereas Case-study 3 showed how increasing the size of a water supply system can decrease its vulnerabilities by connecting various water sources to various water treatment facilities. Larger systems are inherently less vulnerable as they provide a buffer to fire-induced water contamination, as well as the means to manage and counteract its impacts.

Connecting to the above, the case studies also show that the degree of dependence on a water supply system can have implications for its vulnerability. After the 2017 wildfires, large-scale post-fire interventions on hillslopes were made in the Castelo de Bode watershed. Concurrently, no such interventions were made to safeguard the water supply in Ansião, instead reverting to the use of water trucks. This illustrates how water supply systems with a low dependency are more vulnerable as there are less resources assigned to protect it. Interestingly, the risk assessment of phase 1 shows that small reservoirs are mostly at low risk due to generally low dependency, whereas the vulnerability analysis shows that such systems are generally more vulnerable. Smaller reservoirs should thus be considered at higher risk than the initial risk index suggests.

Overall, it becomes clear that Portuguese authorities and water managers are aware of the vulnerability of their systems as they have emergency plans in place to safeguard the water supply. As a developed country, it has the means to do so. At the same time, such solutions are not cheap and neither are they sustainable (Girona-García et al., 2021; Paul et al., 2022). If climatic trends continue, emergency solutions will have to be implemented increasingly often, using resources that could be better spent on proper investments in infrastructure. As such, the real challenge for Portugal is to identify water supply systems with the highest risk to fire-induced water contamination, and then to counteract this risk by reducing either its vulnerability or its exposure to this hazard.

7.2 Academic and practical contributions

This study forms part of the crucial step between the global identification of the problem (Robinne et al., 2016; Hampton et al., 2022) and the local mitigation of the problem. The first part of this step has been performed by Nitzsche et al. (2022) as the authors establish the conditions for this global problem to affect Portuguese reservoirs. The second part of this step is performed in the current study which, applying the work of Nitzsche et al. (2022), assesses the risk of this problem to individual Portuguese reservoirs. As a result, Portuguese authorities can base the allocation of mitigation measures on this work.

More specifically, this study has provided two methods of gauging the exposure of reservoirs to fire-induced water contamination. One of which being an exposure index based on fire size, the other being a measure of yearly probability of contamination based on fire size and post-fire-year conditions. The latter is considered a preferable option as it includes both drivers found in Nitzsche et al. (2022), allowing for more meaningful claims to be made based on this measure. This study has also included reservoir dependence to the risk assessment of Portuguese reservoirs, which reflects the potential impact of a reservoir being contaminated. The resulting risk index provides the first national assessment of reservoir based water supply systems at risk of fire-induced water contamination. Lastly, this study has provided various insights into vulnerabilities of a selection of Portuguese water supply systems, some of which can be used for generalization.

Practically speaking, water supply utilities can use this work to evaluate the risk of fire-induced water contamination to their reservoirs. The national risk assessment can be used to identify areas that require mitigation efforts. The impact vs probability matrix is an important addition to the risk index as it allows water suppliers to approach the mitigation of the problem in individual watersheds/reservoirs: high probability of contamination implies the need for (e.g.) adjustments to forest management and upgrading filtration capacity, whereas high impact of contamination implies the need to (e.g.) establish additional back-up options. Additionally this study offers water suppliers processed data on fire size and probability for their individual watersheds based on data from the last 30 years. Consequently, the results of the improved exposure measure provide water suppliers with detailed estimates of the yearly probability of contamination for eight reservoirs. Lastly, pertaining to the most important conclusion to be made regarding the vulnerability of water supply systems to fire-induced water contamination, being that increasing the size of the water supply system reduces its vulnerability. Water suppliers should (and have) take(n) this to heart, by increasing both total storage volumes, as well as establishing and improving connections between water supply systems. While these types of upgrades require significant financial and temporal investments, they can greatly reduce the impacts of wildfires on the drinking water supply.

7.3 Limitations

The improved exposure measure could, unfortunately, not be applied to all reservoirs as reliable historic data on reservoir volumes is not available for all reservoirs. As there were just eight reservoirs with satisfactory data, and as these reservoirs tended to be on the large side, the selection was not considered to be representative of Portuguese reservoirs in general. For this reason, the measure should not be indexed and could not be used to calculate an improved risk measure. On the bright side, while data on reservoir volumes is not always publicly available, water suppliers might retain private datasets on this characteristic. If so, they could use the methods of this study to calculate the improved exposure measure for the reservoirs that are lacking here. Yet, it would be more preferable if water supply managers would provide more open data, which could be used for further academic research

This study is limited to the effects of wildfires on reservoir based water supply systems. River based uptake facilities, as opposed to reservoir based uptake facilities, were excluded from the quantitative analysis. The main problem is that these facilities can be disrupted by fire-induced water contamination, but it is not known under which conditions exactly. When ash-laden water travels downstream it passes water treatment facilities along the river banks before eventually ending up in a reservoir. The difference here is that, in the case of river based facilities, the concentration of suspended sediments is more variable: it sees highs and lows as a result of fluctuations in precipitation, and suspended sediments concentrations decrease drastically at each succeeding rainfall event. This makes it more difficult to attach a quantitative value to the conditions under which these facilities would be impacted. Thus, the level of confidence in the results of river uptake points will be much lower if the index from Nitzsche et al. (2022) would be applied to them.

Lastly, the risk assessment might not accurately apply to the future. This study has based itself on fire and reservoir data from the past 32 years. As a consequence of climate change, climatic trends in Portugal indicate that it is unlikely that the following 32 years will be the same. As the country will face increasingly dry conditions (Santos et al., 2017), pyro-regions will likely shift, exposing large parts of the country to increasingly frequent and increasingly large wildfires (Calheiros et al., 2021) at times of increased drought.

7.4 Recommendations

As has been emphasized, more complete data on historic reservoir volumes would do more justice to the findings of Nitzsche et al. (2022). The first in-depth analysis showed how post-fire-year reservoir volume and fire size can be combined to reflect the two main drivers of fire-induced water contamination. A two-fold indexation could be made on having probable and very probable significant changes in TSS concentrations, which could subsequently be combined with the hazard index to create a more substantiated risk index. Further, within this study, post-fire-year reservoir volumes and fire size have been assumed to be separate variables, while they might correlate in reality. As droughts can affect both variables, the association between them should also be evaluated on a historical basis (Parente et al., 2019;Campos & Abrantes, 2021 Nitzsche et al., 2022). This would possibly show that significant changes in TSS concentrations are more likely to occur than previously assumed, as problematic conditions of both drivers might coincide rather than being random. This would result in an even more substantiated exposure measure.

Further improvements could also be made to the hazard index in future research. This study has considered reservoir dependency in absolute terms; in this case the yearly quantity of drinking water uptake. However, assessing reservoir dependency in relative terms, that is to evaluate what share of the drinking water comes from reservoir, river and subterranean water uptakes, would provide insight into the fire-induced water contamination risk of a certain research unit. After all, wildfires would affect only a certain share of the drinking water supply, and this addition would show that share for individual municipalities/regions/areas. In addition, this differentiation would be further strengthened by research on the precise effects of wildfires on river water quality parameters.

This study has limited itself to the effects of wildfires on the drinking water supply. As has been mentioned, however, reservoirs are often used for the agricultural water supply (irrigation). While this application can tolerate higher concentrations of TSS, its risk should still be evaluated as it pertains to food security. Following this line, wildfires can also impact the aquatic ecosystems in rivers and reservoirs (Campos & Abrantes, 2021). Risk assessment on the ecology of water bodies would broaden our knowledge on fire-induced water contamination. However, this would be a complicated step as it would entail the evaluation of additional water quality parameters besides total suspended sediments (Silva et al., 2015; Jesus et al., 2022).

Finally, further studies should also take into account, if possible, the expected effects of climate change in Portugal. The country is expected to face generally dryer conditions which will affect fire risk as well as reservoir volumes. Hence, a risk assessment based on historic data might underestimate risk and should possibly be adjusted accordingly.

8. Conclusion

This study has performed a fire-induced water contamination risk assessment of Portuguese reservoirs. Phase 1 has provided the identification of Portuguese reservoirs at risk of fire-induced water contamination, as well as the degree to which they are at risk. This was done through the creation of a risk index which is based on a hazard- and an exposure index. The hazard index reflects the degree of dependence on a reservoir in terms of drinking water. The exposure index reflects the degree to which reservoirs' watershed areas have been exposed to wildfires that burn more than 7% of the watershed area in the last 32 years.

The in-depth analyses of Phase 2 have provided additional insights into the degree of fire-induced water contamination risk of a few selected reservoirs and areas. Firstly, this was done through the addition of an improved analysis of exposure which added the probability of having dry, normal or wet post-fire year conditions to the probability of experiencing a certain degree of burned area percentages. Secondly, this was done by means of an evaluation of water supply systems' vulnerability to fire-induced water contamination.

These findings contribute to the understanding of fire-induced water contamination risk in Portugal. Furthermore, they provide water suppliers with a framework and method of examining the risk status of individual reservoirs. Future research can build on this work by strengthening the hazard and exposure indices, expanding that which is at risk (the drinking water supply) with the agricultural water supply and aquatic ecosystems, and lastly considering future climate impacts.

9. References

Administração Pública (2021). Portal de dados abertos. Retrieved September 16, 2022, from: https://dados.gov.pt/pt/datasets/atlas-da-agua-albufeiras/

Agência Portuguesa do Ambiente (2022). Planos de Gestão de Região Hidrográfica – Captações Superficiais - Setor e Subsetor. Retrieved September 9, 2022, from: https://apambiente.maps.arcgis.com/apps/webappviewer/index.html?id=8d0f5cdf4ab74b7489e7774efa5a5d8b&extent=-1120192.2891%2C4784991.9895%2C-644753.9732%2C5048241.1149%2C102100

Agência Portuguesa do Ambiente (2023b). Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Retrieved January 12, 2023, from: https://snirh.apambiente.pt/index.php?idMain=

Agência Portuguesa do Ambiente (2023c). Areas de Intervencão Priotitárias para a Proteção dos Recursos Hídricos. Retrieved February 6, 2023, from https://apambiente.pt/sites/default/files/_SNIAMB_Agua/DRH/Acoes/Reabilitacao/ProtecaoRHIncendios/Relatorio_IncendiosAgoOut2017_05Dez2017.pdf

Águas do Algarve (2023a) *Projecto da Barragem de Odelouca.* Retrieved January 17, 2022, from: https://www.aguasdoalgarve.pt/sites/aguasdoalgarve.pt/files/publicacoes/brochura_odelouca_0.pdf

Águas do Algarve 2023b) *Sistema Multimunicipal de Abastecimento de Água e Saneamento do Algarve.* Retrieved January 12, 2023, from https://www.aguasdoalgarve.pt/sites/aguasdoalgarve.pt/files/publicacoes/folheto_smaaa_out2019.pdf

Amraoui, M., Pereira, M. G., DaCamara, C. C., & Calado, T. J. (2015). Atmospheric conditions associated with extreme fire activity in the Western Mediterranean region. *Science of the total environment*, *524*, 32-39.

Agência Lusa (2020, January 29). APA ensures the quality of drinking water from Castelo de Bode. via www.Mediotejo.net. Retrieved January 15, 2023, from: https://mediotejo.net/apa-assegura-qualidade-da-agua-para-consumo-a-partir-de-castelo-de-bode/

Basso, M., Vieira, D. C., Ramos, T. B., & Mateus, M. (2020). Assessing the adequacy of SWAT model to simulate postfire effects on the watershed hydrological regime and water quality. *Land Degradation & Development*, *31*(5), 619-631.

Basso, M., Mateus, M., Ramos, T. B., & Vieira, D. C. (2021). Potential post-fire impacts on a water supply reservoir: an integrated watershed-reservoir approach. *Frontiers in Environmental Science*, *9*, 684703.

Beighley, M., & Hyde, A. C. (2018). Portugal wildfire management in a new era assessing fire risks, resources and reforms. *Centro de Estudos Florestais–Instituto Superior de Agronomia/Universidade de Lisboa: Lisboa, Portugal*.

Bodí, M. B., Martin, D. A., Balfour, V. N., Santín, C., Doerr, S. H., Pereira, P., & Mataix-Solera, J. (2014). Wildland fire ash: production, composition and eco-hydro-geomorphic effects. *Earth-Science Reviews*, *130*, 103-127.

Calheiros, T., Pereira, M. G., & Nunes, J. P. (2021). Assessing impacts of future climate change on extreme fire weather and pyro-regions in Iberian Peninsula. *Science of The Total Environment*, *754*, 142233.

Campos, I., & Abrantes, N. (2021). Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems. *Current Opinion in Environmental Science & Health*, *24*, 100293.

Caon, L., Vallejo, V. R., Ritsema, C. J., & Geissen, V. (2014). Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, *139*, 47-58.

Carrão, H., Naumann, G., & Barbosa, P. (2016). Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, *39*, 108-124.

Castellnou, M., Guiomar, N., Rego, F., & Fernandes, P. M. (2018). Fire growth patterns in the 2017 mega fire episode of October 15, central Portugal. *Advances in forest fire research*, 447-453.

Catry, F., Rego, F. C., Moreira, F., & Bação, F. (2008). Characterizing and modelling the spatial patterns of wildfire ignitions in Portugal: fire initiation and resulting burned area. *Transactions on Ecology and the Environment*.

Catry, F. X., Rego, F. C., Bação, F. L., & Moreira, F. (2009). Modeling and mapping wildfire ignition risk in Portugal. *International Journal of Wildland Fire*, *18*(8), 921-931.

Coelho, P. S., Almeida, M., & Mateus, N. (2011). Modelação Matemática da Qualidade da Água em Albufeiras com Planos de Ordenamento – V – Efeito de fogos florestais no regime de escoamento e na qualidade da água de rios e albufeiras. Lisbon: INAG.

Coles, S., Bawa, J., Trenner, L., & Dorazio, P. (2001). *An introduction to statistical modeling of extreme values* (Vol. 208, p. 208). in Springer Series in Statistics https://doi.org/10.1007/978-1-4471-3675-0

Diaz, J. M. (2012). Economic impacts of wildfire. *Southern Fire Exchange*, *498*, 2012-7.

Dumbravă, V., & Iacob, V. S. (2013). Using probability–impact matrix in analysis and risk assessment projects. *Descrierea CIP/Description of CIP–Biblioteca Națională a României Conferința Internațională Educație și Creativitate pentru o Societate Bazată pe Cunoaștere–ŞTIINŢE ECONOMICE*, *42*.

Diário de Notícias (2017, July 8). Floods in recent days have forced the municipality of Ansião to interrupt water collection. Retrieved January 16, 2023, from: https://www.dn.pt/lusa/enxurradas-dos-ultimos-dias-obrigaram-municipio-de-ansiao-a-interromper-captacao-de-agua-8623044.html

Fernandes, P. A. M. (2001). Fire spread prediction in shrub fuels in Portugal. Forest ecology and management, 144(1-3), 67-74.

Girona-García, A., Vieira, D. C., Silva, J., Fernández, C., Robichaud, P. R., & Keizer, J. J. (2021). Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. *Earth-Science Reviews*, *217*, 103611.

Gouveia, C. M., Bastos, A., Trigo, R. M., & DaCamara, C. C. (2012). Drought impacts on vegetation in the pre-and post-fire events over Iberian Peninsula. *Natural Hazards and Earth System Sciences*, *12*(10), 3123-3137.

Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M., & Gowman, L. M. (2009). Implications of changing climate for global wildland fire. *International journal of wildland fire*, *18*(5), 483-507.

FRISCO (2020) University of Lisbon - Centre for Ecology, Evolution and Environmental Changes. Retrieved February 23, 2023, from: https://ce3c.ciencias.ulisboa.pt/research/projects/ver.php?id=220

Hampton, T. B., Lin, S., & Basu, N. B. (2022). Forest fire effects on stream water quality at continental scales: a meta-analysis. *Environmental Research Letters*, *17*(6), 064003.

Iberian Climate Atlas (2011). Agencia Estatal de Meteorología (Spain) & Instituto de Meteorologia (Portugal). Retrieved February 22, 2022, from: https://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/detalles/Atlas-climatologico

Instituto da Conservação da Natureza e das Florestas (2022). Informação geográfica. Retrieved September 29, 2022, from: https://geocatalogo.icnf.pt/catalogo_tema5.html

Jesus, F., Pereira, J. L., Campos, I., Santos, M., Ré, A., Keizer, J., ... & Serpa, D. (2022). A review on polycyclic aromatic hydrocarbons distribution in freshwater ecosystems and their toxicity to benthic fauna. Science of The Total Environment, 153282.

Langhans, C., Smith, H. G., Chong, D. M., Nyman, P., Lane, P. N., & Sheridan, G. J. (2016). A model for assessing water quality risk in catchments prone to wildfire. *Journal of Hydrology*, *534*, 407-426.

Liu, Y., Stanturf, J., & Goodrick, S. (2010). Trends in global wildfire potential in a changing climate. *Forest ecology and management*, *259*(4), 685-697.

Meneses, B. M., Reis, E., Pereira, S., Vale, M. J., & Reis, R. (2017). Understanding driving forces and implications associated with the land use and land cover changes in Portugal. *Sustainability*, *9*(3), 351.

Moody, J. A., Shakesby, R. A., Robichaud, P. R., Cannon, S. H., & Martin, D. A. (2013). Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews*, *122*, 10-37.

Nitzsche, N., Nunes, J. P., & Parente, J. (2022). *Evaluating and Interpreting Post-fire Water Quality Changes in Portuguese Reservoirs* (No. EGU22-4224). Copernicus Meetings.

Nunes, L., Monteiro, J. P., Cunha, M. D. C., Vieira, J., Lucas, H., & Ribeiro, L. (2006). The water crisis in southern Portugal: how did we get there and how should we solve it.

Management of Natural Resources, Sustainable Development and Ecological Hazards, edited by: Brebbia, CA, Conti, ME, and Tiezzi, E., T. Ecol. Environ, *99*, 435-444.

Nunes, A. N., Lourenço, L., & Meira, A. C. (2016). Exploring spatial patterns and drivers of forest fires in Portugal (1980–2014). *Science of the total environment*, *573*, 1190-1202.

Nunes, J. P., Doerr, S. H., Sheridan, G., Neris, J., Santín, C., Emelko, M. B., ... & Keizer, J. (2018). Assessing water contamination risk from vegetation fires: Challenges, opportunities and a framework for progress. *Hydrological Processes*, *32*(5), 687-694.

Pacheco, F. A., & Fernandes, L. F. S. (2021). Hydrology and stream water quality of fire-prone watersheds. *Current Opinion in Environmental Science & Health*, *21*, 100243.

Parente, J., & Pereira, M. G. (2016). Structural fire risk: The case of Portugal. Science of the total environment, 573, 883-893.

Parente, J., Pereira, M. G., Amraoui, M., & Tedim, F. (2018). Negligent and intentional fires in Portugal: Spatial distribution characterization. *Science of the total environment*, *624*, 424-437.

Parente, J., Amraoui, M., Menezes, I., & Pereira, M. G. (2019). Drought in Portugal: Current regime, comparison of indices and impacts on extreme wildfires. *Science of the Total Environment*, *685*, 150-173.

Parente, J., Girona-García, A., Lopes, A. R., Keizer, J. J., & Vieira, D. C. S. (2022). Prediction, validation, and uncertainties of a nation-wide post-fire soil erosion risk assessment in Portugal. Scientific Reports, 12(1), 2945.

Paul, M. J., LeDuc, S. D., Lassiter, M. G., Moorhead, L. C., Noyes, P. D., & Leibowitz, S. G. (2022). Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resources Research*, *58*(9), e2021WR030699.

Peduzzi, P., Dao, H., Herold, C., & Mouton, F. (2009). Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. *Natural hazards and earth system sciences*, *9*(4), 1149-1159.

Pereira, M. G., Aranha, J., & Amraoui, M. (2014). Land cover fire proneness in Europe. *Forest Systems*, *23*(3), 598-610.

Pires B. (2016, April 30). Joaquim Peres, a nova face da Águas do Algarve. *Barlavento.* Retrieved January 16, 2022, from: https://barlavento.sapo.pt/destaque/joaquim-peres-a-nova-face-da-aguas-do-algarve

Rádio Renascença (2017, December 12). Ashes pollute the waters of Góis and Ansião. Government says problem is solved. Retrieved January 15, 2023, from: https://rr.sapo.pt/noticia/pais/2017/12/12/cinzas-poluem-aguas-de-gois-e-ansiao-governo-diz-que-problema-esta-resolvido/100550/

Ramos, A. M., Russo, A., DaCamara, C. C., Nunes, S., Sousa, P., Soares, P. M. M., ... & Trigo, R. M. (2023). The compound event that triggered the destructive fires of October 2017 in Portugal. iScience.

Raoelison, O. D., Valenca, R., Lee, A., Karim, S., Webster, J. P., Poulin, B. A., & Mohanty, S. (2022). Wildfire impacts on surface water quality parameters: Cause of data variability and reporting needs. *Environmental Pollution*, 120713.

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental health perspectives*, *124*(9), 1334-1343.

Reneau, S. L., Katzman, D., Kuyumjian, G. A., Lavine, A., & Malmon, D. V. (2007). Sediment delivery after a wildfire. *Geology*, *35*(2), 151-154.

Ribeiro, L. (2007). Groundwater in the Southern Member States of the European Union: an assessment of current knowledge and future prospects.

Richardson, D., Black, A. S., Irving, D., Matear, R. J., Monselesan, D. P., Risbey, J. S., ... & Tozer, C. R. (2022). Global increase in wildfire potential from compound fire weather and drought. Npj Climate and Atmospheric Science, 5(1), 23.

Robinne, F. N., Miller, C., Parisien, M. A., Emelko, M. B., Bladon, K. D., Silins, U., & Flannigan, M. (2016). A global index for mapping the exposure of water resources to wildfire. *Forests*, *7*(1), 22.

Robinne, F. N., Hallema, D. W., Bladon, K. D., Flannigan, M. D., Boisramé, G., Bréthaut, C. M., ... & Wei, Y. (2021). Scientists' warning on extreme wildfire risks to water supply. *Hydrological processes*, *35*(5), e14086.

Sanabria, L. A., Qin, X., Li, J., Cechet, R. P., & Lucas, C. (2013). Spatial interpolation of McArthur's forest fire danger index across Australia: observational study. *Environmental modelling & software*, *50*, 37-50.

Santos, M., Fragoso, M., & Santos, J. A. (2017). Regionalization and susceptibility assessment to daily precipitation extremes in mainland Portugal. *Applied Geography*, *86*, 128-138.

Sequeira, M. D., Castilho, A. M., Dinis, P. A., & Tavares, A. O. (2020a). Impact assessment and geochemical background analysis of surface water quality of catchments affected by the 2017 portugal wildfires. *Water*, *12*(10), 2742.

Sequeira, M. D., Castilho, A. M., Tavares, A. O., & Dinis, P. (2020b). Assessment of superficial water quality of small catchment basins affected by Portuguese rural fires of 2017. *Ecological Indicators*, *111*, 105961.

Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews*, *105*(3-4), 71-100.

Silva, V., Pereira, J. L., Campos, I., Keizer, J. J., Gonçalves, F., & Abrantes, N. (2015). Toxicity assessment of aqueous extracts of ash from forest fires. Catena, 135, 401-408.

Smith, H. G., Sheridan, G. J., Lane, P. N., Nyman, P., & Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology*, *396*(1-2), 170-192.

Soares, P. M., Cardoso, R. M., Ferreira, J. J., & Miranda, P. M. (2015). Climate change and the Portuguese precipitation: ENSEMBLES regional climate models results. *Climate dynamics*, *45*, 1771-1787.

Stigter, T. Y., Monteiro, J. P., Nunes, L. M., Vieira, J., Cunha, M. C., Ribeiro, L., & Lucas, H. (2007). Strategies for integrating alternative groundwater sources into the water supply system of the Algarve, Portugal. In *Proc. of the 2nd IWA Leading Edge Conference on Strategic Asset Management, Lisbon* (pp. 17-19).

Stigter, T. Y., Varanda, M., Bento, S., Nunes, J. P., & Hugman, R. (2017). Combined assessment of climate change and socio-economic development as drivers of freshwater availability in the south of Portugal. *Water resources management*, *31*, 609-628.

Thiel, A. (2010a). Ecological modernisation and the scalar level of contradictions in Southern European water politics: the case of the Odelouca Dam in Portugal. *Environment and Planning C: Government and Policy*, *28*(3), 492-511.

Thiel, A. (2010b). Constructing a strategic, national resource: European policies and the up-scaling of water services in the Algarve, Portugal. *Environmental management*, *46*, 44-59.

Trigo, R. M., Pereira, J. M., Pereira, M. G., Mota, B., Calado, T. J., Dacamara, C. C., & Santo, F. E. (2006). Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *26*(13), 1741-1757.

Turco, M., Jerez, S., Augusto, S., Tarín-Carrasco, P., Ratola, N., Jiménez-Guerrero, P., & Trigo, R. M. (2019). Climate drivers of the 2017 devastating fires in Portugal. *Scientific reports*, *9*(1), 13886.

TVI Notícias (2005, June 3). Drought in Portugal is the most serious of the last 60 years. Retrieved from January 17, 2023, from: https://tvi.iol.pt/noticias/chuva/meteorologia/seca-em-portugal-e-a-mais-grave-dos-ultihttps://rr.sapo.pt/noticia/pais/2017/12/12/cinzas-poluem-aguas-de-gois-e-ansiao-governo-diz-que-problema-esta-resolvido/100550/mos-60-anos

United Nations (n.d.). Disaster Risk Management. Retrieved October 12, 2022, from https://www.un-spider.org/risks-and-disasters/disaster-risk-management

Varela, M. E., Benito, E., & Keizer, J. J. (2015). Influence of wildfire severity on soil physical degradation in two pine forest stands of NW Spain. *Catena*, *133*, 342-348.

Verkaik, I., Rieradevall, M., Cooper, S. D., Melack, J. M., Dudley, T. L., & Prat, N. (2013). Fire as a disturbance in Mediterranean climate streams. *Hydrobiologia*, *719*, 353-382.

Vieira, J., Cunha, M. C., Nunes, L., Monteiro, J. P., Ribeiro, L., Stigter, T., ... & Lucas, H. (2011). Optimization of the operation of large-scale multisource water-supply systems. *Journal of Water Resources Planning and Management*, *137*(2), 150-161.

Ward, P. J., Blauhut, V., Bloemendaal, N., Daniell, J. E., de Ruiter, M. C., Duncan, M. J., Winsemius, H. C. (2020). Natural hazard risk assessments at the global scale. *Natural Hazards and Earth System Sciences*, *20*(4), 1069-1096.

Writer, J. H., & Murphy, S. F. (2012). *Wildfire Effects on Source-water Quality: Lessons from Fourmile Canyon Fire, Colorado, and Implications for Drinking-water Treatment* (Vol. 3095). US Department of the Interior, US Geological Survey.

10. Appendix

Appendix 1, Automated process designed in Qgis to process 32 years of burned area data (description of each step included)